EUROPEAN ORGANISATION
FOR THE SAFETY OF AIR NAVIGATION

EUROCONTROL

EUROCONTROL EXPERIMENTAL CENTRE

CONTEXT-SENSITIVE SPEECH RECOGNITION
IN THE AIR TRAFFIC CONTROL SIMULATION

EEC Note No. 02/2001

Issued: February 2001

REPORT DOCUMENTATION PAGE

Reference: EEC Note No. 02/2001	**Security Classification:** Unclassified
Originator: EEC - ASC (**A**nalytic and **Sc**ientific)	**Originator (Corporate Author) Name/Location:** EUROCONTROL Experimental Centre B.P.15 F - 91222 Brétigny-sur-Orge CEDEX FRANCE Telephone : +33 (0)1 69 88 75 00
Sponsor: EATCHIP Development Directorate DED.4	**Sponsor (Contract Authority) Name/Location:** EUROCONTROL Agency Rue de la Fusée, 96 B -1130 BRUXELLES Telephone : +32 2 729 9011

TITLE:

CONTEXT-SENSITIVE SPEECH RECOGNITION IN THE AIR TRAFFIC CONTROL SIMULATION

Author	Date	Pages	Figures	Tables	Appendix	References
D. Schaefer	2/01	xiii + 192	57	23	6	91

EATCHIP Task Specification	Project	Task No. Sponsor	Period
-	-	-	1994 to 2001

Distribution Statement:
(a) Controlled by: Head of ASC
(b) Special Limitations: None
(c) Copy to NTIS: ~~YES~~ / NO

Descriptors (keywords):

Air Traffic Control, ATC Simulation, Automatic Speech Recognition, Cognitive Models, Context Knowledge, Dynamic Syntax

Abstract:

This report discusses the use of situation knowledge as a means to enhance the recognition performance of commercially available automatic speech recognizers. A cognitive model of the ATC controller is proposed that continuously observes the present situation and generates a prediction of the sentences the controller is most likely to say. The prediction is made available to the speech recognizer which thus gains a basic form of situation knowledge. The results of an experimental evaluation of this approach in an ATC simulator are discussed.

Dirk Schäfer

Context-Sensitive Speech Recognition in the Air Traffic Control Simulation

This book has been submitted to the German Armed Forces University in Munich, Germany, as a Doctoral Thesis

UNIVERSITÄT DER BUNDESWEHR MÜNCHEN
Fakultät für Luft- und Raumfahrttechnik

Thema der Dissertation:
Context-Sensitive Speech Recognition in the Air Traffic Control Simulation

Verfasser: Dirk Schäfer

Vorsitzender des Promotionsausschusses: Prof. Dr.-Ing. Dipl.-Kfm. Bernhard Katzy

1. Berichterstatter: Prof. Dr.-Ing. Reiner Onken

2. Berichterstatter: Prof. Dr.-Ing. Heinz Winter, Institut für Luft- und Raumfahrt der Technischen Universität Berlin

Tag der Prüfung: 27. November 2000

Mit der Promotion erlangter akademischer Grad: Doktor der Ingenieurwissenschaften (Dr.-Ing.)

Paris, den 25. Januar 2001

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ABBREVIATIONS

A/D	Analogue / Digital
ACT	Adaptive Control of Thoughts
AIC	Air Intercept Control
AIP	Aeronautical Information Publication
API	Application Programmer's Interface
ASCII	American Standard Code for Information Interchange
ASR	Automatic Speech Recognition
ATC	Air Traffic Control
ATCSim	ATC Simulation
ATCSR	ATC Speech Recognizer
ATMOS	Air Traffic Management and Operations Simulator
ATN	Augmented Transition Network
BFS	Bundesanstalt für Flugsicherung (predecessor of DFS)
CAA	Civil Aeronautics Authority
CASSY	Cockpit Assistant System
CBT	Computer Based Training
CCM	Cognitive Controller Model
CE	Callsign Error
COMPAS	Computer Oriented Metering, Planning, and Advisory System
CPU	Central Processing Unit
C-VFR	Controlled Visual Flight Rules
DFS	Deutsche Flugsicherung GmbH (German Air Navigation Services)
DLL	Dynamic Link Library
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
DSP	Digital Signal Processing Chipset
EnCoRe	Enroute Controller's Representation
FAA	Federal Aviation Administration
FFM	Frankfurt (navigation aid)
FFT	Fast Fourier Transformation
FL	Flight Level
GUI	Graphical User Interface
Hdg	Heading
HMM	Hidden Markov Model
IAS	Indicated Airspeed
ICAN	International Commission for Air Navigation
ICAO	International Civil Aviation Organization

IE	Instruction Error
IFR	Instrument Flight Rules
ISA	Instantaneous Self Assessment
ISC	Interactive Speech Card
kts	Knots
LBU	Luburg (navigation aid)
MINDS	Multi-modal Interactive Dialogue System
MoFl	Model der Fluglotsentätigkeit - Model of Controller Behavior
NASA	National Aeronautics and Space Administration
NDB	Non-Directional Radio Beacon
NM	Nautical Miles
NTM	Nattenheim (navigation aid)
PC	Personal Computer
PDI	Phonetic Decoder Interface
PE	Parameter Error
RADAR	Radio Detection And Ranging
ROC/D	Rate of Climb/Descent
RTCA	Radio Technical Commission for Aeronautics
RUD	Rüdesheim (navigation aid)
SWAT	Subjective Workload Assessment Technique
TAU	Taunus (navigation aid)
TE	Total Error
TLX	Task Load Index
UTC	Universal Time Coordinated
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	Very High Frequency Omni-directional Radio Beacon
WR1	Westradar 1
WR2	Westradar 2

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1 Introduction

In the early days of aviation there seemed to be unlimited space for air traffic. But very soon substantial growth rates in aviation revealed that uncontrolled air traffic would expose aircraft to the risk of mid-air collisions. To avoid these risks, the first conventions about air navigation were implemented in the early 1920s. When radio communication between ground stations and aircraft was invented in the early 1930s, the predecessors of today's air traffic control (ATC) services were installed, responsible for maintaining safe separations between all aircraft in the airspace of their responsibility. The pilots, in turn, were obliged to comply with the instructions of ATC controllers.

Although accidents in aviation can have catastrophic effects, traveling by air is very safe when compared to other means of transportation.[1] However, annual growth rates of about seven percent for the number of commercial flights were reported in Germany during the last decades and the increase is predicted to continue in the near future [DFS 98]. Air traffic control services have to cope with steadily growing rates of traffic while maintaining and even increasing today's standards of safety and efficiency.

Computer-based systems can facilitate this task to some degree. However, replacing the human operator by automated systems does not appear to be a viable approach because air traffic control is a fairly complex process, and automated systems, at least in the near future, seem incapable of dealing with other than standard situations sufficiently reliable. Besides that, complete automation would leave the human operator in the role of a passive supervisor. A more promising approach is to design systems that support the controller and free him from tedious routine tasks while helping him to maintain situation awareness. Whenever computer-based systems have been introduced in ATC in recent years, it has continuously been emphasized that they should be designed as assistance systems, keeping the controller in the decision process and leaving it up to him or her whether to delegate tasks to the system or not.

Assistant systems that support the human operator efficiently must be designed in a way that they exactly suit the operators needs and provide the right functionality at the right time. A good understanding of the cognitive processes involved in air traffic control is necessary in order to achieve a good system design. Whether computer

[1] The National Safety Council has calculated that the rate of fatalities among scheduled US airline flights in 1994 was 0.04 per one hundred million passenger miles. The rate of fatalities among automobiles for the same time was 0.86 per one hundred million passenger miles, more than 21 times higher [FAA-1 97].

and human operator can cooperate efficiently becomes a question of crucial importance. Cognitive science approaches and ergonomics can to some degree contribute to the solution of this question. However, new systems cannot be introduced in operational service without extensive testing.

Air traffic control simulation facilities provide a realistic environment for testing and evaluation of new systems without causing safety hazards. Integration of simulation studies in an early phase of the design process also provides a rich source of information for system design. In order to confront the test subjects with the same conditions they would encounter in reality and thus to be able to transfer findings from simulations to reality, the simulation must be highly realistic.

Most ATC simulation environments use the so-called pseudo pilot concept to simulate the communication between the controller and the pilots of aircraft in the control sector. Via a simulated radio connection the controller transmits clearances to pseudo pilots who control the aircraft accordingly and confirm the instructions. Depending on the number of aircraft a pseudo pilot has to operate, entering the clearance parameters and reading back the clearances often results in very high workload. This sometimes causes delayed, erroneous, or even non-existent pilot responses. Obviously, the capacity of pseudo pilots to respond to clearances immediately and reliably is crucial for the quality of the simulation. Therefore extensive training and a sufficient number of pseudo pilots is required, so that ATC simulations are comparatively expensive.

At least some problems correlated to the pseudo pilot concept can be solved by the introduction of automatic speech recognition systems (ASR) in ATC simulators. However, in order not to adversely affect the simulation, an excellent performance of the speech recognizer is crucial. The number of misrecognitions must not exceed those of pilots and pseudo pilots. Also immediate responses to the clearances are required.

Overwhelming advances have been achieved in ASR hard- and software technology during the last two decades. Some 15 years ago, speech recognition was limited to systems understanding a dozen of isolated words with marginal accuracy after having been trained by an individual speaker. Today, speaker-independent ASR systems recognize continuous speech and deal with large vocabularies. However, ASR technology still doesn’t meet the requirements for a successful application in air traffic control and ATC simulation. Recent studies conclude that "today’s speech recognition technology just isn’t good enough for this domain" [Churcher 96].

One approach to enhance the performance of existing ASR systems consists in the use of situation knowledge. A system that continuously observes the situation and assesses the likelihood of each possible instruction could provide some basic form of artificial situation awareness. The scope of this work is to investigate the benefits of this approach for speech recognition in the air traffic control simulation. Additional concerns, such as usability, user acceptance, and perceived workload also are discussed.

Chapter 2 provides an overview of air traffic control and ATC simulation. The history of ATC and its present state are discussed. An introduction to ATC simulators and the pseudo pilot concept is given. The problems correlated to the pseudo pilot concept are outlined and automatic speech recognition (ASR) is proposed as a solution for these problems.

The fundamentals of automatic speech recognition are described in chapter 3. Further, requirements for a successful application of speech recognition in an ATC simulation environment are discussed and the performance of currently available systems is outlined. Related studies and their approaches are discussed in detail.

The use of situation knowledge as a means to increase the recognition performance is presented in chapter 4. Using situation knowledge requires a dynamic assessment of the actual situation and an estimation which instructions might be expected. A cognitive model of the ATC controller is proposed to support a dynamic situation assessment.

The fundamentals of a cognitive model of controller behavior are presented in chapter 5 and the Cognitive Controller Model (CCM) is proposed as a model of mental processes involved in air traffic control. According to existing models of problem solving provided by cognitive psychology the working process in air traffic control is structured and three main processes are identified: observation of the traffic situation, decision making and planning, and controller-pilot communication. Each of these processes is discussed in detail.

Chapter 6 describes the implementation of CCM as a computer program. The structure and architecture of the model are outlined together with its calibration. The performance of the model is discussed by comparing its estimations with data recorded in ATC simulations.

The implementation of the speech recognizer and its interface to the controller model and the ATC simulation are presented in chapter 7. The speech recognizer identifies the clearances issued by the controller and transmits the corresponding parameters to the simulation. It also simulates the response of a pilot with synthetic speech. Each of these functions is described in detail.

Chapter 8 describes the experiments carried out in an ATC simulator in order to evaluate the overall effects the use of situation knowledge has on the recognition performance. Qualified ATC personnel participated in simulation sessions in which aircraft were controlled by means of voice. The effects of ASR technology on user acceptance and controller workload were also investigated.

The results of the experiments are presented in chapter 9. The recognition performance is discussed as well as the usability of the speech recognition system, judged by test subjects and indicated by assessment of subjective workload. Finally, the potential of this approach for future systems is discussed.

Chapter 10 summarizes the findings and gives an estimate of benefits and drawbacks of the Cognitive Controller Model and the use of situation knowledge for automatic speech recognition in the area of ATC simulation.

2 Air Traffic Control and Air Traffic Control Simulation

Steady increases in air traffic have created a crowded sky where unlimited space seemed to exist when the first manned aircraft lifted off a century ago. It soon became apparent that uncoordinated air traffic would suffer from great hazards of accidents. Air traffic control services were implemented and entrusted with controlling the air traffic. Procedures and regulations became more complex and compliance with them more important as the traffic density increased further. Air traffic control services were equipped with increasingly complex technical systems. With the importance of air traffic control, the need to emulate the working environment of controllers in simulation facilities became apparent. This permits the training of controllers and helps to test new systems before their introduction into operational service. In order to simulate the communication between controller and pilot, most simulation facilities use the pseudo pilot concept which means that simulator staff execute and respond to the controller's clearances. The replacement of pseudo pilots with automatic speech recognition would make simulation facilities independent of the costly need for personnel. However, in order not to affect the simulation environment in an unwanted way, its performance must be at least equal to that of human listeners. This leads to several requirements towards the speech recognizer for an undisturbed simulation environment.

2.1 The History of Air Traffic Control

In the early days of manned aviation airborne vehicles were permitted to fly with little or no restrictions. Few aircraft existed and they were only operated with moderate speed and under good weather conditions so that there seemed to be little danger of mid-air collisions. Navigation was based on compass courses between characteristic locations or was completely based on vision, often using roads or railway tracks as navigational aids. The convention to fly right of such features is considered as one of the first rules in air traffic [Colchester 61].

An increase in air traffic following World War I soon demonstrated the necessity of agreements on air traffic rules. Several European countries founded the International Commission for Air Navigation (ICAN) in 1919 and agreed on the International Convention for Air Navigation. The United States did not sign the ICAN convention but implemented some of its concepts when launching a program to establish the Federal Airways System in 1927.

The 1920s and particularly the 1930s saw a significant increase in passenger air traffic and it soon became apparent that aviation would play a major role in a future transportation system if only the navigation could be supported by means independent of the weather [Gilbert 73]. First steps towards instrumental navigation were taken when in 1927 four course radio beacons were installed across the United States, permitting aircraft equipped with a radio receiver to maneuver along one of the four beams. Air routes independent of landmarks were established, using the location of the beacons and the crossing points of beams as fixes. By 1929 radio marker beacons were introduced that permitted to navigate towards the beacon from any direction [RTCA 52]. Also, light beacons were installed to support navigation at night. In 1936 the major airports in Germany were connected by ten night flight air routes, constructed from 157 light beacons [BFS 90]. However, a severe disadvantage of light beacons was that they permitted navigation under good weather conditions only.

In 1930, two way radio telephone communication between aircraft and ground stations came into operation. Until 1932, most US airlines had equipped their aircraft for radio telephone communication with airline ground stations which allowed them to report flight progress and receive meteorological information. The first radio-equipped airport control tower entered service at Cleveland Municipal Airport in 1930 with 20 other airports following during the next five years [Gilbert 73]. However, apart from airport towers, radio transmissions were mostly used for the communication with airline radio operators and dispatchers.

In 1934, the major American airlines installed flight tracking systems for their aircraft when approaching large airports. These systems were based on aircraft position reports to an airline radio operator. In case of a conflict, the radio operators of the concerned airlines communicated with each other and with the tower controller. This soon demonstrated the benefits of a coordinated effort. The major airlines signed the Interline Agreements and consented to the establishment of joined Airway Traffic Control Centers at the airports of Newark, Chicago, and Cleveland which went into operation in 1935 and 1936. In 1936, the Airway Traffic Control Centers were taken over by the US government and five additional centers were established during the next months. The centers derived the traffic situation from aircraft position reports they received via radio transmission and copied to a blackboard. The aircraft positions were then estimated and marked on a map table. In the early 1940s blackboards for entering aircraft position reports were gradually replaced by paper flight progress strips. Each strip covered the flight of one aircraft between two reporting points, presenting the necessary information from the flight plan and allowing the controller to write down reports and advisories with a pencil. By 1942, 23 additional Airway Traffic Control Centers had gone into operation and a complete coverage of the US airway system had been achieved [Gilbert 73].

Figure 2-1 Air traffic control center in the early 1950s [Source: DFS].

In 1947 the International Civil Aviation Organization (ICAO) was founded, a date commonly marked as the beginning of air traffic control. The ICAO, with at that time more than 50 signatory nations, released standards and procedures for air traffic which were then incorporated by the local administrations of the member countries.

The second fundamental advance in air traffic control after the invention of radio communication was achieved with the invention of RADAR (Radio Detection and Ranging) during World War II. Since radar provides a precise position of each aircraft in the vicinity of the radar antenna, it greatly contributed to the accuracy in air traffic control. Due to position estimates that were troubled by reporting delays and inaccurate navigation, huge separations had formerly been necessary which could now be reduced considerably. Moreover, the visualization of the aircraft positions on a radar screen greatly facilitated the work for ATC controllers, depicting an air traffic situation which before had to be constructed mentally from position reports. Beginning in the early 1950s, radar systems went into operation in US ATC facilities.

Radar screens display the positions of all targets in the range of a radar antenna. The radar antenna emits radio wave pulses while rotating around an axis, usually vertical, and receives the pulses reflected by obstacles. By measuring the duration between emission and reception the distance of targets can be calculated, while the bearing to the targets is derived from the angle of the antenna during emission and reception. Thus, a two-dimensional image of the position of all targets in the vicinity

Figure 2-2 Air traffic control center in the early 1970s [Source: DFS].

of an antenna can be produced. Radar systems based on this principles are called primary radar. A drawback of primary radar systems is that they do not provide information about the altitude. Also, the altitudes of targets in the three-dimensional space distorts its depiction in the two-dimensional plane.

Aircraft can be equipped with so-called transponders that receive the pulses emitted by the radar antenna and in turn send a response signal. Transponders transmit additional aircraft-specific information such as an aircraft identification code, altitude, and speed to the ground station. This information can then be displayed on the radar screen next to the aircraft position. Radar systems based on this technology are referred to as secondary radar.

By the mid-70s a semi-automated ATC system had been introduced in the United States, based on secondary radar technology. Although the new systems greatly facilitated the work of ATC controllers, continuous enhancements were required to successfully manage the heavily increasing US air traffic of the late 1970s. The increase was at least partially due to the Airline Deregulation Act of 1978 which created a competitive environment by permitting newly founded airlines to operate on what was before a regulated market.

Although troubled by two World Wars, the development of air traffic control in Germany followed a similar pattern. After World War II the responsibility for air traffic within the German borders remained with the allied forces. As aviation played a major role in World War II, this step was deemed necessary in order to prevent Germany from regaining military strength too quickly. Air traffic control in the American protection zone was coordinated by the Federal Aviation Authority[2] and many American standards and procedures were implemented in West Germany.

In 1953, the allied forces decided that Western Germany should regain air sovereignty. In consequence, the Bundesanstalt für Flugsicherung (BFS) was established and entrusted with coordinating and controlling air traffic in Germany. After regaining full sovereignty, West Germany became member of ICAO.

In the late 1950s and early 1960s faster, jet-powered aircraft with longer ranges came into service. It soon became obvious that efficiency gains in air traffic control would result from jointly coordinating areas larger than the European countries. In 1960, Germany, France, the United Kingdom and the Benelux countries signed the Eurocontrol Treaty to coordinate and harmonize air traffic control throughout Europe. The Eurocontrol organization was put into service at the same time. Centralized air traffic control throughout Europe, however, would touch upon national sovereignties and many Eurocontrol member countries were reluctant to implement it. Advances have been achieved slowly and are still in progress.

Similar to the deregulation in the United States, air traffic deregulation took place in Europe in 1993, resulting in a variety of newly founded airlines and an increase in scheduled flights. At the same time the services of the BFS were transferred to DFS Deutsche Flugsicherung GmbH (German Air Navigation Services), newly founded in 1992 as a limited liability company. Presently DFS employs about 4,900 personnel including 3,600 ATC controllers. In 1997 DFS had to manage a total of 2.2 million commercial flights in the Federal Republic of Germany [DFS 98].

2.2 Air Traffic Control Today

Two categories of flights exist in controlled airspace, visual flight rules (VFR) and instrument flight rules (IFR). Pilots flying under visual flight rules are responsible for maintaining visual separation from other aircraft. To guarantee that other traffic can be detected early enough, minimum visibility requirements are binding for VFR

[2] The Civil Aeronautics Administration (CAA) was founded in 1940, entrusted with the United States Air Traffic Control Services. The Civil Aeronautics Administration was succeeded by the Federal Aviation Agency (FAA) in 1958 which changed its name into Federal Aviation Administration when it was taken over by the newly founded Department of Transportation in 1967 [FAA-1 97].

flights. Pilots may either navigate visually or based on navigational aids. Aircraft flying under Instrumental Flight Rules navigate on air-routes with the help of navigational aids and are not dependent on visibility conditions. Air traffic control services are responsible for maintaining separation between all aircraft and the pilots are obliged to comply with ATC instructions. The requirements for aircraft equipment and pilot qualifications are significantly higher for IFR flights.

The airspace in Germany is vertically divided into the lower airspace between ground and flight level 240 and the upper airspace from flight level 245 to flight level 460, each flight level representing an altitude of 100 feet. The airspace is also classified into different categories, in each of which different procedures and requirements apply. As this classification has been derived from ICAO standards, it is common among most ICAO member countries. A classification of the lower airspace in Germany is depicted in Figure 2-3. In the uncontrolled airspace G only VFR flights are permitted. The airspaces C, D, E, and F are controlled airspaces. Airspace C permits IFR flights and controlled VFR flights[3] only and applies above flight level 100 in all areas and on top of airport control zones in some areas. Airspace D describes the control zones of controlled airports. The remaining airspace above airspace G is named airspace E. Airspace D and E permit both IFR and VFR flights.

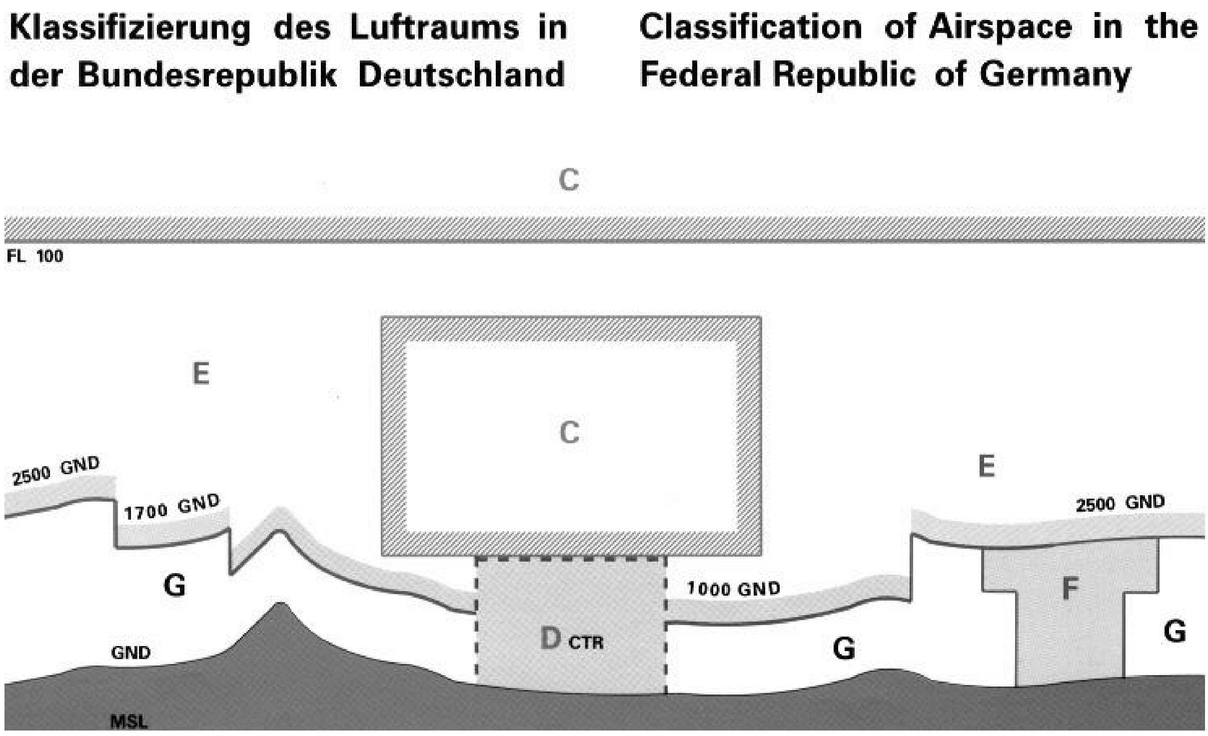


Figure 2-3 Vertical Airspace Structure in Germany [AIP 97].

[3] Flight under IFR conditions with VFR aircraft equipment. The pilot must hold a C-VFR license.

Higher altitudes permit more economic flights regarding travel time and fuel consumption. For economic reasons and to avoid conflicts with VFR traffic, commercial aviation generally flies in airspace C. The remainder of this chapter therefore focuses on airspace C.

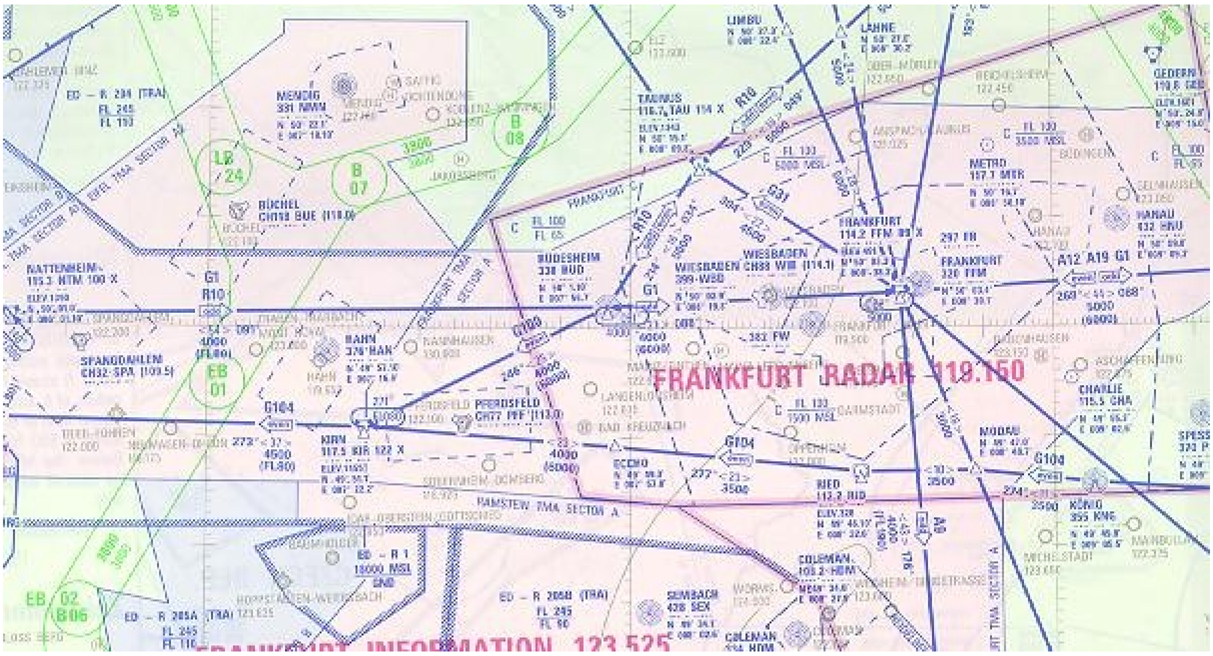


Figure 2-4 Lateral airspace structure, excerpt from aviation chart [AIP 97].

Airspace C is divided into control sectors in which one air traffic controller is responsible for ensuring separations between all aircraft. IFR traffic usually navigates on published air-routes. The segments of these routes consist of the connections between two navigational aids, such as Non Directional Radio Beacons (NDB) or Very High Frequency Omni-directional Radio Beacons (VOR). Figure 2-4 depicts an excerpt of an aviation chart for the vicinity of Frankfurt airport in Germany.

Air traffic control services may be divided into the following categories:

- tower, apron, and ground control
- approach and departure control
- enroute control.

Tower, apron, and ground services control traffic at and around airports, maintaining visual contact to the aircraft. Approach and departure control services control approaching and departing traffic in the vicinity of airports while enroute control is responsible for aircraft in controlled airspace above flight level 100. A tower controller working position is depicted Figure 2-5 in while Figure 2-6 shows the working position of an enroute controller.

Figure 2-5 Control tower at München airport [source: DFS].

Figure 2-6 München enroute control center [source: DFS].

For all approach, departure and enroute control services, the major sources of information are

- the radar screen
- paper flight strips
- radio/telephone communication with aircraft pilots and other ATC controllers.

Figure 2-7 depicts a radar screen based on secondary radar technology. Note for example the aircraft with the callsign SAB513 (Sabena flight 513) heading east. The second line in the aircraft label specifies the current flight level (92), the ground speed (29 = 290 knots) and the aircraft weight category (M = medium). Secondary radar displays are in operational service since 1980 and all aircraft flying in controlled airspace in Germany must be equipped with transponders.

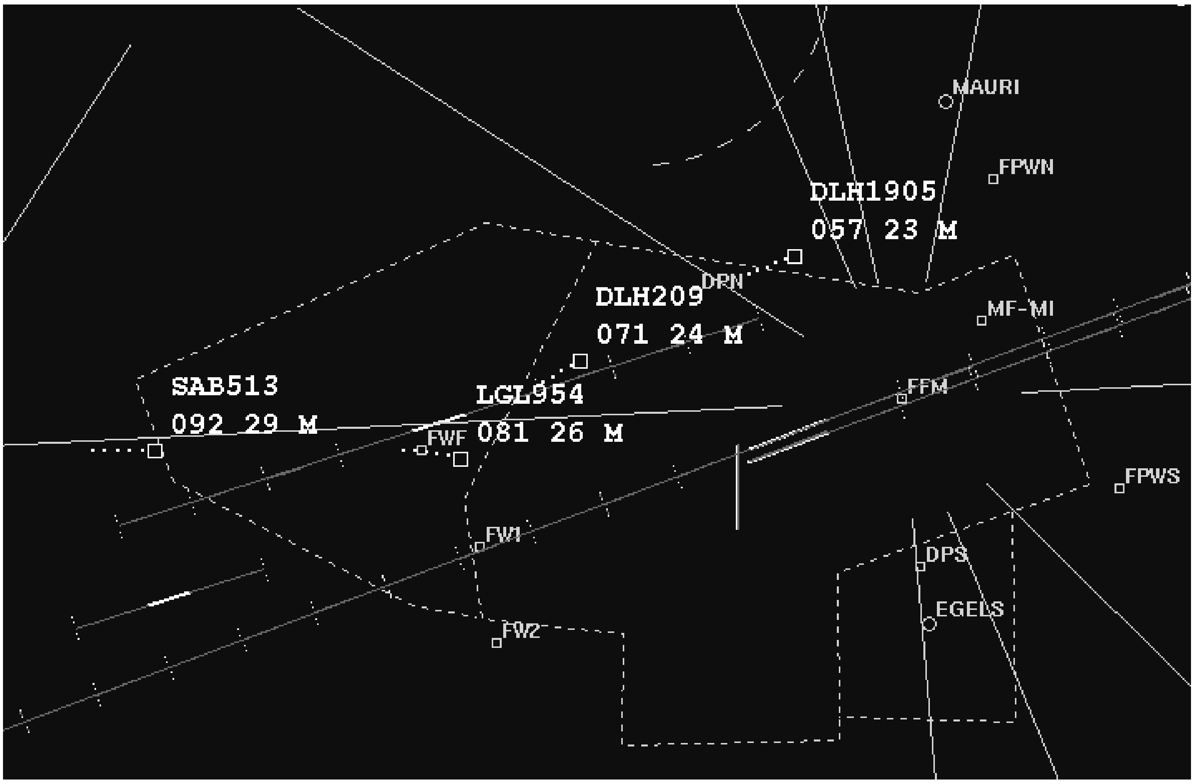


Figure 2-7 Radar screen based on secondary radar.

Pilots of aircraft flying under instrument flight rules must file a flight plan prior to departure giving details about aircraft equipment and the requested route to the destination airport. The flight plans are processed centrally in order to avoid conflicts and to provide the relevant information to all concerned control sectors. For each aircraft flying in a sector a paper flight strip is printed, displaying the necessary information for that sector. The flight strips are handed to controllers a few minutes before the aircraft enters the sectors to inform them of the traffic they have to expect. Figure 2-8 depicts a paper flight strip. It contains (from left to right) the scheduled time overhead the fix Frankfurt (FFM) (10.15 UTC), the scheduled flight level (FL120), aircraft type and weight category (B747, heavy), callsign (DLH126), maximum speed (510 knots), and the routing within the sector (entering the sector overhead waypoint Luburg (LBU), proceeding via Frankfurt (FFM) and Taunus (TAU)).

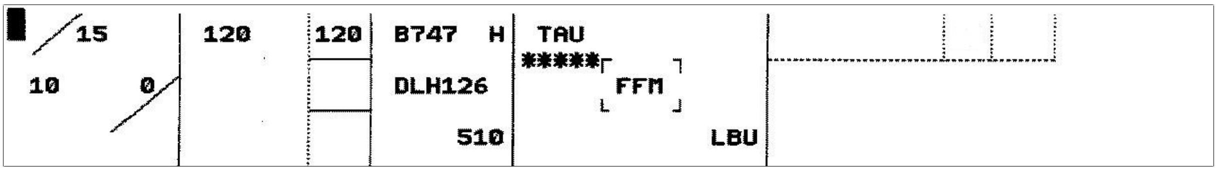


Figure 2-8 Paper flight strip.

The paper flight strips are generally stored on a strip board and sorted by the time at which an aircraft is expected to enter the sector. The ATC controller may write on the flight strip with a pencil to keep track of control advisories he or she issued to the aircraft. Figure 2-9 depicts a strip board with paper flight strips.

Usually a team of two controllers takes responsibility for the traffic within an ATC sector, consisting of a planning controller and an executive controller. The planning controller reviews the flight plan information, identifies possible conflicts on a strategic basis and develops solutions which he proposes to the executive controller. The executive controller solves conflicts on a short-term basis and issues clearances to the aircraft pilots. If traffic density permits, the executive controller alone coordinates traffic in the sector.

The executive controller communicates with the pilots of aircraft in his sector on a very high frequency (VHF) radio frequency which is published in navigation charts and which all pilots flying in this sector have to monitor. A communication is typically initiated by a controller issuing an instruction, addressing the aircraft by its callsign. The pilot reads back the clearance to acknowledge it. Other pilots listen to the communication and derive a mental picture of the traffic situation in their vicinity, an effect referred to as the party line effect. In order to allow for a fast and efficient communication and to minimize the risks of misunderstanding, the phraseology of pilot controller communications has been standardized by ICAO.

Although the principles of air traffic control have remained mostly unchanged during the last four decades, continuous improvements have been achieved. Only in this way was it possible to handle the increasing traffic density efficiently and safely. Between 1986 and 1997 the number of IFR flights in the Federal Republic of Germany doubled from 1.08 million to 2.21 million. During the same time, the number of hazardous situations was continuously reduced: in 1997 a total of only 15 aircraft proximities[4] have been reported in German airspace, only one of which was caused by ATC services. No accidents or incidents occurred in that year [DFS 98].

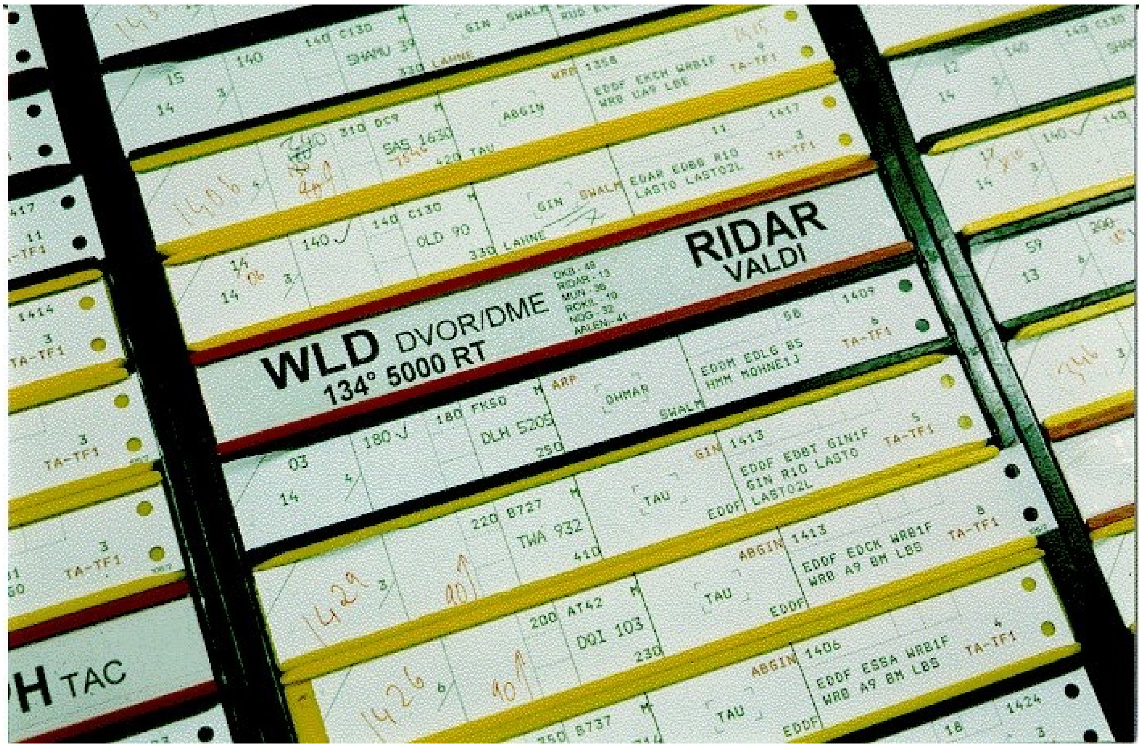


Figure 2-9 Flight strip board [source: DFS].

To be able to safely and efficiently deal with the anticipated growth in air traffic it is required to develop new concepts and controller assistance systems. These systems have to be optimized and tested extensively prior to their introduction into operational service. Air traffic control simulators serve as experimental testbeds, providing realistic conditions for controllers without causing hazards to real air traffic. The fundamentals of ATC simulators will be discussed below.

2.3 Air Traffic Control Simulation

ATC training simulators provide an efficient supplement to theoretical training and training on the job. By gradually increasing the complexity of the training scenarios, students can be confronted with situations tailored to their growing skills. Emergency scenarios hopefully never encountered in reality may be generated without imposing hazards upon real aircraft. Training simulators are also used to maintain the skills of experienced controllers in critical situations. In Germany, the German Air Navigation Services operates a variety of ATC simulators for training purposes.

[4] Violations of the minimum separation between two or more aircraft or between an aircraft and ground obstacles without damage to humans or the airframe are referred to as aircraft proximities. Incidents involve the damage of airframes or injury of persons while accidents involve fatalities.

Air traffic control simulators are also used for research purposes. This helps to test and evaluate new ATC concepts and systems throughout the design phase and before introduction into operational service. The results of the simulations permit the assessment of system performance and usability and the identification of weak points, so that the system can be enhanced accordingly. Also, research simulation facilities are used to scrutinize the mental processes involved in the work of ATC controllers. Simulations allow for the generation of scenarios according to the specific scope of the investigation and the reproduction of these scenarios if necessary. All relevant data can be logged for analysis. ATC research simulators are mostly operated by ATC equipment manufacturers and research facilities. The German Aerospace Center (DLR) operates the Air Traffic Management and Operations Simulator (ATMOS) in its Braunschweig research center with three radar controller working positions for enroute and approach/departure sectors. Figure 2-10 depicts one of the three controller working positions of DLR's ATMOS.

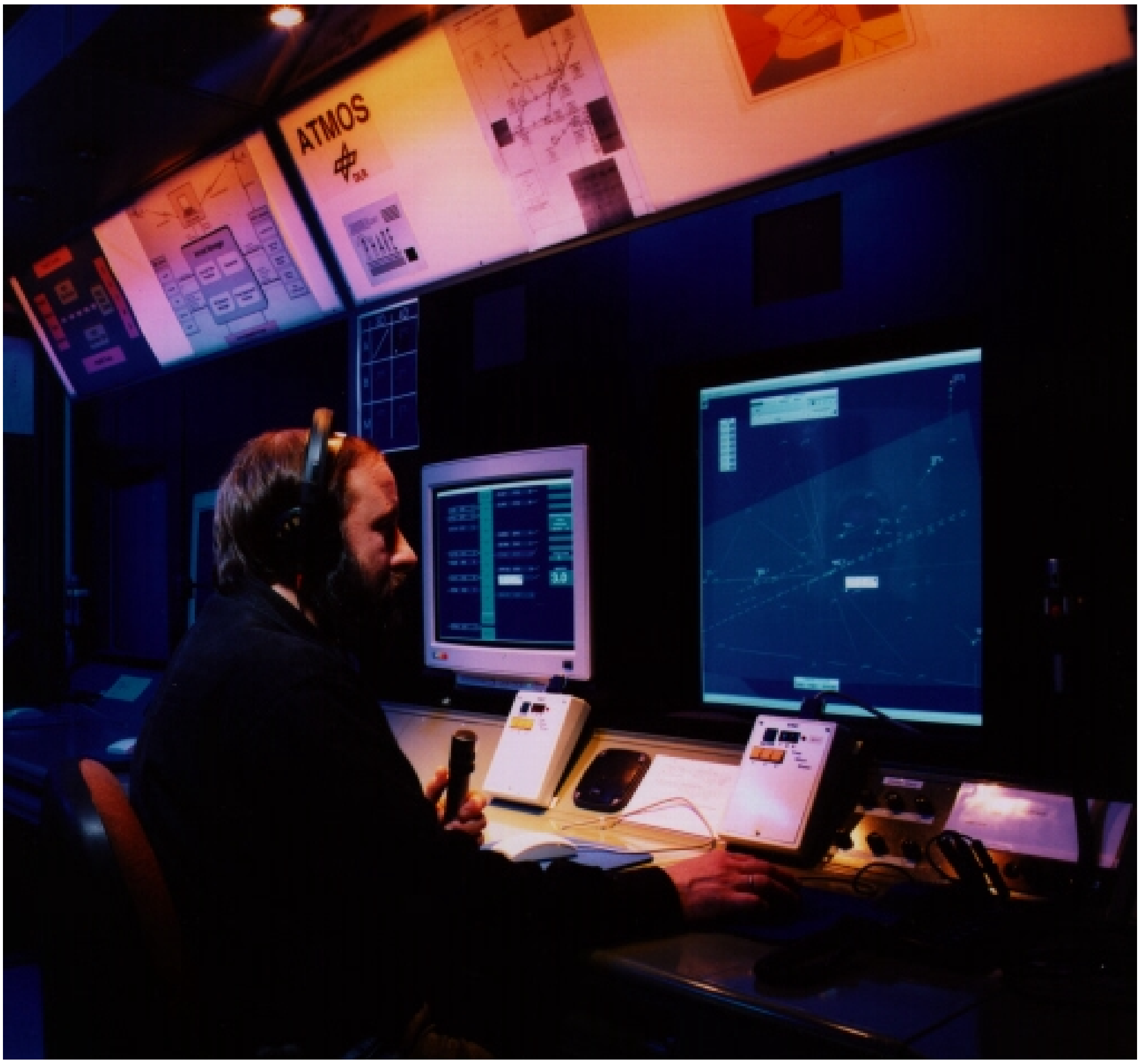


Figure 2-10 Controller working position at DLR's ATMOS.

According to the specific field of use, the fidelity of ATC simulators may vary considerably. Simple mouse-operated standalone systems serve to familiarize student controllers with basic control procedures while generating realistic working environments for research purposes requires more complex systems. Common among most simulators, however, is that artificial aircraft symbols are presented on a display simulating the radar screen. The simulated aircraft correspond to computer-generated data possessing static and dynamic properties such as callsign, position, altitude, speed, and heading. Control advisories can be entered to the simulation computer via an interface so that the aircraft executes the desired maneuvers.

Most ATC simulation facilities use the pseudo pilot concept to simulate the communication with aircraft pilots. Each controller working position is equipped with a radio communication link to pseudo pilots in an adjacent room. The pseudo pilots listen to the clearances and enter the relevant parameters via a terminal which is connected to the simulation computer. They also read back the clearances, giving the controller the impression he or she had communicated with a real aircraft pilot. Figure 2-11 schematically depicts the pseudo pilot concept.

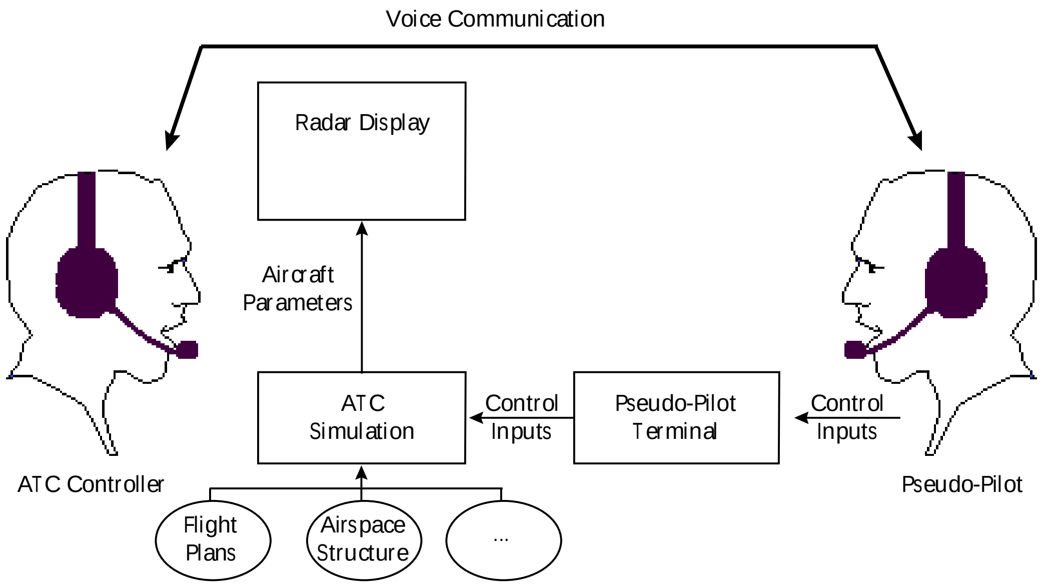


Figure 2-11 The pseudo pilot concept.

Figure 2-12 depicts the six pseudo pilot stations of DLR's ATMOS, each pseudo pilot controlling up to six aircraft. A computer screen displays the relevant data for aircraft operated by a pseudo pilot. Clearance parameters are entered via a customized keyboard.

At least one pseudo pilot is required per controller working position. However, as pseudo pilots have to enter the control parameters and read back the instructions at

Figure 2-12 The six pseudo pilot stations of DLR's ATMOS.

the same time, their workload often becomes unacceptably high. In order to avoid distortions of the simulation fidelity caused by pseudo pilot induced delays or mistakes, often more than one pseudo pilot is required per controller. The need for many pseudo pilots makes simulations very expensive. A possible solution to this problem is the use of automatic speech recognition (ASR) to replace the pseudo pilots.

2.4 The Application of Speech Recognition

The replacement of pseudo pilots with an automatic speech recognition (ASR) system could help to solve at least some of the problems correlated to the pseudo pilot concept. Figure 2-13 depicts the concept of replacing the pseudo pilots with an automatic speech recognition system. The controller speaks the clearance in the same way as in reality or in conventional simulators. Not a pseudo pilot but a speech recognizer listens to the instructions and identifies the concerned aircraft and the type and parameters of the clearance. This information is then transmitted to the simulation computer and a speech synthesis system generates a synthetic pilot answer. The controller working environment itself remains unchanged.

The syntax contains all sentences the controller might use at any point during the simulation and is typically constructed once as part of the system development process. The syntax contains sequences of words in a text-based notation, while the dictionary contains parametric descriptions of the words used in the syntax. Due to

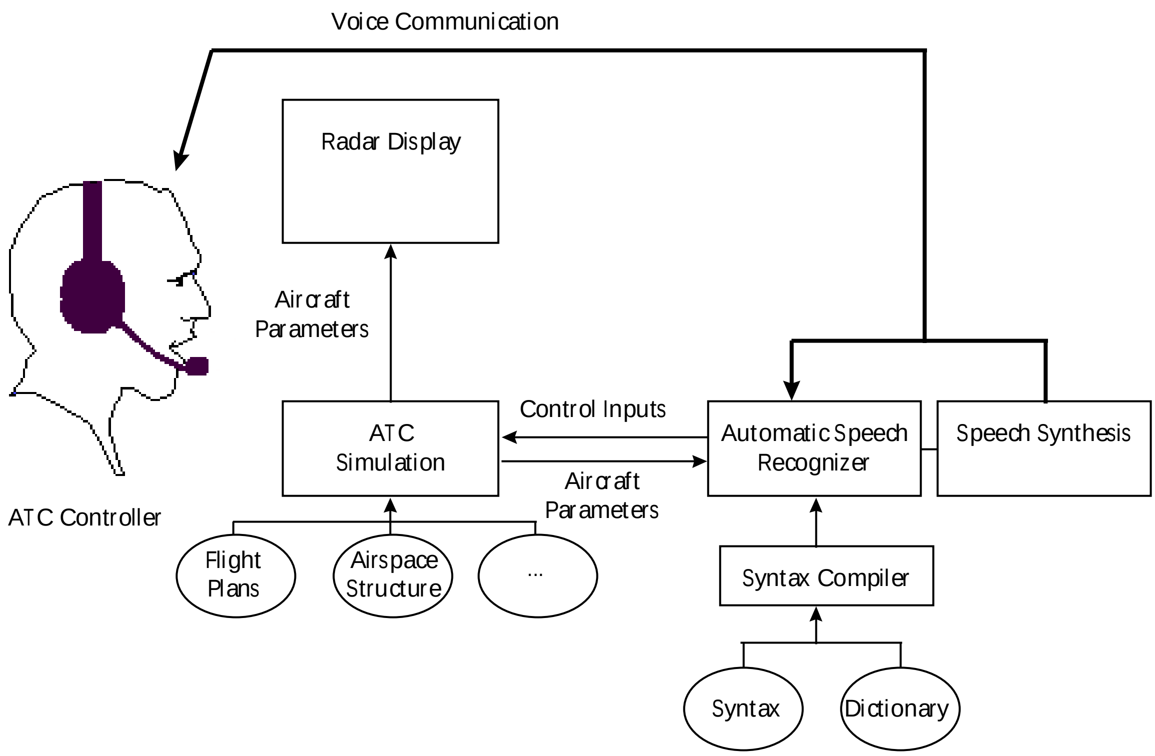


Figure 2-13 Automatic speech recognition in the ATC simulation.

the fact that the speech recognizer requires a fully digitized and parametric search space, the syntax and the dictionary are compiled prior to use by the speech recognizer which is usually done once as a part of the system development process.

Simulations for research purposes often aim at quantifying the benefits of new systems in terms of performance, accuracy, and operator's workload. Affecting the experimental conditions would mean to affect these measurements and it would no longer be possible to transfer results and implications derived during simulation to operational practice. The process of communicating is highly routined by daily practice and its disruption could have adverse effects. A speech recognition system must therefore allow the controller to communicate and transmit his control advisories in exactly the same way he or she communicates with aircraft pilots or pseudo pilots. The simulated aircraft must execute the instruction immediately and a read back must be performed in a natural way. The requirements crucial for successful application of automatic speech recognition in the ATC simulation domain are listed below.

- Control Advisories: The speech recognizer must understand all clearances necessary to control the aircraft in the ATC sector.
- Continuous Speech Recognition: The speech recognizer must permit the controller to speak in a continuous and natural way. Isolated word recognition requiring

short breaks between words would attract additional attention and thus affect the amount of attention the controller could allocate to the control task.

- Speaker-independent Recognition: Speaker-dependent recognition requires adaptation of the ASR parameters to the speaking characteristics of individual subjects by speaking an extensive set of sample sentences. As the voice varies from day to day, a re-training for the same speaker is sometimes required. Speaker-independent recognition systems do not need speaker-adaptation. The simulation would not have to be configured before starting and, if necessary, another controller could take over during the simulation.
- Synthetic Pilot Responses: Read-back of clearances and pilot inquiries must be simulated with a synthetic voice in a natural way. A visual feedback of the recognition results would be intrusive because the controller would either ignore it or, by scanning it, trouble his of her perception of the information presented on the radar screen and the paper flight strips. Also, controllers are used to scan pilot read-back in order to ensure that the pilot understood the clearances correctly. Any modification of this pattern would result in a disruption of the experimental conditions.
- Immediate Response and Execution: Especially in situations of high traffic density or conflicts, advisories are often issued in quick sequence and, as controllers wait for the read-back of one clearance before speaking the next clearance, any delay would adversely affect the simulation. The time a speech recognition system needs to respond to and execute the clearance must not exceed the response time of pilots and pseudo pilots.
- Phraseology: The phraseology controllers use to speak the instructions often deviates slightly from the ATC phraseology as standardized by ICAO and published in the Aeronautical Information Publications (AIP). While the deviations vary with different controllers, each individual seems to employ his or her favorite wording quite consistently. Adapting to the wording of the ICAO standards would require additional concentration. Therefore, a speech recognition system would be highly desirable that would permit the most frequent deviations from the ICAO standards.
- Recognition Accuracy: Incorrect or incomplete recognition of clearances greatly delays the simulation because another control action is necessary to correct the mistake. Perfect recognition can neither be expected from pilots and pseudo pilots nor from automatic speech recognition. However, the recognition error rate of a speech recognition system should not exceed those of pilots or pseudo pilots.

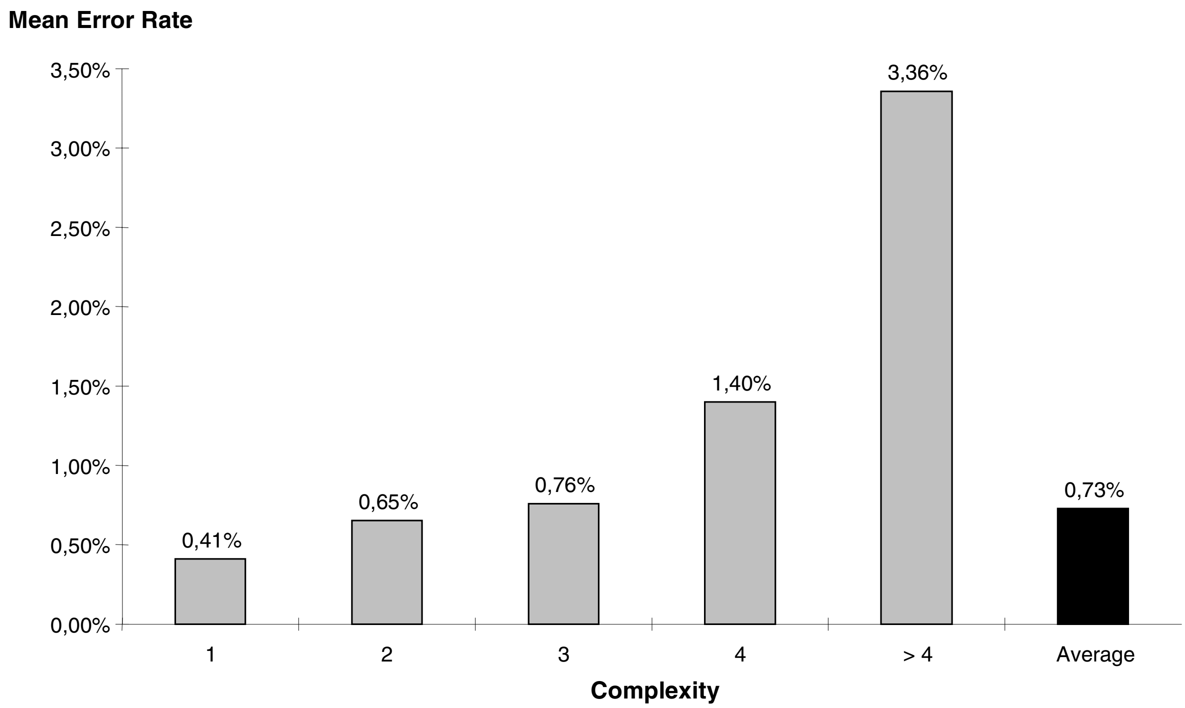


Figure 2-14 Number of misrecognitions among US line pilots [Cardosi 93].

The mean number of incorrectly or incompletely recognized control advisories in pilot controller transmissions was the scope of an investigation Cardosi conducted among US airline pilots in 1993 [Cardosi 93]. Cardosi analyzed forty-seven hours of ATC communication with 5,032 controller-pilot transmissions, which included 3,576 clearances. She then classified the clearances according to the number of pieces of information each instruction contained, which she named complexity level. For example, "Northwest 123, cross ten miles west of Pullman at and maintain flight level 200" was considered to contain four elements. The number and percentage of incorrectly or incompletely recognized clearances was then analyzed for each complexity level. The results are depicted in Figure 2-14. Not surprising, the percentage of misrecognitions increases with the complexity of clearances. In total, only 0.73 per cent of all clearances were recognized incorrectly or incompletely.

Pseudo pilots have to control a number of aircraft listed in a table on the computer terminal, so that attention is distributed across several aircraft. Also, pseudo pilots are often less trained than airline pilots. The rate of incorrectly or incompletely understood control advisories among pseudo pilots may therefore differ from that of line pilots. To determine the average rate of misrecognitions among pseudo pilots in DLR's ATMOS, twelve hours of voice transmission of simulations were analyzed containing 1,805 clearances. These clearances were then classified according to the number of instructions each clearance contained. For example, "Lufthansa 456, descend to flight level 110 with 2,500 feet per minute or more" was classified as

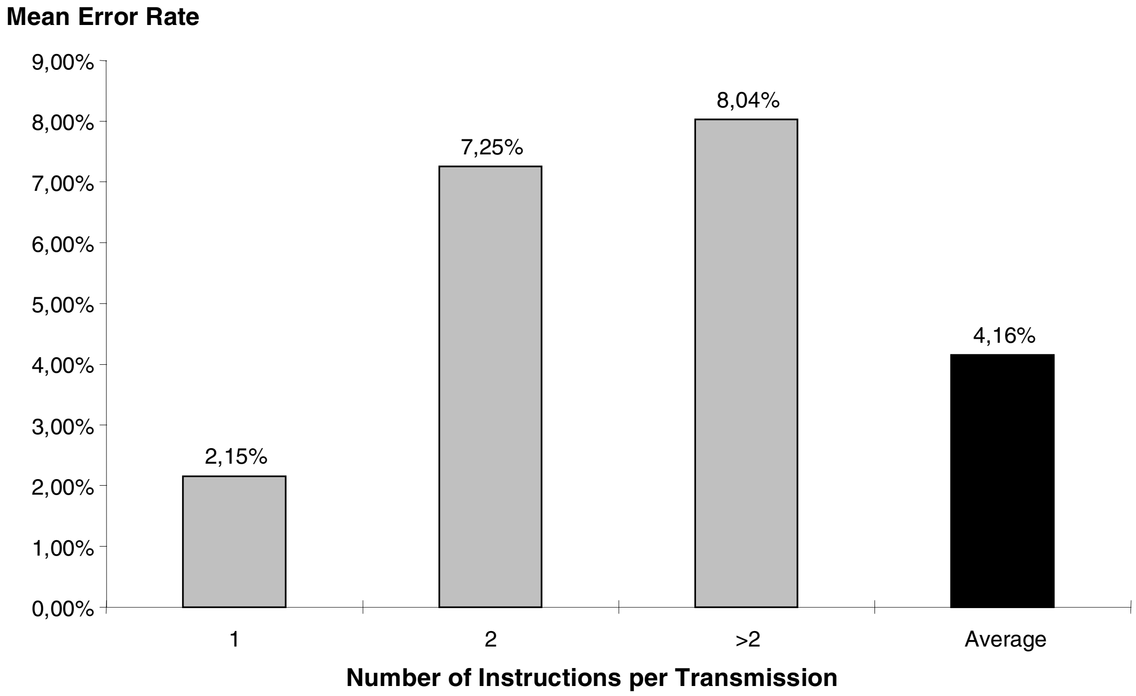


Figure 2-15 Error rate among pseudo pilots in DLR's ATMOS.

containing two instructions[5]. The percentage of misrecognitions was identified for each category. Figure 2-15 gives the results. The average percentage of incorrectly or incompletely understood clearances was 4.2 percent. Again, the mean percentage of misrecognitions increases with the complexity of the clearance.

The error rate is highly correlated to the number of aircraft pseudo pilots have to control and their level of practice. The results of this investigation in DLR's ATMOS can therefore not easily be transferred to other simulation facilities. However, controller participating in simulations in ATMOS consider the performance of pseudo pilots sufficient for untroubled experiments. It may be expected that a recognition rate of 95 percent or above would be acceptable for a speech recognizer.

2.5 Summary

The pseudo pilot concept as applied commonly in air traffic control simulations has several drawbacks. The most important disadvantage is the high number of personnel required for simulation runs. A promising approach to mitigate these disadvantages is the replacement of pseudo pilots by automatic speech recognition technology. Realistic simulation environments require a speech recognizer that is able to understand and respond to the instructions given by the controller in the

[5] The number of instructions per transmission does therefore not equal the complexity level as determined by Cardosi [Cardosi 93].

same way as pilots or pseudo pilots. The speech recognizer must understand at least 95 percent of all instructions correctly and respond and execute the instructions with little delay. The answer of the aircraft pilot must be generated by a speech synthesizer in a naturally sounding voice. The system must further permit the controller to speak in a natural, continuous way and to use expressions other than the standardized ATC phraseology. A speaker-independent system is desirable as it does not have to be adapted to the speaker prior to simulations.

3 Automatic Speech Recognition Technology

Natural, spoken language is the most convenient and efficient way of communicating with other people and it appears very desirable to communicate with machines in exactly the same way. However, the enormous complexity of natural language and the difficulties in constructing sensory systems capable of decoding spoken signals correctly are obstacles to this vision. At least limited success is possible in fields where well-structured and less complex languages are used. The ATC language has been standardized in order to permit fast, efficient and unambiguous communication in a noisy and safety-critical environment. Various efforts have been made to introduce automatic speech recognition in the air traffic control domain. Although promising approaches are documented, results obtained under laboratory conditions cannot be transferred to operational conditions and the requirements for successful application in the ATC or ATC training domain are not met by speech recognition systems currently available.

3.1 Voice-based Man-Machine Communication

Spoken language is considered to be the most natural and convenient way of communicating with other people. For a long time, people have been seeking for possibilities to communicate with machines in exactly the same way. Vocal communication is often more convenient and efficient than traditional ways of man-machine interaction. Besides, machines capable of understanding spoken language would gain a human-like appearance. Voice-based man-machine communication requires:

- a <u>speech recognition system</u> in order to identify the words and sentences[6] that have been spoken,
- a <u>speech understanding system</u> (language parsing system), in order to infer the meaning of the spoken sentences and to initiate adequate actions,
- a <u>speech synthesis system</u> in order to generate an acoustic response.

Speech Recognition

The speech recognition system converts the spoken utterance into a sequence of words or phonemes. To permit for natural communication with humans the system must be able to recognize any spoken utterance in any context, independent of speaker and environmental conditions, with excellent accuracy, reliability, and speed. For a variety of reasons, today's automatic speech recognition systems are far from reaching the performance of their human counterparts:

[6] Contrasting to the traditional and linguistic meaning, speech recognition technology uses the term 'sentence' as synonym for 'sequence of words' and it will be used accordingly in this document.

- Humans possess a much more sophisticated sensory system for the interpretation of acoustic signals.
- Humans use additional sources of information, e.g. visual information such as gestures and speaker physiognomy.
- Humans generally keep track of the actual context as well as of the history of the spoken dialogue.
- Humans have access to much broader and sophisticated sources of knowledge about the actual context, including common sense.

Speech Understanding

After the spoken words have been transcribed by the speech recognition system, the meaning of these words must be inferred by a speech understanding system. The difficulty of understanding language depends very much on the structure and complexity of the sentences and the context in which they have been spoken[7]. For many years, linguists have been trying to acquire and structure knowledge about languages in a standardized form and implement it on computer systems. Although some very restricted fields can be described with moderate fidelity, science is far from achieving linguistic models of entire natural languages. Therefore, machine understanding of natural spoken language will at least in the near future remain vision.

Speech Synthesis

Once spoken language has been recognized by the ASR and adequate actions and answers have been inferred by the speech understanding system, an acoustic response must be synthesized. Although a synthetic voice may sound unnatural and sometimes difficult to listen to, speech synthesis is considered a problem solved at least in principle. Also, the required responses can sometimes be recorded from live speech and then simple displayed, so that the ’synthetic’ voice sounds quite natural.

By restricting speech applications to a limited domain and by standardizing the spoken phrases, at least some problems correlated to speech recognition and language understanding can be alleviated greatly. If the operator uses standardized phrases rather than to express his wishes in spontaneous speech, only certain sequences of words have to be taken into consideration during the speech recognition process. Also, the process of language understanding can be facilitated significantly because the speech understanding process is reduced to identifying one out of a variety of possible sentences and initiating an action correlated to that sentence.

[7] The complexity of natural languages appeared so immense to psychologist and linguist Chomsky that he claimed it was impossible to apprehend any language without a-priori, genetic knowledge about the structure of the language [Anderson 93]. That may or may not be the case, however, it illustrates how complex the process of language understanding actually is.

Recent improvements in speech recognition and computer hardware technology have given access to a variety of applications in which speech recognition is a valuable and efficient replacement or supplement of traditional ways of man-machine communication. Rather than understanding natural language, these systems provide an interface to control machines and computers with speech in a standardized phraseology.

3.2 Fundamentals of Automatic Speech Recognition

As early as the fourth century BC, Greek philosopher Aristotle possessed a surprising knowledge of the physics of sound. In 350 BC he wrote:

> All sounds are produced because air is set in motion by expansion or compression or when it is clashed together by an impact from the breath or from the strings of musical instruments [Aristotle in Taylor 89].

However, it was not before the middle of the 19^{th} century that acoustics became a scientific branch of physics. Researchers such as Willis, Herman and Helmholtz investigated the production of sound and particularly the production of speech. Thanks to their work and a number of subsequent investigations we now have a fairly good understanding of the mechanics of speech.

A tone consists of pressure waves in a medium such as water or, most frequently, air. The pressure waves can be described in terms of their frequency, corresponding to the pitch, and their amplitude, corresponding to the loudness of the tone. Sounds generally involve a multitude of tones changing over the time, so that they must be described by dynamically analyzing all frequencies.

Speech may be analyzed similar to any other acoustic event, i.e. by dynamically analyzing the frequencies of the pressure waves. However, it was soon found that speech events are generally a conjunction of characteristic acoustic patterns, later referred to as phonemes, so that words can be described as sequences of phonemes. The majority of automatic speech recognizers is based on the analysis of the acoustic event of speech in order to identify the spoken phonemes and thus to infer which words and sentences have been spoken.

According to Rabiner & Juang the beginning of serious speech recognition research dates back to at least 45 years ago [Rabiner & Juang 93]. However, the first steps have been taken as early as 1916 when Flowers proposed a voice-operated typewriter which in he describes as [Flowers 16 in Taylor 89]:

> a visible-writing machine recording our thoughts as rapidly as we speak.

His invention based on mirrors which were attached to resonant circuits and reflected light beams to a photo cell when a spoken phoneme caused resonance in the circuit corresponding to that specific phoneme. Flowers' invention could actually identify isolated phonemes according to their specific wave patterns. Distortions of phonemes due to the subsequent phoneme in a word, an effect referred to as co-articulation, however, made it impossible for Flowers' machine to identify entire words or even sentences.

There is a striking similarity between the vision Flowers had in 1916 and the description of current state-of-the-art speech recognizers designed for the same task:

> You can dictate text and commands directly into your favorite applications, control your computer and express yourself in the easiest way of all ... by speaking. As you dictate, you'll see your words transformed directly on your screen [IBM 97].

The analysis of pressure waves permits to identify the phonemes correlated to a speech signal. The phoneme sequences are then transcribed into words and sentences. The spoken utterance is recorded and converted into a digital format by use of an analogue-digital converter, often applying means of frequency analysis such as Fast Fourier Transformation (FFT). Thus a dynamic frequency description of the spoken sentence is produced. This pattern is then compared to the patterns in the search space which contains a description of all valid sentences, i. e. the sequences of words the ASR has been configured to recognize. The principles of automatic speech recognition systems are depicted schematically in Figure 3-1.

The dictionary contains the vocabulary, i. e. all words the ASR has been designed to recognize. The words are stored as sequences of phonemes and a phoneme database is used that contains statistical descriptions of all phonemes, including variations in the speaking characteristics among different speakers, if the ASR has been designed to be operated by more than one speaker. The phoneme database is derived by statistical analysis of speech samples of a broad variety of different speakers. The syntax contains a description of valid combinations of words to sentences. Thus, a complete description of all valid sentences is available for the pattern matching process.

Variations among different speakers and even dynamic variations of the speaking characteristics of individuals must be considered as well as possible disturbances such as background noise. The speaker model describes how to interpret words as phoneme sequences and how to consider variations in the speech characteristics. Speaker models are typically based on Hidden Markov Models or Neural Nets.

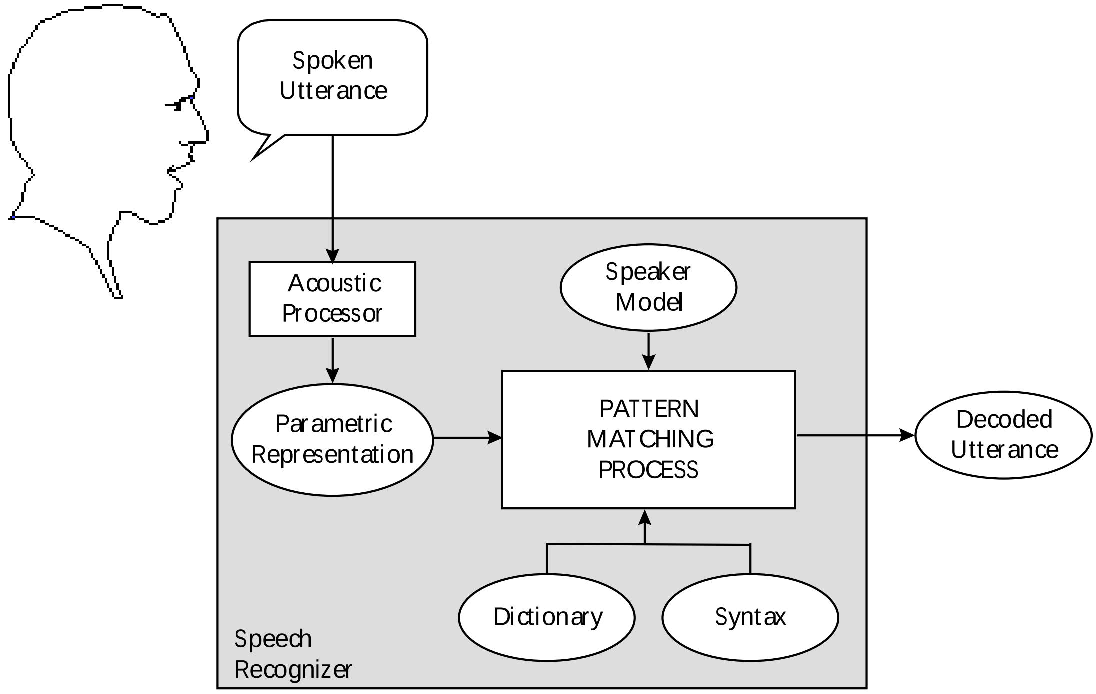


Figure 3-1 The principles of automatic speech recognition.

During the pattern matching process hypotheses about the best match between the spoken sentence and all sentences specified in the syntax are dynamically constructed and assessed. After a hypothesis about the best match has been selected and confirmed with sufficient reliability, the corresponding sentence is returned as the result of the decoding process and transmitted to the user. Automatic speech recognition systems differ very much in their specific properties. Characteristics of ASR systems include:

- Speaker dependency: Prior to use, speaker-dependent systems must be trained to the speaking characteristics of individual operators. Speaker-independent systems are designed to be operated by any user without training. A database covers the speaking characteristics of the intended speaker population in a statistical description. An intermediate implementation between speaker-dependent and speaker-independent systems are speaker adaptive systems. These systems are speaker-independent but possess an additional module allowing them to adapt to the characteristics of individual users.
- Isolated word recognition vs. continuous speech recognition: Isolated word recognizers require a brief pause between two words in order to identify the word boundaries. Continuous speech recognizers permit the operator to speak in a natural way without pauses.
- Phoneme based vs. word based systems: The frequency descriptions of the words in the search space can either be generated using a phoneme database plus a dictionary or by using a word database. Since phoneme based systems

make better use of system resources and provide greater flexibility in constructing new words, most ASR systems today use phoneme databases.

- Structure of the syntax: Deterministic syntaxes specify sequences of words in a deterministic way, e.g. in the form of transition diagrams. Probabilistic syntaxes use transition probabilities for pairs or trigrams of words, i.e. the probability of one word following one or two other words. The transition probabilities are derived by statistical analysis of many sentences in the domain in which the recognizer will be operated. As the effort to generate deterministic syntaxes increases dramatically with a growing number and complexity of the sentences, ASR systems with large search spaces often use probabilistic syntaxes.
- Recognition performance: The recognition performance can be described in terms of recognition speed and recognition accuracy. While the recognition speed refers to the time the system needs to decode a spoken utterance, the recognition accuracy refers to the percentage of successfully decoded utterances[8].

The recognition performance depends greatly on some of the other parameters mentioned above. Speaker-dependent systems generally perform better because they consider the speaking habits of individual speakers only. Isolated word recognition is more reliable than continuous speech recognition, because the identification of word boundaries is a source of errors when decoding sentences. The greater the search space, i.e. the higher the number of valid sentences, the higher is the likelihood of an erroneous recognition. The speech recognition application typically determines the required system characteristics, including a minimum recognition performance. An ASR system with the corresponding properties is then chosen and adapted to the application. The resulting recognition performance is then judged sufficient or insufficient for successful application.

Some 20 years ago commercially available speech recognition technology was limited to speaker-dependent systems capable of identifying a handful of isolated words with moderate accuracy. Computer and speech recognition technology improved considerably during the latest decades and today speech recognition technology is commercially used in a variety of applications, including:

- Call centers: The majority of inquiries in a call center, where customers seek information or wish to place orders, follows standard patterns. Therefore at least some of the conversations can often be standardized and handled by speech

[8] The recognition accuracy is further divided into word recognition accuracy and sentence recognition accuracy, the first referring to the percentage of words that have been decoded successfully while the later indicates the percentage of correctly identified sentences.

recognition and synthesis systems. ASR systems for call center applications must be speaker-independent but only require a very limited vocabulary and syntax.

- Voice operated command and control: Voice control often provides advantages over traditional ways of interaction with technical systems, particularly if the operator cannot use his hands or focus his eyes on the system. Examples of these applications include car telephones and the control of welding robots. Command and control systems normally use very limited vocabularies and are often designed as speaker-dependent isolated word recognizers. A very high recognition performance and robustness against background noise are often crucial.
- Dictation: Dictation systems serve to enter text into a text processor directly via voice. These systems require vocabularies containing the most frequent words in a language, typically around 60,000 [IBM 97]. Dictation systems are typically speaker-adaptive isolated word recognizers that use probabilistic syntaxes. As an erroneous recognition can be corrected easily the recognition rate does not necessarily have to be very high for efficient system use.

3.3 Present State of the Art

The complexity of natural language enables us to communicate our most sophisticated ideas efficiently, allowing for human endeavors such as poetry, humor and irony. Understanding the meaning of spontaneous speech, however, is a very complex process, far beyond the capabilities of machines imaginable from the present point of view. Applications of today's speech recognition technology are more promising in areas where spoken communication takes place in a standardized form with little or no ambiguities and a very limited vocabulary [Harrison et al. 86].

Communication in air traffic control shows a moderate complexity and limited vocabulary. Background noise and distortions during radio transmission deteriorate the speech quality, the costs of errors are extremely high and communication takes place under time-critical conditions. To permit efficient communication under such adverse conditions, the ATC phraseology is almost completely standardized and ambiguities are eliminated as far as possible. Still, the introduction of speech recognition into operational air traffic control raises many unanswered questions about safety and system usability and reliability. Air traffic control simulation provides a non safety-critical environment in which, apart from distortions and background noise, the communication takes place in exactly the same way. For these reasons, ATC simulation has become a field of interest for many speech recognition researchers. Still, previous efforts in the application of speech technology in ATC simulation have achieved only very limited success [Weinstein 91].

A study at the US Naval Training Systems Center in 1989 focused on the integration of computer technology for advanced training of air intercept control (AIC)[9] students including simulation of the controller pilot communication [Hamel et al. 89]. A subgoal of the study was to investigate the suitability of ASR for AIC training purposes. In a first system layout pseudo pilot stations were installed allowing control of the simulated aircraft by keyboard input. A second layout replaced the pseudo pilot stations by a speech recognition system permitting the student to speak the commands directly to the simulation computer. Two off-the-shelf speaker-dependent ASR systems were chosen that provided continuous speech recognition and allowed the definition of a deterministic syntax. Speech synthesis systems were used to generate a pilot response. The vocabulary consisted of 19 words typical for simple control exercises. The syntax showed a very low complexity, comprising between 100 and 200 sentences. The initialization time in which the ASR acquired templates of the individuals speaking habits averaged at about 25 minutes. The sentence misrecognition rate, i.e. the percentage of incorrectly identified messages averaged at 4 to 5 percent while the sentence non-recognition rate, i.e. the percentage of rejected messages averaged at 15 to 17 percent. The response time averaged at 5 seconds which is greater than the time pseudo pilots require for data entry. It was found that the gender of the speaker did not influence the recognition, while the speakers emotional state inflicted by stress or frustration effected the recognition as well as the time of day. Fully synthetic speech was considered of limited use because it sounded unnatural and was hard to listen to. Speech synthesis based on playback of pre-recorded sentences was found to be convenient and acceptable.

The Intent Monitoring System developed by Magnavox combined speech recognition and reasoning techniques to increase recognition performance in the ATC domain [Dunkelberger et al. 95]. A system that possesses knowledge about the intentions of the ATC controller could greatly facilitate his or her work. As the intentions are mostly encoded in the speech signal, the key to intent recognition is speech recognition. Promising applications for intent-aware assistance systems include target tagging and compliance monitoring. Magnavox used a two step process: In a first step, a speaker-independent continuous speech recognizer analyzed the spoken signal using a non-exact grammar including fuzzy sets and transcribed it into a N-best list of sentence matches. The second step applied phrase spotting and reasoning techniques using situational information to correct recognition errors and to infer the relevant phrases, i.e. the relevant items of information in the utterances. Experiments were carried out based on instructions transcribed from tower control communications, which were spoken in everyday ATC manner, so that the phraseo-

[9] Air intercept controllers control fighter aircraft during attack and landing maneuvers in the vicinity of ships.

logy did not necessarily comply with ICAO standards. The results indicate a 90 percent phrase recognition using the speech recognizer plus the phrase spotting and reasoning techniques. As the sentence usually consisted of several phrases, the sentence recognition rate was much lower.

A study at the School of Computer Studies at the University of Leeds, UK investigated the possibility of supporting controller pilot communication with automatic speech recognition [Atwell et al. 95, Churcher 96]. The idea was to retrieve relevant pieces of information from the ATC clearance and transmit them to the aircraft in a digital format either for direct aircraft control or as an additional information in case that the pilot understood the clearance incorrectly or incompletely. The ASR would be located at the ATC center rather than onboard of the aircraft for two reasons. First it was easier to install an ASR at the controller's working position than to equip each aircraft in the control zone with a recognizer certified for airborne operation. Second the signal quality would be much better before the speech suffered distortions caused by radio transmission.

A state-of-the-art speaker-independent continuous speech recognizer was used and tested under laboratory conditions. The ASR allowed the user to specify the relevant sentences in a syntax. After transcription and analysis of ATC transmission samples at Leeds airport, a generic language model was generated. The active vocabulary covered the words relevant for ATC transmissions. Three syntaxes were designed:

- a base syntax, allowing for any combination of words in the vocabulary
- a key-phrase syntax, defining relevant key phrases and allowing for any combination of words around the key phrases
- a corpus-based syntax defining phrases for each part of the transmission.

A sample selection of ATC transmissions at Leeds airport was transcribed and read by test subjects. The recorded utterances were then decoded by the ASR using either of the three syntaxes. While the base grammar and the key-phrase grammar averaged at about 20 percent and 22 percent word recognition rate, the rate increased to 55 percent using the corpus-based grammar[10]. After a further restriction of the third syntax, the word recognition accuracy increased to 66 percent, the sentence recognition rate at that time being 23 percent. A system decoding three out of four clearances incorrectly would be a disturbance rather than an assistance for the pilot. The authors conclude:

[10] The study used the word recognition rate, i.e. the number of correctly recognized words. As a complete sentence would only be decoded correctly if all words were decoded correctly, the percentage of correct sentences would be much lower.

> Thus our most important conclusion is that we have demonstrated that current state-of-the-art speech recognition is just not good enough for this domain [Churcher 96].

A study at the Eurocontrol Experimental Centre analyzed the performance of a speaker-dependent, word-based continuous speech recognition system provided with the TRACON/Pro ATC training simulator developed by Wesson Int. [Hering 95, David & Pledger 95]. The phraseology is limited to the ICAO standards implemented by the FAA in the United States. The ASR must be trained to the speakers voice in a session of between 35 and 40 minutes duration prior to use.

Experiments were conducted with eight controllers each completing five sessions of 30 minutes duration. Seven of the eight test subjects were native English speakers. The scenarios were adapted to the skills of the controllers in order to obtain comparative levels of workload. On the average, a clearance was issued every 30 seconds during the simulations. The subjective workload was measured with different techniques in order to assess the intrusiveness of workload assessment techniques on the speech recognition performance. The measurements were taken either using the method of Instantaneous Self Assessment (ISA) or the Subjective Workload Assessment Technique (SWAT) and either entered using a keyboard or prompted by an experimenter. The fifth scenario did not measure the workload. Subjective workload was again measured after each experiment using the NASA Task Load Index (TLX) technique.

Although the system manufacturer claims an average recognition rate of above 95 percent, the mean percentage of correctly identified clearances was only 81.2 percent during the Eurocontrol experiments. It was found that the online measurement of subjective workload was intrusive, i.e. the recognition performance decreased. The effect was stronger for the SWAT technique than for the ISA technique. Furthermore, the results indicate that an increased workload has a negative effect on the recognition performance.

A subsequent study compared three commercially available speech recognizers using recordings of the controller pilot communication during simulations at the Eurocontrol ATC simulation facility [Hering 98]. As the spoken sentences included words yet unknown to the recognizer plus errors and aborted or interrupted utterances, and even a few advisories in the French language, the speech samples form what Hering describes as "worst-case conditions" for the recognizers. As the study aimed at the installation of a central speech recognition system in a simulation network, microphone-independent ASR systems were chosen that used the limited frequency range of standard telecommunications facilities. The recognition rates, accordingly were very poor and averaged between 26 percent and 39 percent word recognition rate. Female speakers exhibited slightly better results.

A parallel computational approach to increase the accuracy of combined speech recognition and language processing in the ATC domain has been proposed by Chung, Moldovan and DeMara in 1993 [Chung et al. 93]. A commercial speech recognizer was used to understand phrases which were transcribed from ATC communications. These, in most cases, were not in compliance with the official phraseology. The system used semantic networks for knowledge representations and memory-based parsing techniques applied in a close interaction between low-level phoneme sequences and higher-level knowledge sources. The syntax was comparatively simple, consisting in approximately 1400 nodes with a vocabulary of 200 words. Tests indicated a strong increase in the decoding speed and an average recognition rate of 80 percent.

The MINDS system (Multi-modal INteractive Dialogue System) developed at Carnegie Mellon University in 1989 combines natural language processing approaches with speech recognition for a problem solving dialogue [Young et al. 89]. The MINDS system has been designed for information retrieval from a database describing vessels of the US Navy. During experiments the users were confronted with a damaged ship and had to find out whether the ship could continue its mission or better be replaced by another ship. To solve this problem they had to retrieve information from the database, interacting with the system via voice, keyboard, and mouse. The system displayed information on a computer terminal and gave acoustic feedback. For the speech recognition task the SPHINX system designed by Carnegie Mellon University was used, one of the most powerful speaker-independent systems for large vocabulary continuous speech recognition.

MINDS uses a vocabulary of circa 1000 words and limits the recognition search space using syntactic and semantic restrictions. Besides, it uses higher level knowledge sources to restrict the search space dynamically. This knowledge includes plans and goals, problem solving strategies, focus, ellipsis[11], and user domain knowledge.

The system possesses a knowledge base with domain concepts, hierarchical goal trees, and a user model. Based on the actual context and the dialogue history, MINDS uses its higher level knowledge to generate a set of predictions about probable sentences. These predictions are then transcribed into a semantic network using grammar subsets. Tests were carried out with sentences from a typical prob-

[11] The interpretation of elliptic, i.e. grammatically incomplete sentences relies on use of contextual information such as the dialogue history, e.g. the use of the words ‘it’ in an actual context.

lem solving task as described above. The search space included 3.8 x 10^{19} sentences when complete semantic grammars were used without contextual information and was reduced to 1.0 x 10^{9} sentences with predictions about probable sentences. The word error rate decreased from 17.9 percent to 3.5 percent. The major innovations introduced by MINDS are the use of multiple knowledge sources and the predictive use of contextual knowledge for the restriction of the speech recognition search space.

Some of the ideas proposed by Young et al. and implemented in MINDS were transferred to the ATC domain during a prototype development at LIMSI/CNRS in France aiming at the introduction of speech recognition in the ATC training domain in order to replace pseudo pilots [Matrouf et al. 90a, Matrouf et al. 90b]. A speaker-dependent continuous speech recognizer was applied which used word transition probabilities for pairs of words. Static knowledge sources involved a hierarchical representation of clearance structures based on Minsky's frame theory (see chapter 6.1) plus a word confusion matrix for error correction during the recognition process. Dynamic knowledge sources involved the dialogue history and the context, i.e. the actual flight parameters of each aircraft in the simulation. The approach focused on limiting the search space of possible clearance categories, referred to as concepts, dynamically to improve the recognition accuracy.

As proposed by Young et al. three levels of predictions were distinguished. Syntactic and semantic predictions limited the phraseology to the most commonly used sentences in the ATC domain and allowed only for meaningful instructions. The predictions were implemented by rules in order to dynamically estimate the word transition probabilities. Pragmatic knowledge focused on:

- <u>Punctual exchange</u>: When the system asks a question, the universe of responses is limited and the system can predict the response category.
- <u>Dialogue history</u>: Before speaking an instruction, the controller occasionally asks the pilot for the value of a parameter. If an utterance is a question concerning a category, there is a high probability that the next message belongs to the same category.
- <u>Callsigns</u>: Only aircraft presently in the sector are taken into consideration.
- <u>Concepts</u>: non-expert controllers use only certain concepts.

Experiments were carried out with six speakers reading ATC instructions from a table and answering system inquiries in a simulation. Three ASR setups were tested. A traditional speech recognizer setup without transition probabilities served as the reference. The second setup used static word transition probabilities. The third setup used dynamically updated transition probabilities. Both the acoustic accuracy (accuracy of literal transcription of the sentence) and the semantic accuracy (accuracy of correctly identifying the meaning of spoken instructions) are depicted in Table 3-1.

	Base system	System with transition probabilities	System with dynamic transition probabilities
Acoustic accuracy	68%	74%	78%
Semantic accuracy	84%	96%	96.5%

Table 3-1 Recognition accuracy in the experiments of Matrouf et al.

Results indicate that the benefits of using dynamic knowledge are comparatively small: the semantic recognition rate increased from 96 percent to 96.5 percent. Besides, the experimental design is representative for laboratory conditions rather than for operational service in air traffic control as the instructions have been read from a board rather then being uttered spontaneously.

In a co-operation between LIMSI/CNRS, CENA, Sextant Avionique and Vecsys, the prototype developed at LIMSI was equipped with speech synthesis for pilot responses and connected to an air traffic control simulator [Marque et al. 93]. The syntax was extended to the French ATC phraseology, as it is common practice in France to use both the French and the English language in air traffic control. The effort aimed at the introduction of the system in ATC student training in France. According to personal conversations with the authors, the performance has been judged insufficient after initial experiments at Voisy and Orly airports. Especially the digit recognition was considered critical and the speaker training, required in consequence of the speaker-dependency, were considered an obstacle to its introduction.

A successful application of speech recognition has been demonstrated for a knowledge-based pilot support system for IFR flights [Onken & Gerlach 93, Gerlach 97]. CASSY (Cockpit ASsistance SYstem) possesses several modules for autonomous flight planning, crew vigilance and crew support during the flight plan execution. The automatic flight planner calculates and optimizes flight plans which are proposed to the crew. The piloting expert forecasts pilot behavior expected for the execution of the flight plan. The pilot intent and error recognition module observes pilot behavior and tries to determine if deviations from the forecasts are either due to changes in the intentions of the crew or due to errors. In the first case the valid flight plan is adapted to the new intentions while in the latter case a warning is issued. Additional modules are the execution aid, monitoring module and the dialogue manager which constitutes the human-machine interface of CASSY.

During flight planning and avionics tasks many eyes-busy and hands-busy situations occur. Therefore, speech recognition was identified as a valuable complement to the traditional ways of human machine interaction The dialogue manager of CASSY uses a speaker-independent, continuous speech recognizer for flight planning tasks, the control of avionics systems and for understanding ATC instructions read back by the pilot. To achieve the high recognition rates required in the aviation domain situation knowledge is used to dynamically compose the ASR search space. The syntax of possible sentences is constructed as an augmented transition network (ATN) which gives valid transitions between the words in the vocabulary so that sentences are legal paths in the network[12]. The transition probabilities in the network are then estimated in a situation dependent manner, using knowledge about

- valid flight plans,
- expected and deviating pilot behavior,
- flight state, aircraft system states,
- environmental parameters (such as ATC instructions),
- pilot inputs.

The speech recognizer uses situation knowledge generated by the other components of CASSY. Commands the pilot or ATC could issue are represented in frames and used to construct the syntax. The speech recognizer is used in a mode in which it returns a network of word hypotheses as the decode. The utterance is divided into segments so that phonemes are issued as possible decodes for sequences of segments. Additionally, for each decoded word a score is provided representing the quality of the match. The identification of the spoken sentence consists in finding the path in the syntax network whose combined score, calculated from the score in the word hypotheses network and the syntax, is maximum.

Evaluation under experimental conditions proved the approach to be very powerful. The command recognition rate increased from 77.3 percent to 96.7 percent for pilot instructions and from 62.3 percent to 87.0 percent for ATC instructions repeated by the pilot. Experiments with line pilots during typical flight missions showed an overall recognition rate of 85.5 percent.

3.4 Summary

Although the language in air traffic control is limited, standardized, and mostly unambiguous, the required recognition rate and the time pressure under which controllers work have so far impeded the successful implementation of speech recognition technology in ATC as well as ATC simulation. Although promising approaches have been

[12] Augmented Transitions Networks will be discussed in chapter 6.1.

presented during the last years, no satisfying solution has yet been found and additional efforts besides refining the sensory system and the pattern matching algorithms of speech recognizers appear promising.

One reason why human performance in understanding spoken sentences is yet unparalleled by machines is the fact that humans, unlike machines, possess a broad knowledge about whatever subject they are currently communicating about, including situation knowledge. Accordingly, some approaches to improve the performance of automatic speech recognizers include the use of situation knowledge either in order to predict possible utterances or to interpret what has been said. Experiments have proved this approach to be quite powerful and feasible for further investigations.

4 The Use of Context Knowledge for Automatic Speech Recognition Systems

Among other approaches, the restriction of the pattern matching search space is a powerful means to improve the speech recognition performance. The use of dynamic and situation-dependent knowledge in order to predict sentences the user may speak requires a dynamic assessment of the situation, a costly though rewarding approach. User models of information processing and problem solving can be used to implement knowledge about how the users actions are depending on situation factors. Past approaches to design cognitive models of air traffic controllers either focus on information processing or on raw task analyses. No existing model is capable of predicting what controllers will do in a certain situation. However, a prediction is required to support the speech recognition process. A variety of knowledge acquisition techniques are presented that can be used to identify controller expert knowledge, a prerequisite for its implementation in a model.

4.1 Approaches to Improve the Performance of Speech Recognition Systems

The application domain usually defines the requirements for an automatic speech recognition system. After an ASR system has been chosen and adapted to the application, initial tests are carried out in order to decide whether the recognition accuracy and response time are sufficient for successful use. As this is often not the case, continuous efforts are necessary to improve the recognition performance both for the development of new systems and in order to make optimum use of existing systems.

The principles of automatic speech recognition are depicted in Figure 4-1 (compare Figure 3-1 on page 28). According to the different modules of automatic speech recognizers, a variety of approaches are possible to improve the recognition performance. Manufacturers of speech recognizers mostly focus on approaches that are directly concerned with the hardware and recognition algorithms, such as signal preprocessing, improvements of the speaker model and the word/phoneme databases, and background noise suppression.

Refinements of Hardware and Preprocessing

The acoustic processor converts analogue signals from the microphone into a digital format which is then again converted into a parametric description. Both the design of the acoustic processor and the algorithms for the parameter conversion can be enhanced to improve the recognition accuracy. However, technology has reached a level of saturation in these fields.

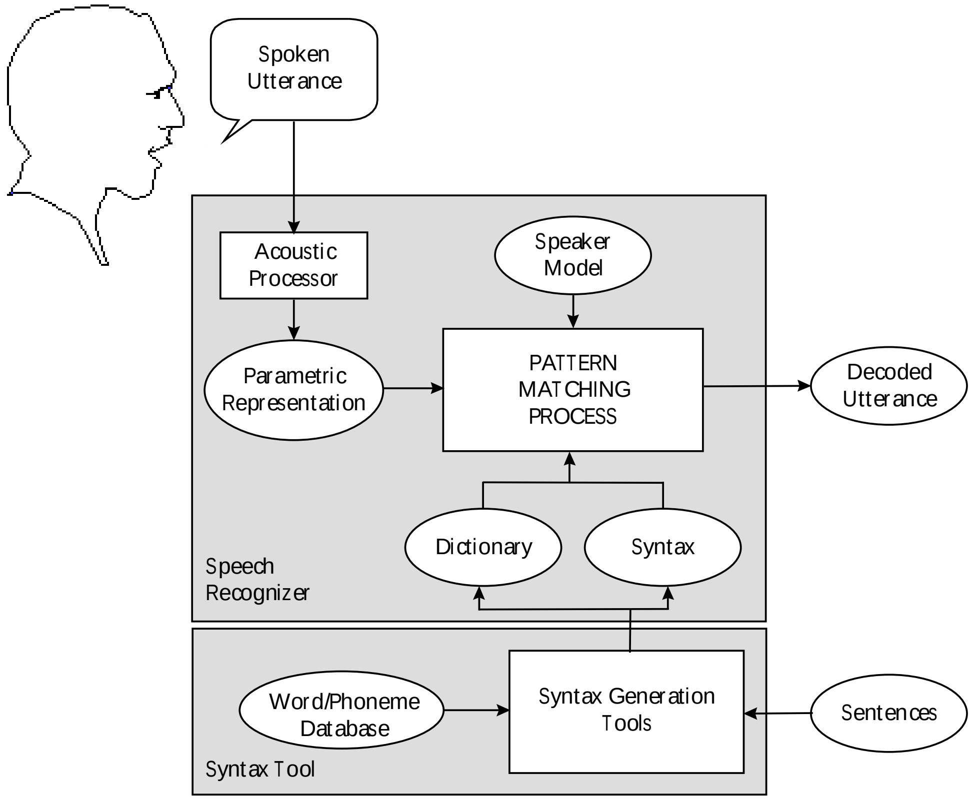


Figure 4-1 The principles of automatic speech recognition (2).

Improved Speaker Models

Most modern ASR systems are designed to be used by many speakers, each possessing different speaking habits. Even the speaking habits of an individual speaker may vary over the time and attributes such as pitch, velocity, and loudness change even within one utterance. The speaker model which describes the characteristics of the speech signal must consider all these variations. Usually, possible variations among a variety of parameters are specified by stochastic means. An efficient speaker model is crucial for the recognition performance: On one hand possible variations among a multitude of speakers must be taken into account. On the other hand, the description must be limited to the most common variations in order to gain a non-ambiguous specification of phonemes so that confusion with other phonemes are suspended as far as possible. Many efforts in the ASR research focus on improving the speaker models.

Refined Word/Phoneme Databases

Speaker-independent systems use databases containing acceptable pronunciations of the words or phonemes of a language[13], based on speech samples of large populations of potential users. A representative and sufficiently large population of speakers is crucial for a good recognition performance. In some cases improvements can be obtained by collecting additional speech samples and adapting

[13] ASR systems are usually based on phoneme or word databases (see chapter 3.2).

the database. For example the pronunciation of Germans speaking English may vary from those of native English speakers in a specific way. If an English recognition system is used in a domain where German speakers communicate in the English language, its performance may be enhanced by collecting a new database or adapting the existing database with speech samples of German speakers. However, collecting and analyzing large quantities of speech samples is a costly process.

Background Noise Suppression

Most speech recognizers use noise suppressing microphones in order to eliminate distortions of the speech signal caused by background noise. As the wave patterns of noise signals are generally different from those of speech signals, noise models can further be used to describe background noise mathematically and to filter it from the relevant acoustic signals.

For reasons of competition, the algorithms of the speech recognizer are generally not made available to the customers who are therefore not able to modify the ASR itself and basically focus on adapting existing speech recognizers. Approaches such as decode post-processing, redundancy and syntax adaptation are mostly used by customers who wish to integrate an ASR system into a specific application.

Decode Post-Processing

Analyzing the decode after the recognition has been completed can help to identify at least some recognition errors. For example, some applications use word confusion matrices containing pairs of words that, due to their phonetic similarity, are frequently confused. If a sentence is decoded that is grammatically incorrect but contains a word that is frequently confused with another word and if after exchanging one word for the other the sentence would be correct, it is likely that the words have actually been confused during the decoding process. Speech recognizers that return a detailed record of the decode facilitate post-processing. For example, the ASR may return a so-called N-best list containing a number of possible decodes that match the spoken utterance best, including the respective levels of confidence for each decode. The possible decodes may even be returned as sequences of words or phonemes including word/phoneme decode confidences. A successful application of both the word confusion matrix and post-processing of weighted phoneme chains has been presented by Gerlach [Gerlach 96].

Redundancy

By using at least three different speech recognizers and comparing their decodes, the overall recognition performance can be improved. If at least two of the three systems return the same decode it is accepted, otherwise the decodes are rejected and the system prompts for the utterance again. A study described by Barry et al.

revealed that this approach holds the potential for improving the recognition accuracy when three ASR of approximately the same performance are used. However, at least three different recognition systems and an additional module to compare the decodes are required [Barry et al. 94].

Adaptation of the Syntax

During the pattern matching process the spoken utterance is compared to each sentence specified in the syntax. There are basically two kinds of errors that may occur during the pattern matching process:

- Lack of sentences: The search space does not contain the utterance. In this case the decode is refused or a different but phonetically similar utterance is returned as the best match.
- Confusion of sentences: The spoken utterance is contained in the search space but confused with a phonetically similar utterance which is then returned as the best match.

Figure 4-2 schematically depicts the likelihood of occurrence of the two errors in relation to the size of the search space, i.e. the number of sentences in the syntax. The error due to a lack of sentences in the search space can be eliminated if the syntax contains every sentence the user may ever say. Unfortunately, this increases the number of phonetically similar sentences, resulting in a higher likelihood of confusions. The syntax should on the one hand contain all relevant sentences and on the other be restricted as far as possible so that the sum of both errors is minimized.

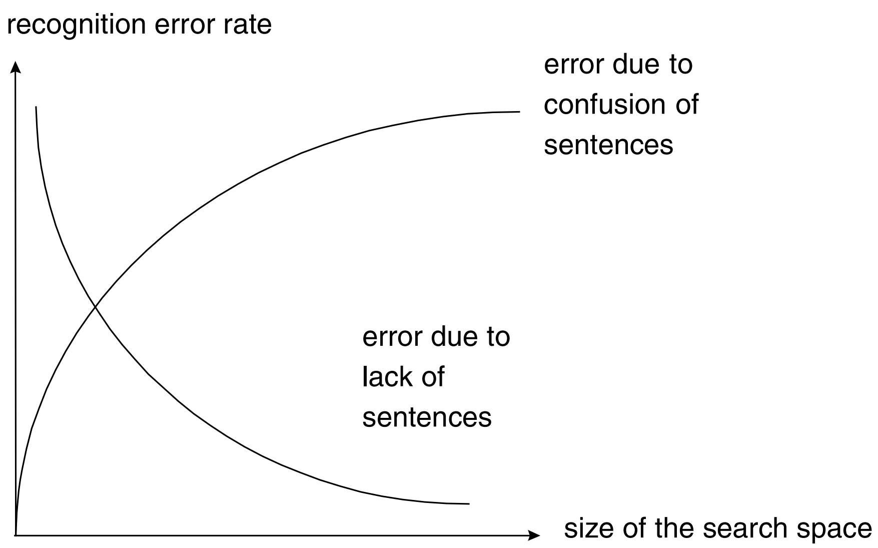


Figure 4-2 Two types of recognition errors (schematically).

4.2 The Use of Static and Dynamic Knowledge for the Syntax Definition

The SPHINX system developed at Carnegie-Mellon University is considered to be one of the best speech recognition systems worldwide. But even the SPHINX system has a word recognition error rate of nearly 30 percent for speaker-independent, connected speech recognition when recognizing word sequences generated at random from a vocabulary of 1000 words, i.e. without using knowledge about the structure of correct sentences [Young et al. 89]. Higher level knowledge sources are applied to reduce the number of valid sentences, i.e. legal sequences of words in the syntax. Young et al. propose a distinction of three different categories of knowledge:

- syntactic knowledge: knowledge about the structure of grammatically correct sentences in a language,
- semantic knowledge: knowledge about sentences that are meaningful in a certain domain,
- pragmatic knowledge: knowledge about the context and the actual system state.

Although the basic ATC vocabulary consists of only 200 to 300 words, composing sentences from any sequences of these words would result in an enormous search space. Table 4-1 illustrates how the three types of knowledge may be applied to restrict the number of valid sentences in the air traffic control context.

<table>
<tr><td>Syntactic Knowledge (structure of grammatically correct sentences)
Phraseology of a Descend Clearance:
<Callsign>, DESCEND TO FLIGHT LEVEL <FL></td></tr>
<tr><td>Semantic Knowledge (knowledge about meaningful sentences)
Flight Levels in the lower airspace: between 100 and 240 in steps of 10
<Callsign>, DESCEND TO FLIGHT LEVEL <100|110|...|240></td></tr>
<tr><td>Pragmatic Knowledge (knowledge about actual state)
The present FLIGHT LEVEL is 130, descends are valid to flight levels below
<Callsign>, DESCEND TO FLIGHT LEVEL <100|110|120></td></tr>
</table>

Table 4-1 Syntactic, semantic and pragmatic knowledge.

Syntactic and semantic knowledge is static and must only once be obtained and implemented into the syntax. As the structure and parameter ranges of ATC clearances are standardized by international conventions, most approaches to introduce speech recognition in air traffic control use syntactic and semantic knowledge. Pragmatic knowledge is dynamic and its use requires to analyze the situation and derive estimates about sentences that are likely in the actual situation. As the situation analysis must be performed continuously and the results must immediately be transmitted to the speech recognizer, a considerable effort is required.

One approach to implement pragmatic knowledge is the definition of syntax subsets. According to the actual situation, an appropriate subset is loaded and used for the decoding process. This approach is referred to as context-switching and often used in applications with simple dialogue structures such as call-centers where, according to the dialogue context, only a small set of words or sentences is relevant. Domains with a higher complexity often do not permit the use of syntax subsets associated with distinct situations. Rather than to classify complex situations, it is often more promising to describe them by a number of parameters.

A first step in generating a situation-tailored syntax consists in ignoring clearances that are syntactically and semantically correct but not valid in the actual context. For example, clearances to aircraft which are currently not in the control sector may be excluded from the search space. Further, descend clearances to aircraft within the control sector may be limited to altitudes below the current altitude, etc. Whether an ATC instruction is realistic in the actual situation can generally be derived from the actual aircraft parameters and the airspace structure. A discrimination between realistic and less realistic instructions is a deterministic decision and can be formalized and implemented with moderate effort.

Controller activities are not a random selection of all actions that are physically possible but an application of specific procedures in order to achieve specific goals and, therefore, the search space can be reduced even further. If it were possible to estimate the probability of occurrence of ATC instructions as a function of parameters describing the actual airspace situation, the search space could be limited to the most probable instructions. However, predicting which instructions the controller may apply in a certain situation requires a deep understanding of his or her work.

One approach to obtain and implement knowledge about user behavior consists in the employment of statistical means. Provided a sufficient quantity of data can be collected and the major determinants of the user's behavior can be identified, the frequency of specific instructions equals the probability that it will occur under similar conditions in the future. Statistical analysis is a powerful tool for knowledge acquisition and a major advantage is that it can also be used if little or nothing is known about the domain under investigation. However, domains in which the system behavior is determined by a great number of parameters require the collection of huge amounts of data and it is often not possible to identify which parameters are of particular relevance. In the field of air traffic control additional means apart from statistical analysis are required to predict user behavior with sufficient reliability.

It may be rewarding to analyze and understand the processes involved in air traffic control and to implement this knowledge in a model in order to derive an estimation what the controller can be expected to do under certain conditions. Even if the effort is considerable, a user model is a powerful tool as it allows to integrate knowledge from a variety of sources to provide a more or less precise estimate for the majority of situations, even for those, for which little or no statistical data is available. As a starting point, a detailed analysis of the ATC controller's work and the cognitive processes involved in air traffic control are required.

Psychological user models contribute to understanding the basic mechanisms of human information processing and problem solving. The review of these studies will contribute to the design of a model as required to support speech recognition in the ATC domain.

4.3 Cognitive Models of Human Performance

Not only among psychologists but also among engineers and software designers a variety of motivations exists to develop cognitive models of human behavior. Psychological research is interested in the study of cognitive processes involved in human thinking and problem solving in order to understand human behavior. The results of psychological research are often used by other disciplines of science, such as ergonomics or human engineering.

A detailed understanding of human problem solving permits an adequate design of the human-machine interface with regard to an optimum selection and presentation of information. A more intuitive understanding of the technical processes the user wishes to control can be obtained if the presentation of the required information corresponds to the internal model he possesses of his environment. Even a predictive evaluation of the quality of human-machine interfaces is possible if the mental processes and required information can be derived from the task. Models of cognitive processes may also be implemented as computer-based systems serving as intelligent agents to which the user delegates a part of the planning or execution tasks or as supervisory systems. The human operator thus can be freed from tedious routine occupations with more cognitive resources remaining for higher level tasks.

A model of human information processing proposed by Wickens is depicted in Figure 4-3 [Wickens 92]. Physical stimuli are captured by the sensory apparatus and remain in the short-term sensory store for a period of 0.1 to 0.5 seconds after the stimulus has terminated physically [Johannsen 93]. The stimuli are then retrieved during the process of perception in what Wickens refers to as a "many to one mapping", that is, each stimulus is assigned to one perceptual category. As the process of perception

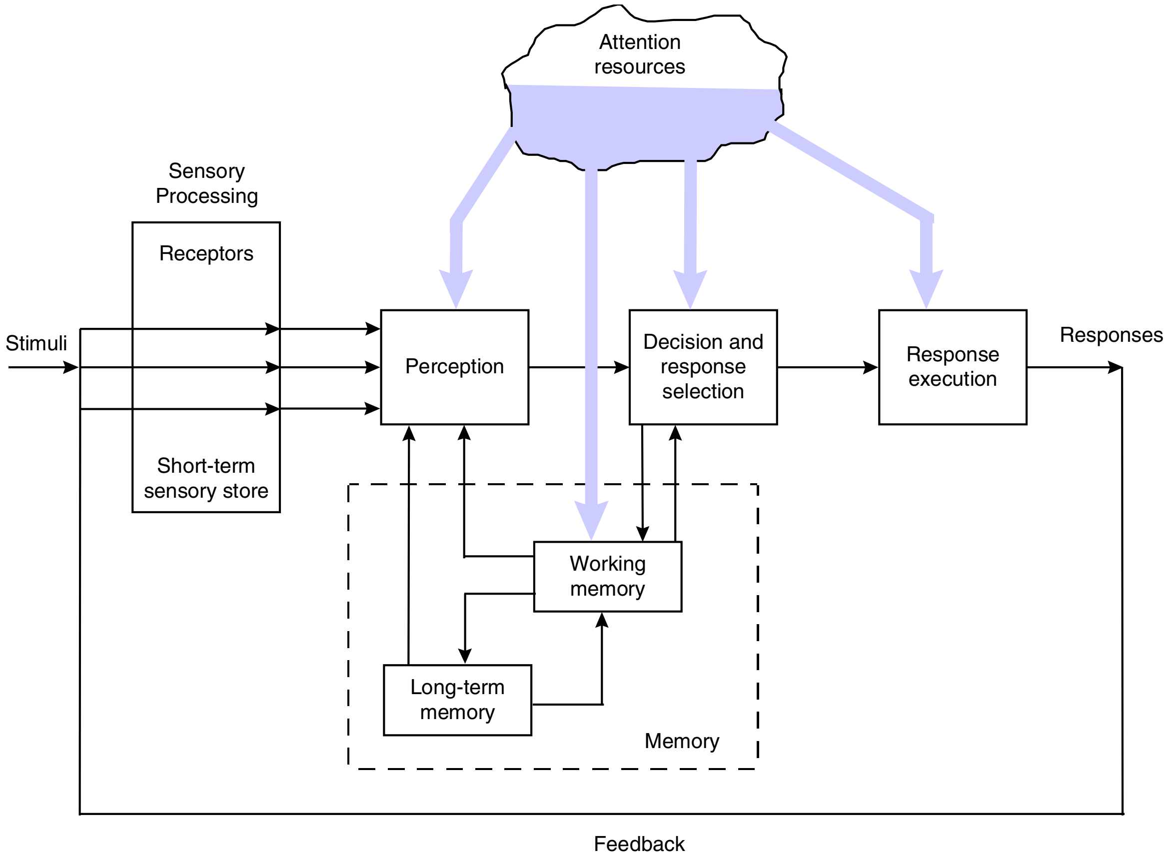


Figure 4-3 Model of human information processing [Wickens 92].

depends largely on the individual experiences no unique deterministic correlation exists between a physical stimulus and its subjective perception [Johannsen 93].

Once the stimulus has been categorized, the operator must decide upon appropriate action. The decision process may take place on different levels of elaboration ranging from problem solving to reacting automatically. After a response has been chosen it must be executed. The outcome of the action is consequently monitored and the corresponding events are perceived again as they cause physical stimuli. Attention must be attributed to many of the steps following the short-term sensory store to function properly. Attention may thus be regarded as a "searchlight"-like means to select relevant pieces of information and to derive and execute the appropriate responses. Also, attention must be regarded as a resource of limited capacity and its allocation as a process of conscious or unconscious weighting of information, events and mental processes.

While the model proposed by Wickens is mostly concerned with information processing, a model proposed by Rasmussen and depicted in Figure 4-4 focuses on the problem solving process. Rasmussen distinguishes three levels of performance of skilled human operators that, according to their level of experience, are relevant for their interaction with the environment [Rasmussen 83, Rasmussen 86]:

- Skill-based behavior represents sensory-motor performance which takes place as highly integrated patterns of behavior without conscious control. In routine situations, little or no attention is directed towards skill-based behavior.
- Rule-based behavior applies to familiar situations for which stored rules or procedures exist that have been learned during instruction, derived empirically or composed in a process of conscious problem solving during previous encounters of similar situations. The goals are typically stored implicitly in the rules or procedures. Rule-based behavior is generally based on explicit knowledge and controlled consciously.
- Knowledge-based behavior is applicable when unfamiliar situations are encountered for which no stored rules, procedures, or skill-based reactions are available. In these situations, the behavior involves problem solving in a goal-driven way, using the explicit knowledge and information the human possesses about his environment.

Plans developed during a process of knowledge-based problem solving may be stored as rules for future encounters of similar problems, while rules executed frequently may take the shape of skills and be performed in an increasingly automated manner.

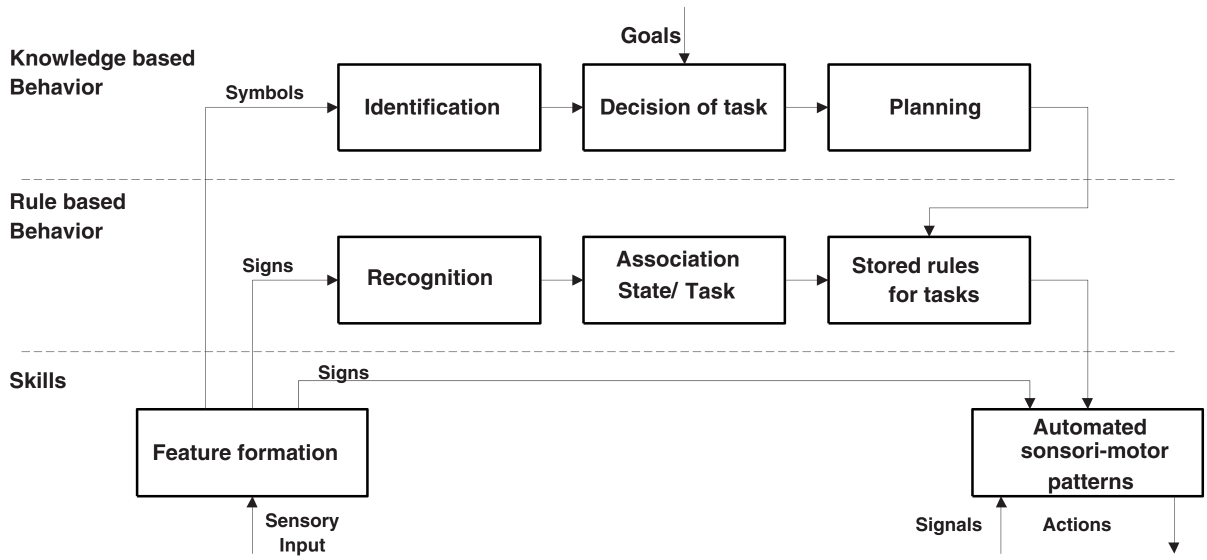


Figure 4-4 Model of three levels of performance [Rasmussen 83].

A model of the acquisition of human expertise has been proposed by Anderson [Anderson 83 in Kolrep 96]. ACT (Adaptive Control of Thoughts) distinguishes between declarative and procedural knowledge. Declarative knowledge is knowledge about objects and facts while procedural knowledge involves production rules with conditions and actions. Production rules are applied in a two-step process: the first step is a selection of procedures with conditions matching items in the working memory. The second step is a decision which production rule shall be executed, taking into account the quality of the match of the conditional part and the strength of the production rule which reflects how often the rule has previously been executed successfully and therefore, "how easy it comes to the individual's mind". The acquisition of knowledge includes three phases:

- During the cognitive phase, declarative knowledge is used in combination with more general strategies to control the problem solving process. The sources for declarative knowledge include written and aural instructions and manuals.
- During the associative phase declarative knowledge is converted into domain specific production rules. Two kinds of learning processes exist for these conversions:
  - Proceduralization: The conditions under which a successful action has been executed are directly linked to the action to generate a new production rule.
  - Composition: Two or more production rules that are frequently used successively are combined to one single rule.
- In the autonomous phase, production rules are adapted by tuning mechanisms:
  - Generalization: The conditional part of a production rule is generalized if the rule turns out to be successful under other than the original conditions.
  - Discrimination: If necessary, the context of validity of a production rule is reduced by using more narrow conditions.
  - Strength adaptation: The specific strength of each production rule is adapted according to the frequency of its successful application.

Although developed in a different context, the ACT model shows striking similarities to the model proposed by Rasmussen, as the cognitive phase, the associative phase, and the autonomous phase correspond to what Rasmussen refers to as knowledge-based, rule-based, and skill-based behavior. ACT explains mechanisms by which knowledge involved in the problem solving process is refined, adapted and converted into elaborate and less attention consuming forms by frequent use.

Figure 4-5 depicts a conceptual model of operator's tasks based on Rasmussen's model which has been proposed by Rouse & Rouse. This model served as a basis

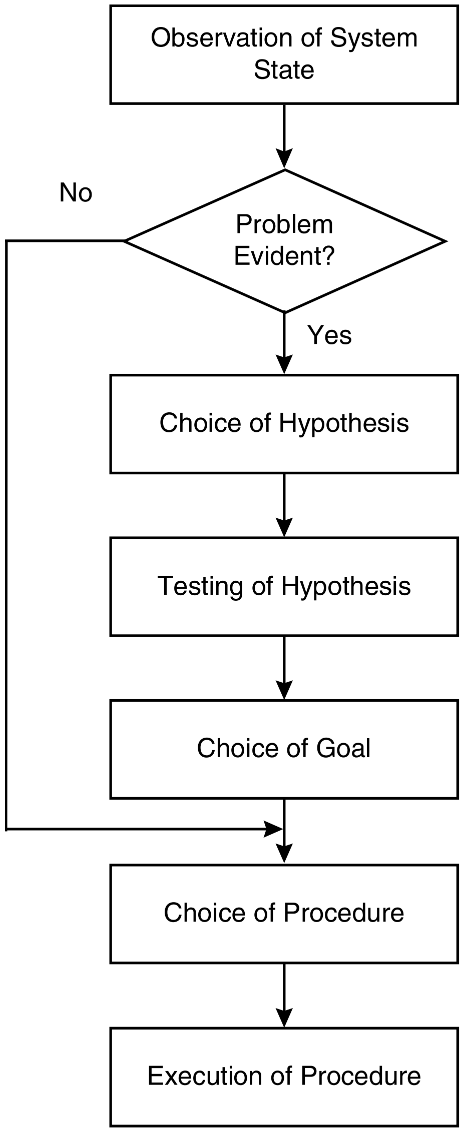


Figure 4-5 Conceptual model of operator's tasks [Rouse & Rouse 83].

for a human error classification scheme that would permit to attribute errors to the step in the problem solving process during which they occurred [Rouse & Rouse 83].

After the relevant information has been retrieved, the user decides whether a problem exists, i.e. an unforeseen and unwanted situation has occurred for which no standard procedure is available. Provided there is a problem to solve, the user first constructs a hypothesis about the state of the system or environment he interacts with. He or she then tests the hypothesis by comparing conclusions derived from the hypothesis with the observations in the real world. After a goal is selected a procedure is chosen that correlates to that specific goal and the procedure is executed. Provided no problem exists that requires explicit problem solving, adequate procedures are chosen and executed directly after observation of the system state. This loop corresponds to rule based behavior described by Rasmussen.

4.4 Models of Air Traffic Control as a Cognitive Process

According to a definition given by Dörner, air traffic control may be called a complex situation [Dörner 95, Dörner et. al. 83]. Aspects of complex situations are:

- Complexity and interdependency: A multitude of aspects and variables exist in the systems the user wishes to control and at least some of the variables are mutually interdependent so that actions executed to influence one aspect of the system often have unwanted impacts on other aspects. For instance, reducing the speed of one aircraft in order to maintain a safety separation to the preceding aircraft may have an unwanted effect on the separation to a third aircraft behind.
- Opaqueness: Not all system variables can be monitored directly, some must actively be retrieved while yet others can only be guessed. An air traffic controller may, for example, ask pilots about the minimum and maximum speed or about the climb performance of their aircraft. However, he or she may only guess about the meteorological conditions in a certain area.
- A dynamic system, i.e. a system that changes its state even without input from the operator often causes time pressure. The need to obtain complete and valid information and to decide upon an optimum action often competes with the necessity to react under time pressure. Air traffic is a highly dynamic system, even further complicated by the inertia in the pilot-controller collaboration.
- Incomplete system knowledge: The operator's knowledge about the system he or she wishes to control may be incomplete or even partially incorrect. Even if air traffic controllers are highly skilled, they often cannot have exact knowledge how a specific aircraft type may perform in a certain maneuver. Moreover, how and how quickly the aircrew will react to ATC instructions depends on individual factors the controller can hardly know.
- Conflicting goals: The overall-goal to guide each aircraft safely and efficiently through the sector results in a multitude of quickly changing subgoals. Often, actions executed in favor of one goal have negative effects on other goals.

Experiments to find out how the control strategies of ATC controllers change with an increase in the traffic density have been discussed by Spérandio [Spérandio 77, 78 in Kolrep 96]. In situations of moderate traffic density, the controller tries to permit maximum efficiency and comfort in addition to the primary goals to avoid unsafe situations and to maintain safety separations. However, with an increase in traffic he or she abandons all non safety-relevant goals in order to guarantee safety. While the controller attends to each aircraft in an individual way during periods of low traffic density, groups of aircraft following standard procedures with equal speeds are generated when the traffic density increases. With a further increase, he or she returns to standard procedures such as assigning holding patterns. This adaptation of strategies to the traffic situation permits the controller to avoid too high workloads.

A multitude of dynamically changing parameters determines the traffic situation and the controller must continuously update his or her mental representation. Whitfield & Jackson refer to the air traffic controllers picture as a structured and continuously updated mental representation of the traffic situation [Whitfield & Jackson 82]. Anderson demonstrated that as a consequence of experience, a variety of unconscious mechanisms are developed that permit an efficient use of the working memory [Anderson 93]. For example, experienced chess players are capable to remember a greater number of positions than novice players, as they mentally group sets of three to five pieces. It is very probable that memory organization mechanisms such as these also apply to air traffic control.

Leroux claims that two mechanisms of monitoring the traffic situation exist that permit the controller an efficient use of his working memory [Leroux 91]:

- For aircraft towards which, due to their safe distance from other traffic, no particular attention must be directed, sentry parameters are monitored, such as the cleared flight level or the expected altitude when reaching a waypoint. The compliance with the sentry parameters is monitored occasionally while the actual parameters are not explicitly remembered.
- Additional attention is directed towards aircraft which deviate from the expected behavior or are in close proximity of other traffic. For these aircraft, relevant parameter monitoring applies, i.e. the actual parameters are monitored frequently and stored in the working memory.

Not only the present situation must be monitored, but the future state and behavior must also be estimated in order to detect possible conflicts and to derive adequate control advisories. As this involves the dynamics of multiple aircraft in three dimensions, a great percentage of the air traffic controller's mental capacities is directed towards visuo-spatial tasks of high complexity. Isaac found that the capabilities of three-dimensional mental representation among ATC controllers are significantly higher than among non-controllers [Isaac 94 in Kolrep 96]. He also found a good correlation between their 3-dimensional memory and their skills as estimated by their superiors.

Redding, Cannon & Lierman presented an analysis of the tasks involved in the work of air traffic controllers [Redding, Cannon & Lierman 91]. They differentiated between the control and problem solving strategies of novice, intermediate, and expert controllers and derived implications for the training of controller disciples. The development of a mental model[14], i.e. an internal representation of the environment, plays a crucial role for the acquisition of skills. Lenorovitz et al. identified a variety of factors influencing the work of controllers, including his or her experience and the size and structure of the sector [Lenorovitz et al. 91]. An implication of their findings is that the ATC controller's working position should be customizable in order to meet the unique demands of each individual controller working in a specific air sector.

Detailed task analyses of air traffic control have been presented by various authors [Seamster et. al. 93, Vortac et. al. 94 in Kolrep 96]. Most of the controller's activities are directly correlated to one of the following tasks:

- monitoring the present traffic and the compliance of aircraft with instructions,
- estimating future positions and testing whether conflicts may arise in the future,
- deriving adequate control advisories to direct aircraft along preferred routes and to avoid conflicts,
- communication with pilots and with other controllers,
- entering data to flight strips and computers.

An early attempt to sketch the mental processes involved in air traffic control has been proposed by Bisseret. Without experimental proof, Bisseret argues that the main mental activity of the ATC controller was a categorization task [Bisseret 71]. From the present state of single aircraft, the controller would estimate the future relative positions of pairs of aircraft and classify these pairs as either possibly conflicting or non-conflicting. Flow-charts were drawn for this reasoning process, with flight levels and relative positions on top of a hierarchical structure of information associated with each aircraft. According to the mental flow-chart, the operative memory of the controller is organized by and for the reasoning processes. In experiments set up to test the operative memory, Bisseret found that the number of attributes used to memorize aircraft averaged at three, independent on traffic density and controller qualifications. The number of non remembered aircraft decreased with higher qualification.

A decomposition of the mental tasks of air traffic controllers has been proposed by Winter and Van Hood [Winter & Van Hood 95]. The analysis is based on the recognize-act-cycle (or stimulus-response-cycle) [Boff et al. 86, Kantowitz & Sorkin

[14] A mental model refers to an internal representation of the environment including it's dynamics and causal relations and provides the basis of the user's interaction with his or her environment. As opposed to that, a cognitive model refers to an external model of cognitive processes.

83] according to which the goal-directed interaction of an operator with his or her environment can be modeled according to the discrete steps of Monitoring, Diagnosis, Plan Generation, Plan Selection, and Plan Execution. The operator's activity is directed towards two meta-goals:

- Establishing and maintaining safe separation between aircraft
- Providing flight path (or ground path) guidance information/instructions to the aircraft.

During the situation assessment phase the actual state is monitored, i.e. the operator updates his or her mental model of the airspace situation. In case that the actual state of the system deviates from the desired or expected state, the diagnosis function is activated to analyze the situation of specific aircraft as well as the overall airspace state. Hypotheses about reasons for unexpected behavior are constructed and assumed or rejected. If operator interference is required in order to meet the above mentioned meta-goals, one or more plans are generated. If more than one plan is apt to attain the desired future system state, one plan must be selected. As the air traffic consists of a multitude of interdependent sub-systems, each plan must be carefully analyzed with regard to wanted or unwanted impacts on other traffic participants. The execution of a plan usually consists in speaking the appropriate instructions to one or more aircraft.

Freed and Johnston focused on simulating cognitive processes of the man-machine collaboration to evaluate of new ATC technologies [Freed & Johnston 95]. A model predicting the occurrence of errors and the time and attention requirements that the completion of each task causes among the different sensory and cognitive modalities could help to assess the performance of the human-machine interaction and serve as a complement to costly simulations with controllers. The major components of a model proposed by the authors are concerned with:

- knowledge acquisition,
- action control,
- vision and visual attention,
- speech production,
- hand movements.

Whereas mechanisms of visual attention, information retrieval, and action control are central to the model, no attempts are discussed to predict controller behavior in terms of decision making. The model is limited to two cognitive modalities: the more elaborate "recalling and executing routine plans" corresponds to the rule-based behavior described by Rasmussen while "mapping perceptual events to motor responses" corresponds to skill-based behavior.

As a means to study man-machine interaction and evaluate human-machine interfaces in air traffic control, Leroux tried to create an explicit cognitive model of the ATC controller and implement it as an expert system [Leroux 91]. He subdivided the controller's knowledge base into the categories meta-knowledge, declarative knowledge and situation knowledge, the latter containing all the information that would change during the control process. The memory model distinguishes the working memory that contains all the relevant information and the operative memory for the presently non-relevant information. A memorization module updates the memory and classifies pieces of information as relevant or non-relevant. As discussed above, sentry-parameter monitoring applies to aircraft or pairs of aircraft for which no conflicting situation is expected, while relevant parameter monitoring applies for possibly conflicting aircraft. The implementation of the model into a fuzzy-set based expert system is mentioned, but no details or experimental results are given.

The goal of the research project EnCoRe (Enroute Controller's Representation) at the Technical University of Berlin was to develop a model of the dynamic mental representation enroute ATC controllers possess of the air traffic situation. The allocation of attention is central to the model MoFl (Model der Fluglotsentätigkeit - Model of Controller Behavior) which has been developed during the project. The main components of MoFl are depicted in Figure 4-6. In accordance to Whitfield &

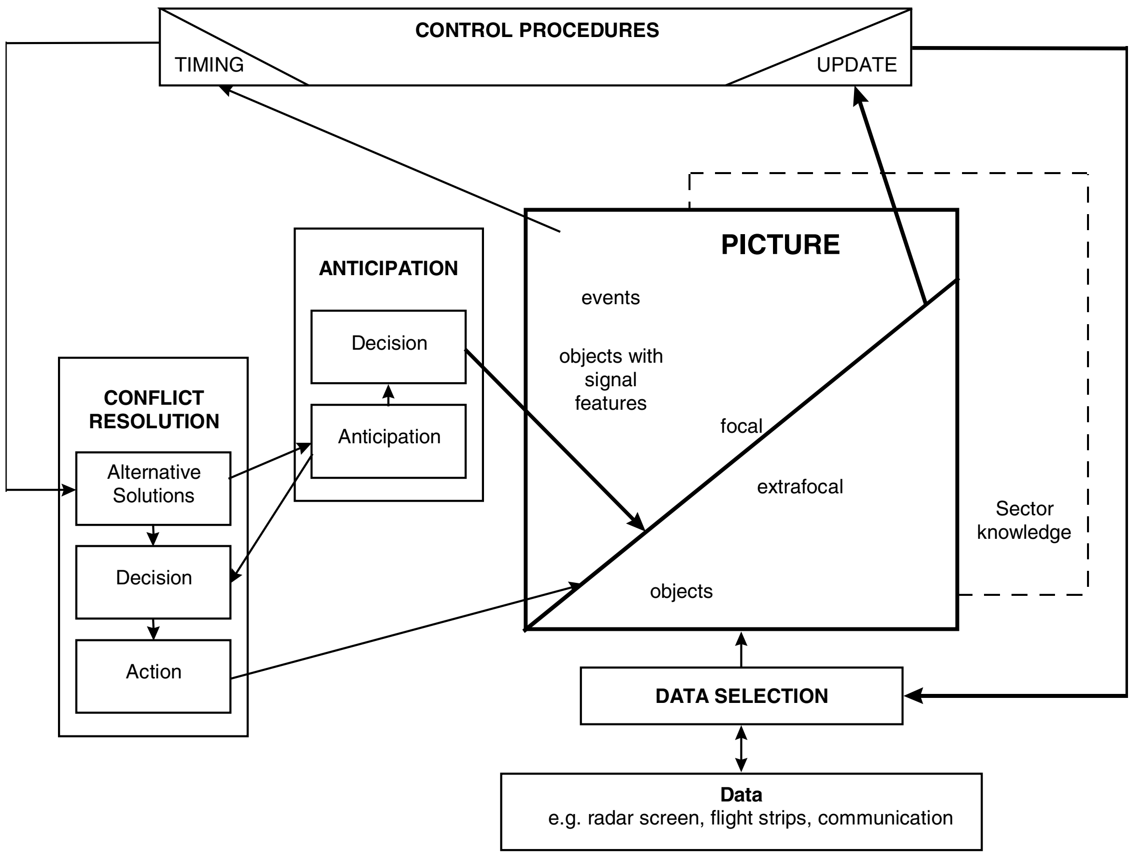


Figure 4-6 Components of the controller model MoFl [Niessen et. al. 97].

Jackson the term picture was chosen for the mental representation of the traffic situation. The picture is divided into a focal part and an extrafocal part. The focal part contains aircraft of specific relevance, such as possibly conflicting aircraft, aircraft during climb or descent maneuvers or aircraft that recently entered the sector. The extrafocal part of the picture contains aircraft without particular relevance due to less critical operations. The contents of the focal part of the picture are updated more frequently and are more attention-demanding than the extrafocal contents. Three major components of information processing operate on the picture:

- The monitoring cycle includes data selection from different sources of information plus a regular update of the aircraft attributes. Due to pre-attentive signal extraction of their attributes, aircraft are classified as either focal or extra-focal.
- The anticipation cycle operates on the focal part of the picture, estimating the future states of the respective aircraft. The anticipation is based on a dynamic mental model involving spatial, temporal and causal relations between the objects under consideration. Provided a potential conflict is detected between two or more aircraft, an event is generated in the focal picture.
- In case of a potential conflict, the conflict resolution cycle initiates a timing process to decide which conflict has to be resolved first. Then solutions for these conflicts are generated or recalled and a decision is made about the most adequate solution. This solution is then executed.

Hints have been found that aircraft are mentally grouped and that for aircraft in close vicinity short-term information, such as the actual flight level and speed, are memorized, while for other aircraft mid-term parameters are memorized, e.g. the cleared flight level [Bierwagen et. al. 94]. MoFI has been implemented in ACT-R, which was designed for the computer-based implementation of Anderson's Adaptive Control of Thoughts (ACT) theory. The model allows to monitor the information processing cycles in a conflict-free enroute scenario [Niessen et. al. 97, Bierwagen et. al. 97].

4.5 Expert Knowledge Acquisition

Air traffic controllers are 'experts' which means that much of their knowledge is available on an intuitive or even unconscious level. Nisbett and Wilson investigated the human capability of introspection for situations in which intuitive decisions are involved [Nisbett & Wilson 77]. They conclude that

> " ... when people attempt to report on their cognitive processes, that is, on the processes mediating the effects of a stimulus on a response, they do not do so on the basis of any true introspection. Instead, their reports are

> based on a priori, implicit causal theories, or judgments about the extent to which a particular stimulus is a plausible cause of a given response."

Apparently, the mechanics of decision processes cannot be observed reliably by asking subjects about the reasons for their decisions. The problem of expert knowledge acquisition is well recognized in the field of artificial intelligence where, driven by the desire to make expert knowledge available at multiple locations and for multiple tasks at the same time, expert systems have been developed. Before implementing expert knowledge in computer-based systems, it must be acquired and structured. Knowledge engineering techniques have been developed for the acquisition and analysis of expert knowledge. These techniques include:

- Introspection: The subject reflects about his or her own mental processes and the reasons that lead to decisions or actions. While introspection had been widely used in the early days of psychology, the limitations of this approach have lately become transparent. The reflection about mental processes may sometimes interfere with these processes and a great percentage of human knowledge is resident in an intuitive or unconscious way, so that it can hardly be verbalized. As Nisbett and Wilson point out, subjects may sometimes be capable to give reasons for their behavior that sound sensible but do not necessarily reflect the mental processes [Nisbett & Wilson 77].
- Think aloud protocols: The subject verbalizes every thought or consideration that comes to his mind while solving a problem. He or she is instructed not to reflect about these utterances or to structure them in a way considered desirable but to say freely whatever comes to his or her mind. This method is based on the assumption that thinking often takes place in the form of a mental dialogue. However, when intuitive knowledge and semi-automated patterns are applied, subjects are mostly unable to think aloud. Besides, this technique may interfere with tasks that require verbal communication.
- Inquiries and questionnaires: The subject is asked about specific aspects of his or her behavior in a standardized form. The questions must be restricted to such fields and posed in such a manner that the subject is able to answer appropriately. In order to avoid interference with the primary task, inquiries and questionnaires are mostly used off-line.
- Direct observation: The experimenter observes the subject’s behavior and takes notes of his of her observations. This helps to answer questions or construct hypotheses about behavioral aspects independent on the subjects capability of verbalization. However, direct observation is limited to physical processes and only very indirectly helps to construct hypotheses about mental processes.

- Teach back techniques: The subject is asked to instruct another person who accomplishes the task under observation and to give detailed reasons for every instruction. The advisories are collected and transcribed for later analysis. However, teach back experiments are mostly limited to problem solving for which explicit knowledge exist. If the task itself requires verbal activity, teach back approaches can affect the problem solving process itself.
- Statistical analysis of experimental protocols: If both the parameters classifying the situation and the user's responses to that situation can be logged, these protocols can be analyzed statistically. This does not permit an observation or even an understanding of the mental processes underlying the user's behavior. However, correlations between situational data and responses may be detected by statistical means.
- Data Mining: Advanced statistical methods such as data mining (or knowledge discovery in databases) use a variety of algorithms to retrieve knowledge from huge databases. Data mining can be employed to detect hidden patterns in the database, to classify and cluster objects and to generate models of the objects described by the data.

All methods of knowledge acquisition possess specific advantages as well as disadvantages (for a detailed discussion of these techniques see [Engelhardt 97]). Therefore, a combination of several methods of knowledge acquisition has been used to identify the knowledge relevant for controllers' behavior.

4.6 Summary

A cognitive model of the air traffic controller would be a great help for supporting the speech recognizer with situation specific knowledge. A cognitive model could perform an estimation of those clearances that are possible and probable in the actual air traffic situation, in order to limit the speech recognition search space to the most probable sentences. However, this requires a very powerful cognitive model because an estimation must be performed in runtime, on the one hand restricting the search space as far as possible, while on the other hand only removing those sentences that with great probability will not be used. Existing models mostly focus either on the information processing aspects or provide a very raw task analysis of air traffic control. No existing model performs a prediction or estimation what an air traffic controller may actually do in a certain situation. However, this function is strictly required in order to support the recognition process. A variety of knowledge acquisition techniques are available and can be used to identify knowledge of air traffic controllers.

5 A Cognitive Model of the ATC Controller

The Cognitive Controller Model (CCM) is proposed as a model for rule- and skill-based mental processes involved in standard and routine situations of air traffic control. Corresponding to existing cognitive user models CCM consists of three functions for situation observation and classification, decision making, and execution of actions. Rather than to aim at a deterministic forecast, CCM provides a selection of the most probable user actions. Knowledge acquisition techniques are discussed that help to identify the knowledge required for the model and it is found that a combination of several techniques should be used. Besides, it seems reasonable to limit the scope of CCM to one specific ATC sector, because the controller's activity is to a large degree dependent on the sector geometry. The mental processes involved in situation observation and classification, decision making, and execution of actions are discussed in detail, based on simulations in an enroute sector.

5.1 The Cognitive Controller Model (CCM)

Existing models of cognitive processes in air traffic control mostly focus on information processing and attention allocation aspects or provide raw task analyses. A model designed to support the recognition process must generate a prediction about the most probable user actions and should therefore focus on behavioral aspects. However, even if the internal processes are not of primary interest, they must be analyzed attentively, as it seems that black-box approaches are not very promising for the ATC domain. In [Bisseret 71] Bisseret states that:

> "... a knowledge of external behavior alone seems insufficient: the controller's actions are fairly infrequent and simple; his external activity does not add much to his load. Even the verbal communication remains intrinsically not very complex. It is rather the operation of the mental processes resulting in these messages which sets up the real control complexity."

Apparently, modeling the decision processes is the most promising approach in order to predict controller behavior. However, there are always several solutions to one problem and it cannot be decided objectively if and at what time actions are required. A variety of parameters influences the decision process and, due to individual preferences and expertise, each controller demonstrates a unique pattern of behavior. Deterministic predictions what individual controllers will actually do in a certain situation, therefore, are very difficult to accomplish.

A user model must take into account as much knowledge about cognitive processes as necessary. The quality of the model, however, is determined by the quality of the clearance predictions rather than by the quality with which the cognitive processes are mapped. The model must meet the following requirements:

- Generation of a situation-tailored prediction of the most probable ATC instructions, as restricted as possible and as large as necessary in order to include the largest percentage of advisories.
- Translation of ATC instructions into the sentences, i.e. sequences of words, the controller is expected to speak.
- Implementation in a computer-based model, which generates predictions continuously and in real-time.

Casner investigated the predictability of ATC clearances during line flights in the United States, i.e. the likelihood that an ATC clearance in a certain situation could be anticipated by pilots due to earlier encounters of a similar situation [Casner 94]. A considerable number of instructions could be foreseen by pilots who had been flying on this route before, while the predictability depended on the flight phase and the sector geometry. He concluded that the controllers' actions are determined by situational factors and individual factors at roughly 50 percent each. Even if Casner's work demonstrates that it is hardly possible to predict an individual controller's actions, it illustrates the benefits of situation knowledge.

Controllers are highly skilled and trained; during normal operation very few situations occur that require explicit problem solving. Most situations have been encountered and dealt with before, so that, in terms of Rasmussen's model, most controller activity can be described as rule-based and skill-based activity. A great percentage of controllers activity consists of visuo-spatial representation and tasks of mental arithmetics associated with system observation and preparation for the decision making.

The Cognitive Controller Model (CCM) is proposed as a model of the cognitive processes involved in air traffic control. CCM focuses on 'standard situations' in which procedures apply that have been learnt or derived at an earlier encounter of a similar situation. CCM does not map explicit problem solving. Also, CCM is limited to the executive controller and does not consider the more strategic conflict checking and problem solving tasks of the planning controller. The Cognitive Controller Model consists of three functions that correspond to three steps in the model proposed by Rouse & Rouse (see Figure 4-5, page 49), provided that no problem exists that would require knowledge based problem solving. In this case the model is reduced to three modules: Observation of System State, Choice of Procedure, and Execution of Procedure. Accordingly, CCM possesses three functions:

- Observation Function: The relevant parameters of each aircraft in the control sector are observed, such as position, flight level, heading, speed, etc. Additional information, such as aircraft type, flight plan, and destination is assessed in order to obtain a complete picture of the situation. Based on these parameters, the dynamics and positions of each aircraft are estimated during a certain period of time in the future. This allows to estimate whether and at what time a conflict may occur between two or more aircraft and if actions are required.
- Decision Function: After classifying the actual situation, adequate procedures are chosen. These procedures are directly linked to the characteristics of the situation. The choice of procedure involves determining a suitable control advisory and the corresponding parameters. According to the aim of the model, the result of this function is a selection of the most probable clearances.
- Phraseology Function: After an adequate clearance has been determined it must be executed, i.e. the control advisory must be verbally transmitted to the aircraft. The phraseology function determines which sentences the controller may speak to express his or her instructions.

5.2 CCM Functional Architecture

Figure 5-1 depicts the introduction of the Cognitive Controller Model CCM into the ATC simulation and speech recognition environment (compare Figure 2-13 on page 19). CCM continuously observes the simulation and keeps track of dynamic data

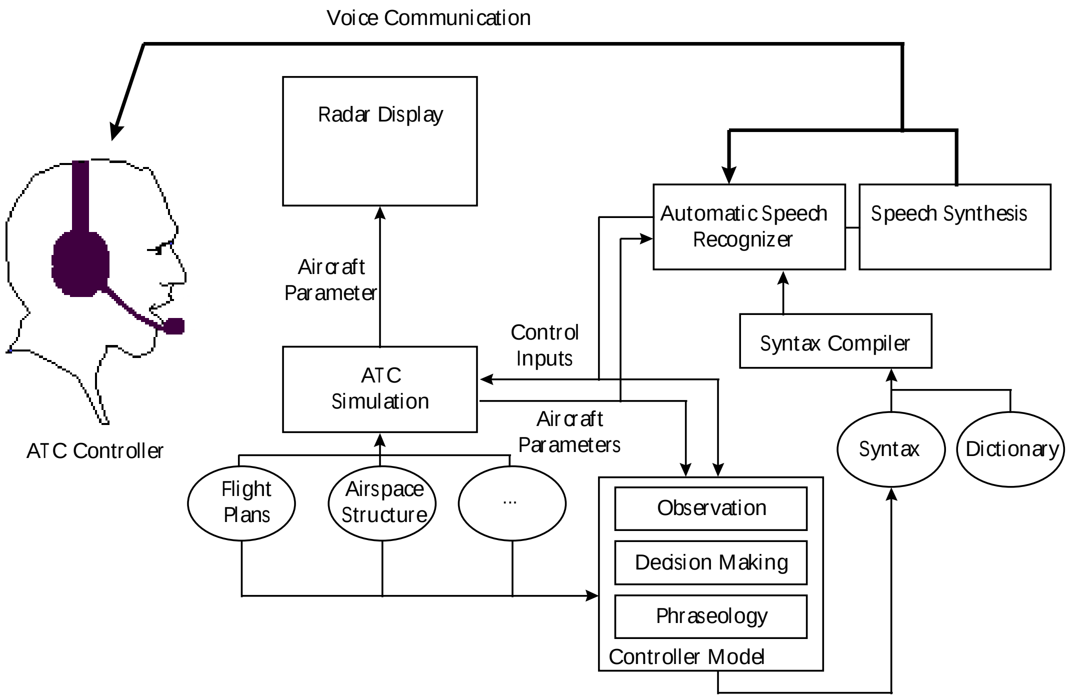


Figure 5-1 CCM in the simulation and speech recognition environment.

such as aircraft parameters and clearance history as well as static data such as flight plans and airspace geometry. On basis of the information it possesses of the present state of the simulation, CCM generates an estimate of the most probable clearances. It then uses the phraseology associated with each clearance to construct a dynamic syntax, which contains the sentences CCM considers likely in the actual situation. The syntax must then be compiled with the dictionary prior to being used by the ASR. In order to ensure that the speech recognizer is in possession of an updated syntax with minimum delay, the syntax construction must be repeated frequently. Presently, CCM generates an updated syntax once per second.

In a first step physically possible and impossible clearances are distinguished and a syntax is generated which comprises the possible clearances. For example, only clearances for aircraft which are at present in the sector are possible, or a descent clearance is only possible if a flight level below the present flight level of the concerned aircraft is advised. Compared to the static syntax, the syntax comprising possible clearances already leads to a considerable reduction of the number of sentences. However, further restrictions of the search space are feasible. In a second and more sophisticated step the set of clearances that appear probable in the actual situation is elaborated. Based on the behavior and strategies of air traffic controllers that have been observed in experiments and simulations, CCM decides which instructions the controller will probably use. The set of probable clearances is a subset of the possible clearances.

Both syntaxes are compiled and transferred to the speech recognizer for decoding the next sentence. The recognition process uses the syntax of probable clearances which in most cases includes the actually spoken sentence. However, as a certain likelihood remains that the actual utterance is not included in the set of probable clearances, the syntax of possible clearances is used to repeat the decoding if no satisfying match is found during the first cycle. If the spoken utterance is not included in the set of probable sentences but a phonetically similar sentence exists, this sentence is often returned erroneously by the speech recognizer. This kind of recognition error cannot be eliminated completely but restricted as far as possible by designing a lean search space.

Figure 5-2 depicts the structure of the Cognitive Controller Model. After the initialization of the airspace structure, a loop of three functions is continuously executed: the observation function, the decision function and the phraseology function. The observation function retrieves the relevant dynamic information from the simulation data file and generates and updates aircraft objects. Hereafter a conflict probe is executed for each pair of aircraft in the sector. The decision function generates a set

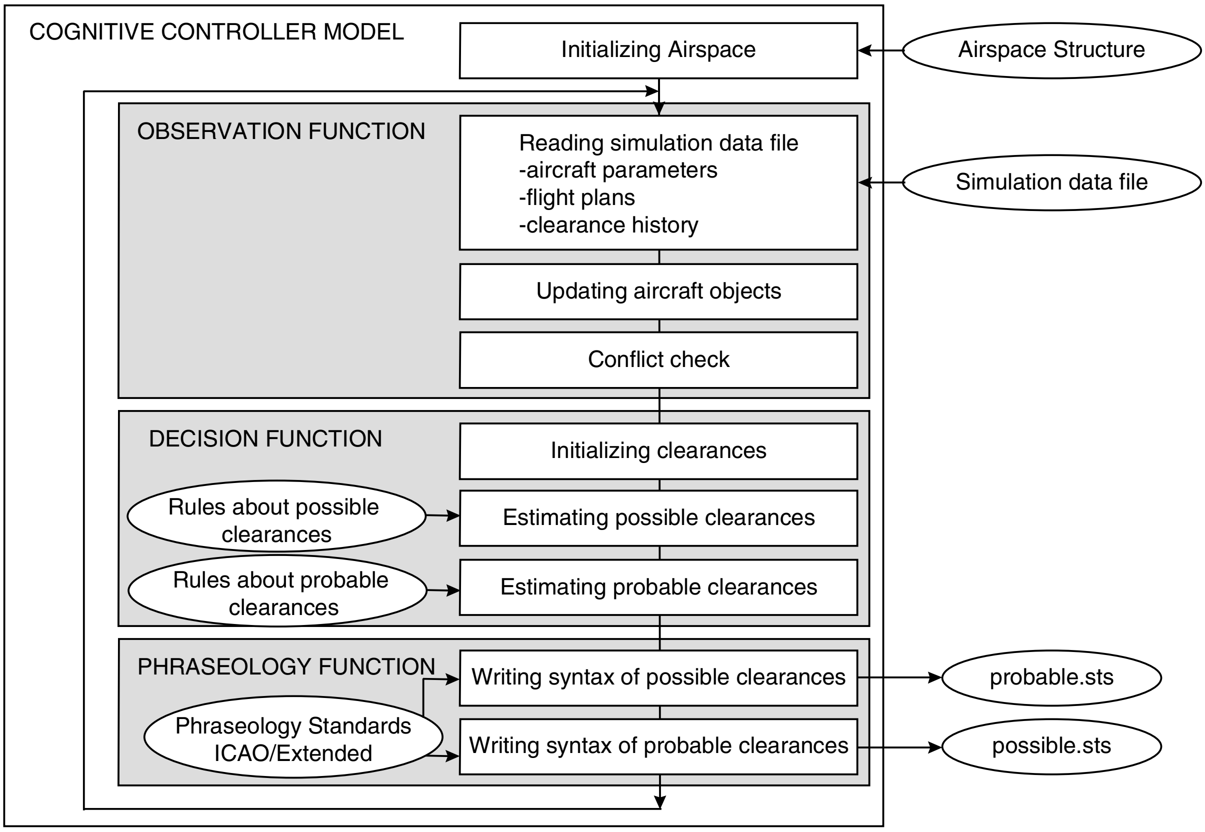


Figure 5-2 The structure of the Cognitive Controller Model.

of clearances that are currently possible, plus a set of the most probable clearances. The decision function uses two different databases of rules, one for the possible and one for the probable clearances. The phraseology function translates the parametric selections generated by the decision function into the phrases that the controller may actually speak. The clearances and the associated phrases are written to the syntax files probable.sts and possible.sts which are then transmitted to the speech recognizer.

5.3 Air Traffic Control in Frankfurt Westradar 1

Besides general ATC knowledge, sector specific knowledge such as airspace geometry and standard procedures influences the controller's decisions making. Therefore, a controller model capable of estimating the probabilities of clearances must be adapted to each sector. In order to study the feasibility and benefits of context-sensitive speech recognition, it seemed convenient to limit the scope of the model to an appropriate airspace. The sector should be representative in terms of the procedures used and the traffic density. However, it would be helpful if the traffic density permitted some verbal communication with the controller in order to facilitate the knowledge acquisition process.

The sector Frankfurt Westradar 1 (WR1), schematically depicted in Figure 5-3, is a lower airspace enroute sector west of Frankfurt airport, extending vertically from flight level 100 to flight level 245. WR1 is scheduled as a one-way sector, so that the traffic uses the air route between Nattenheim (NTM) and Rüdesheim (RUD) only in west-eastern direction. The major part of the traffic consists of arriving aircraft with destination Frankfurt, the remaining aircraft being overflights with various other destinations. The border to the adjacent sector Frankfurt Westradar 2 (WR2) south of WR1 is defined by a line in east-western direction south of the air route NTM-RUD. WR2 is mostly used for departure traffic and itself scheduled as a one-way sector.

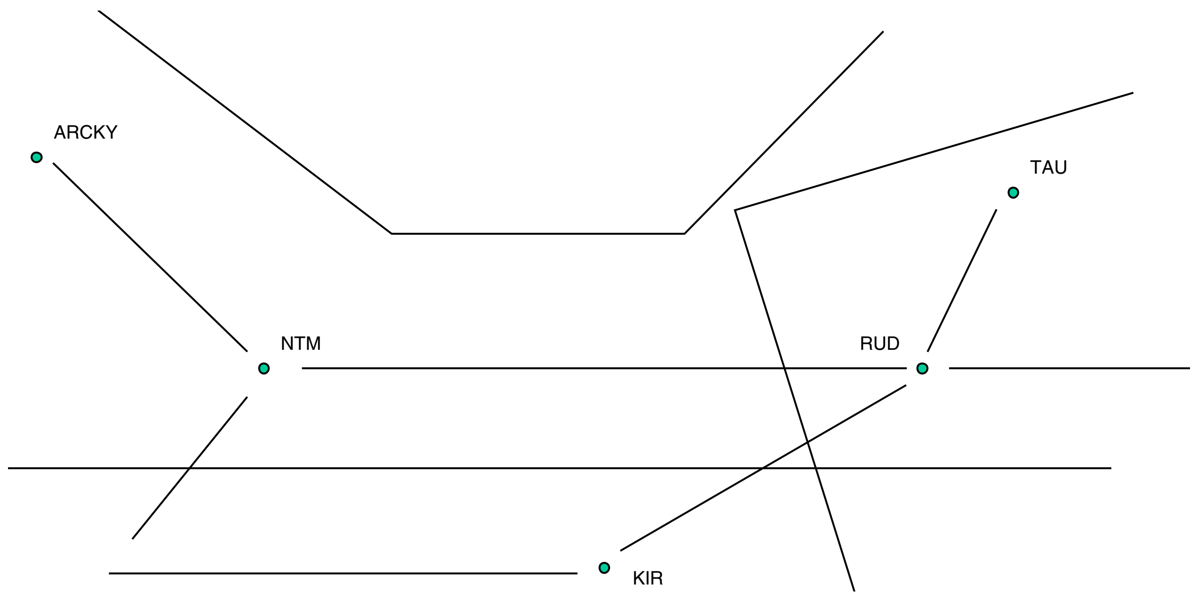


Figure 5-3 Structure of Frankfurt Westradar 1.

The greatest percentage of the arrival traffic enters WR1 flying from ARCKY to NTM between flight level 200 and flight level 250. A handover agreement guarantees that the controller of the adjacent sector Frankfurt Arrival receives the inbound traffic under standard conditions. According to the handover agreement, the aircraft are delivered to Frankfurt Arrival overhead the waypoint RUD at flight level 90 at an indicated airspeed of 250 knots. However, the controllers of WR1 and Frankfurt Arrival can agree on other conventions if required.

The airspace structure of WR1 has been implemented at DLR's Air Traffic Management and Operations Simulator (ATMOS). During extensive simulations controllers were observed and interviewed. Different controllers participated in the simulations, all holding a WR1 sector license. The simulations took about 90 minutes each and were recorded for later analysis. Recorded data included:

- electronic protocols of the simulation parameters, aircraft parameters, and pseudo pilot inputs of 13 simulations,
- observations and inquiries during 14 simulations,
- video-tapes of controller activity during 20 simulations,
- audio-tapes of the communication between controller and pseudo pilots during 9 simulations,
- think-aloud protocols of 3 simulations,
- a teach-back protocol of one simulation.

Each clearance recorded during the simulations was categorized according to the clearance type. The frequency of occurrence of the different clearance categories is depicted in Figure 5-4.

In a first step the electronic transcripts were statistically analyzed in order to identify correlations between the occurrence of specific clearances and the parameters of aircraft, such as the aircraft position or altitude. For some clearance categories correlations were detected, however, these usually corresponded to simple explanations. For other categories no correlations between aircraft parameters and the frequency of occurrence of clearances could be detected. Therefore it seemed that statistical analysis could support the knowledge acquisition process but that it should be combined with other techniques. Often procedures and strategies were observed that could not efficiently be described as correlations between different parameters and, consequently, hardly be discovered by statistical means.

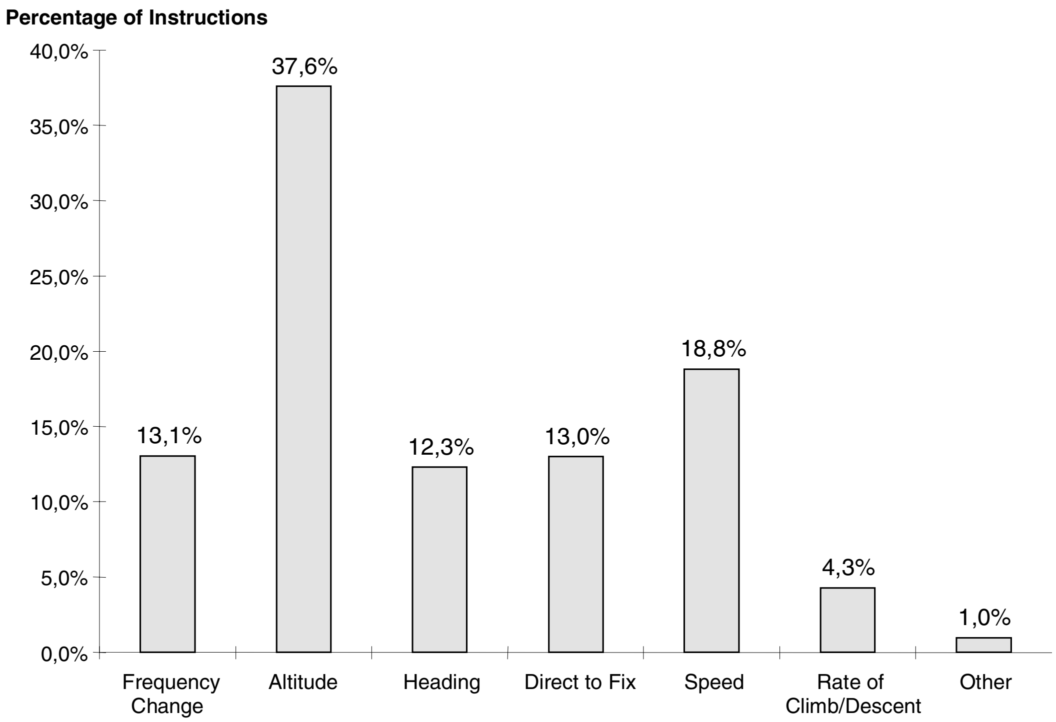


Figure 5-4 Frequency of different clearance categories in WR1.

Think aloud protocols were found to interfere greatly with the controller's verbal communication with the pseudo pilots. Besides, it was necessary to continuously remind the participants to utter their thoughts. For both reasons, think aloud protocols did not contribute very much to the knowledge acquisition process. For back-teaching even greater interference with the communication with pseudo pilots was observed. Furthermore, decisions often had to be made under time pressure which did not permit the controller to fully explain specific decisions. Therefore, back-teaching was abandoned for knowledge acquisition.

Rather than just to describe correlations between situation parameters and the frequency of clearances, it was attempted to understand and to model the controller's decision making. Observation of air traffic controllers during simulation runs as well as inquiries during and after the simulations were the prime means for knowledge acquisition. The experimenter sat next to the controller to note observations and hypotheses and discuss them with the controller during or after the simulation. About 20 hours of simulation with three ATC controllers were attended in this way. Audiotapes of the verbal communication with the pseudo pilots were transcribed and statistically analyzed to identify the phraseology items used most frequently.

5.4 The Observation Function

The first step in the ATC controller's cognitive activity is the observation and classification of the air traffic situation. He or she constructs a mental representation of the aircraft states as well as the entire air traffic situation in order to detect possible conflicts and to decide upon adequate measures. A complete description of the situation requires the monitoring of a great number of continuously changing parameters and would exceed the human mental capacities. Mechanisms of memory storage are unconsciously applied that help to alleviate the mental workload and to efficiently deal with the situation. Aircraft and situation parameters are classified as relevant or less relevant and only the most relevant data is used for the mental representation. Furthermore, more attention is directed towards aircraft or pairs of aircraft that for some reason require close observation.

By means of paper flight strips or equivalent electronic means, the controller is informed in advance at what time, from which direction, and at which flight level an aircraft will enter the sector. When flying into the sector, the aircraft issues an init call providing its callsign and flight level. At that point a mental aircraft object is constructed. After the aircraft has been guided through the sector and advised to change to the frequency of the adjacent control sector, its maneuvers are still observed until it is out of range of possible conflicts to other aircraft.

Aircraft are mentally referred to by their callsign, consisting of an airline code and a flight number. Often, the controller uses only the airline for identification, provided not more than one aircraft of the same airline is in the sector. The aircraft position is mostly memorized visually rather than by figures of the aircraft position in a coordinate system. If required for a conflict check or to assess the remaining flight time, the distance to other targets, aircraft or fixes, is estimated. The vertical position is referred to by the flight level and cleared flight level. The flight level is continuously changing during climb and descent maneuvers so that updating the mental object would require constant observation whereas the cleared flight level remains constant until the aircraft is instructed otherwise. For aircraft whose vertical maneuvers are considered uncritical because there is little risk of approximation to other targets, only the cleared flight level is remembered. If for some reason the vertical movements must be watched more attentively, the flight level becomes the relevant parameter and is checked continuously.

The way in which other parameters are memorized depends on the aircraft status. For instance, the cleared heading is remembered if assigned, or the cleared fix is stored if the aircraft flies according to flight plan or has been instructed to fly directly to a specific fix. Additional parameters such as airspeed, heading, and rate of climb or descent are rarely remembered, but extracted from the flight strip or aircraft label or inquired from the pilot if necessary. The parameters of clearances are generally marked on the paper flight strips. Thus the controller keeps track of the flight progress and his instructions.

Checking for future conflicts takes place in a two-step process. In a more intuitive manner, the sector is scanned for possibly conflicting situations, i.e. groups of two or more aircraft for which a close approximation cannot be excluded. Limited attention is directed towards aircraft the controller perceives to be "safe". If the anticipated route of two or more aircraft may approximate more closely and at a similar altitude, more attention is directed towards each of these aircraft. Based on rules of thumb[15], the future position of each aircraft is then estimated explicitly, and it is checked more thoroughly which separation will remain at the point of closest approximation. The "expert" way of classifying situations as either conflicting or safe is the intuitive, pattern-based way, derived from the more explicit way of calculating future positions. Which mechanisms apply in a given situation is a matter of expertise and no clear distinction can be made at what point a controller will perform an explicit estimation.

[15] Controllers often use simple rules such as: „the distance the aircraft will cover in one minute equals its ground speed divided by 60“ or, less precise: „an aircraft covers about five miles per minute“ to assess future positions.

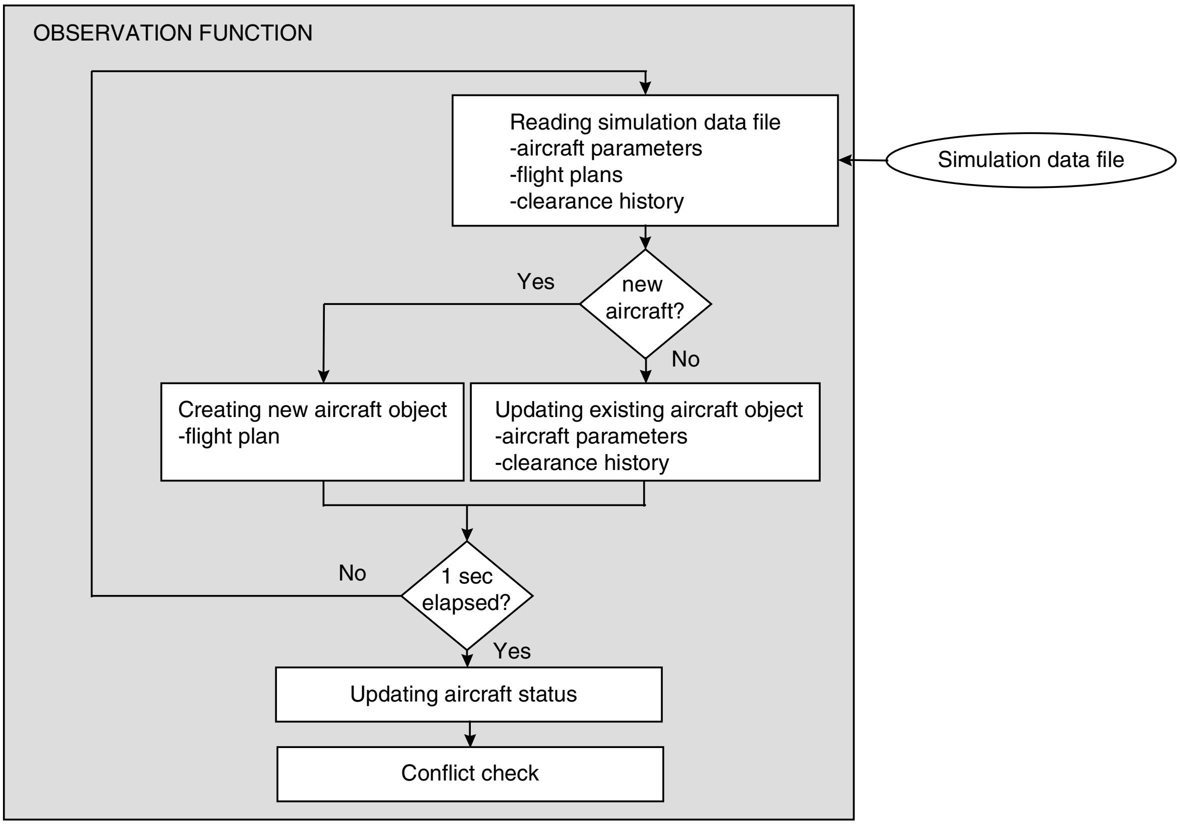


Figure 5-5 The observation function.

After situations have been diagnosed as safe or after conflicts have been resolved, attention is withdrawn from the respective aircraft.

Figure 5-5 depicts the structure of CCM's observation function. After an entry in the simulation data file is read that refers to an aircraft, the depicted loop is executed. The aircraft-related data may concern aircraft position and parameters or clearances that have been issued by the controller and received via mouse or speech recognizer. In case that a new aircraft enters the sector, the complete flight plan information is written to the simulation data file a few minutes in advance. An aircraft object is generated and initialized when the flight plan is read from the simulation data file. After reading one line in the simulation data file, the observation function determines which aircraft is concerned and whether an aircraft object already exists for that aircraft. If the entry concerns an aircraft for which an aircraft object has already been generated, the object is updated with aircraft parameters, such as position, flight level and speed or with clearance parameters[16]. New aircraft parameters are written to the file every four seconds, corresponding to a typical rotation cycle of radar antennas.

[16] CCM requires knowledge about the clearance history because past clearances also determine the aircraft state. Clearances are therefore also read from the simulation data file.

All aircraft-related entries in the simulation data file are read and processed successively until a time span of one second has elapsed. To reduce the complexity and the number of parameters that must be remembered, each aircraft is mentally classified with status categories. These states can be considered as auxiliary parameters, facilitating the application of rules in the decision function. Still, they were identified in accordance with the way ATC controllers mentally group and distinguish aircraft:

- The lateral status distinguishes an aircraft flying on course to a waypoint, either according to flight plan or because it has been explicitly cleared to do so (TOFIX), an aircraft flying on a cleared heading (HEADING), an aircraft in a holding pattern (HOLD) or circling (CIRCLE).
- The vertical status distinguishes climbing aircraft (CLIMB), descending aircraft (DESCENT) and aircraft maintaining their present altitude (MAINTAIN).
- The control status distinguishes the controller's responsibility for the aircraft. After the init call but prior to being assumed by the controller an aircraft is assigned the control state INIT. After it has been assumed and is under control the state changes to CONTROL. After the aircraft has been advised to contact the controller of the adjacent sector, the control state changes to HANDOVER.
- With status, CCM further distinguishes between arrival traffic with destination Frankfurt (ARRIVAL) and overflights with other destinations (OVERFLIGHT). Typically, different control strategies are applied for arrival traffic and overflights.

After the states have been determined, a forecast of the future position of each aircraft is performed in order to predict the traffic situation within a planning time horizon. Future speed, heading and vertical speed are calculated based on the actual and the cleared parameters and used for the calculation of the position increments. The future positions and flight levels are calculated incrementally with a resolution of four seconds.

The position forecasts are used to check for conflicts between two or more aircraft. The future lateral and vertical separation between every pair of aircraft in the sector is calculated in steps of four seconds within the planning time horizon. Pairs of aircraft whose estimated vertical and lateral future separation is less than the required minimum safety separation of six nautical miles laterally or ten flight levels vertically are marked as conflicting. According to experiments with controllers the planning time horizon during which the future traffic state is considered by executive controllers ranges between two and five minutes. CCM currently uses a time horizon of two minutes which seems to be sufficient to support the decision making process.

5.5 The Decision Function

After the traffic situation has been observed and analyzed, the controller must decide if and which measures are required. The meta-goal of efficiently controlling each aircraft through the sector without causing hazards to other traffic consists of a variety of quickly changing and interdependent subgoals for individual aircraft or sets of aircraft. However, it was observed that controllers had more difficulties to specify subgoals that determined their decisions than to describe situations under which they would apply certain strategies. Control strategies can be described by three items controllers remember explicitly when asked about their decisions. These are

- an abstract description of the required action,
- conditions under which it can be applied,
- an estimated effect.

To derive possible control actions that belong to a strategy, the abstract description must be translated into explicit control advisories, depending on the actual aircraft state. Because approaching aircraft account for most of the traffic in the sector WR1 and since arrivals are more complicated to handle than enroute traffic, the following considerations are limited to arrival aircraft in the sector Frankfurt Westradar 1. The scope is also limited to conflict-free traffic. In case that a conflict has to be solved, different strategies have to be considered that are beyond the scope of this study.

Control advisories are generally not only depending on the status and parameters of one particular aircraft but also on the entire traffic situation, for example on the status of preceding aircraft. The first aircraft in each simulation, with no traffic ahead of it, is a special case, suitable to demonstrate how control could take place if no dependencies on other traffic had to be considered. Figure 5-6 depicts possible control procedures for an isolated aircraft.

- The aircraft enters the sector at position 1, announcing its presence with init call and the controller confirms radio contact. At that point, the aircraft typically flies between FL 200 and FL 250 with an indicated airspeed of about 300 knots.
- According to its flight plan, the aircraft proceeds via the fixes Nattenheim (NTM), Rüdesheim (RUD) to Frankfurt (FFM, east of RUD). However, the controller sometimes advises the aircraft to turn left at position 2 and left again at position 3, knowing that proceeding on a shorter flight route saves time and fuel and is highly appreciated by pilots. He or she may also advise the aircraft to proceed directly to RUD or FFM when at position 2.
- In order to deliver aircraft to the arrival sector on the scheduled handover level of FL 90 the controller has to advise a descent a some point. With common descent rates ranging between 1500 and 2000 feet per minute, an aircraft starting its des-

cent overhead NTM will reach flight level 90 a few miles prior to RUD. Thus, a descent to FL 90 is often advised somewhere around NTM. However, if aircraft reached FL 90 outside the lateral boundaries of the arrival sector, in Figure 5-6 indicated by a line west of RUD, they would enter airspace E, an area in which traffic navigating under visual flight rules (VFR) is also permitted. Therefore some controllers advise a descent to flight level 100 in a first step, followed by a further descent to flight level 90 as soon as the aircraft is overhead the approach area. Due to the lower air density flying at higher altitudes with constant airspeed is less fuel- and time consuming. Therefore pilots generally prefer to maintain a higher flight level as long as possible and the controller, if possible, usually complies.

- In most cases, at some point in the sector a speed reduction to the handover speed of 250 knots indicated airspeed is advised. Again, pilots appreciate a speed reduction late in the arrival.
- When the aircraft has reached the handover fix Rüdesheim (RUD) at an adequate flight level and with adequate speed, it is advised to change to the radio frequency of Frankfurt Arrival control.

Controlling one isolated aircraft may appear simple at first glance. However, it demonstrates that even in this case there is little chance of predicting exactly if and at which point the controller will speak a particular instruction. If a number of aircraft have to be controlled instead of a single aircraft, the complexity increases further.

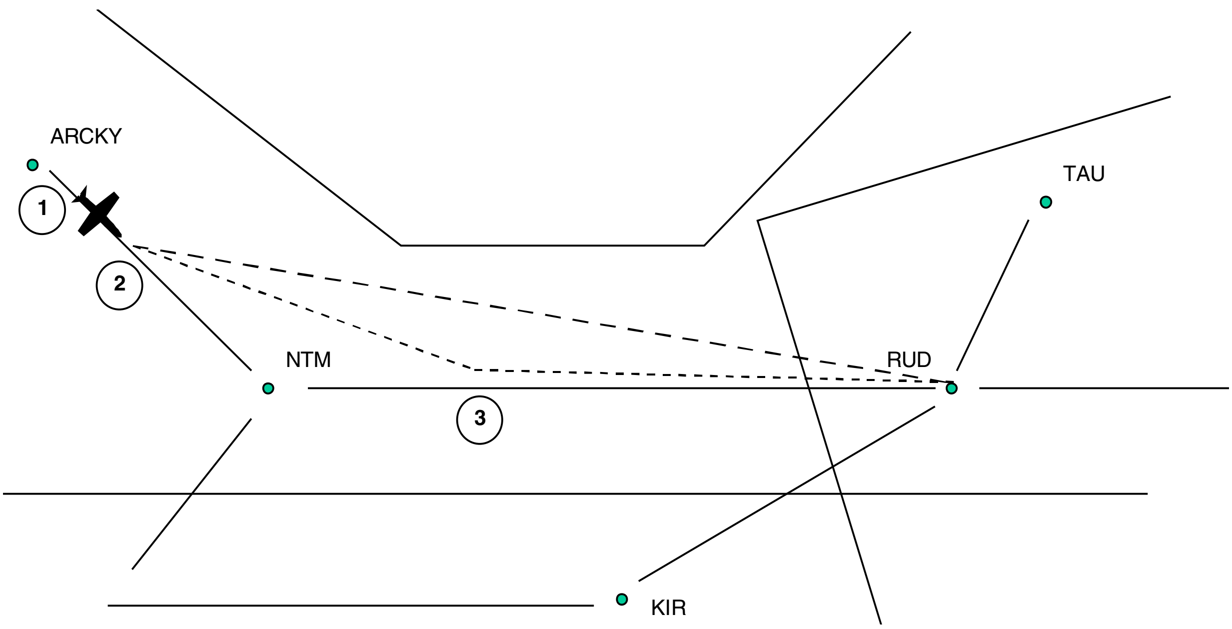


Figure 5-6 Possible control advisories for an isolated aircraft.

Figure 5-4 (page 64) depicts the frequency with which clearances of the different categories are issued. The control strategies are mostly concerned with clearances regarding lateral control (guiding aircraft along a suitable lateral routing by heading and waypoint clearances), vertical control (advising flight levels and vertical speed), speed control (instructing the airspeed if necessary), and communication (instruction to change to the radio frequency of other sectors).

Lateral control

Lateral control strategies are often used to guide aircraft away from the standard routes on which they would otherwise proceed. This can be done in order to maintain separations between aircraft, to meet handover sequences or time proposals[17], or to shorten the way. Lateral control is concerned with advising a cleared heading or the way to a fix. Also, aircraft can be advised to circle at their present position or to enter a holding pattern.

A strategy frequently applied to control the separation between two or more aircraft without speed control is what controllers call a "lineal holding". It consists in advising a turn of about 10 to 40 degrees away from the standard route on which the aircraft is flying. A while later the aircraft is turned back again to the route so that it is delayed due to the longer distance it has to fly. Lineal holdings are often used to increase the separation to the preceding aircraft or to delay the aircraft in order to meet a handover time proposal. A typical lineal holding is depicted in Figure 5-7. The

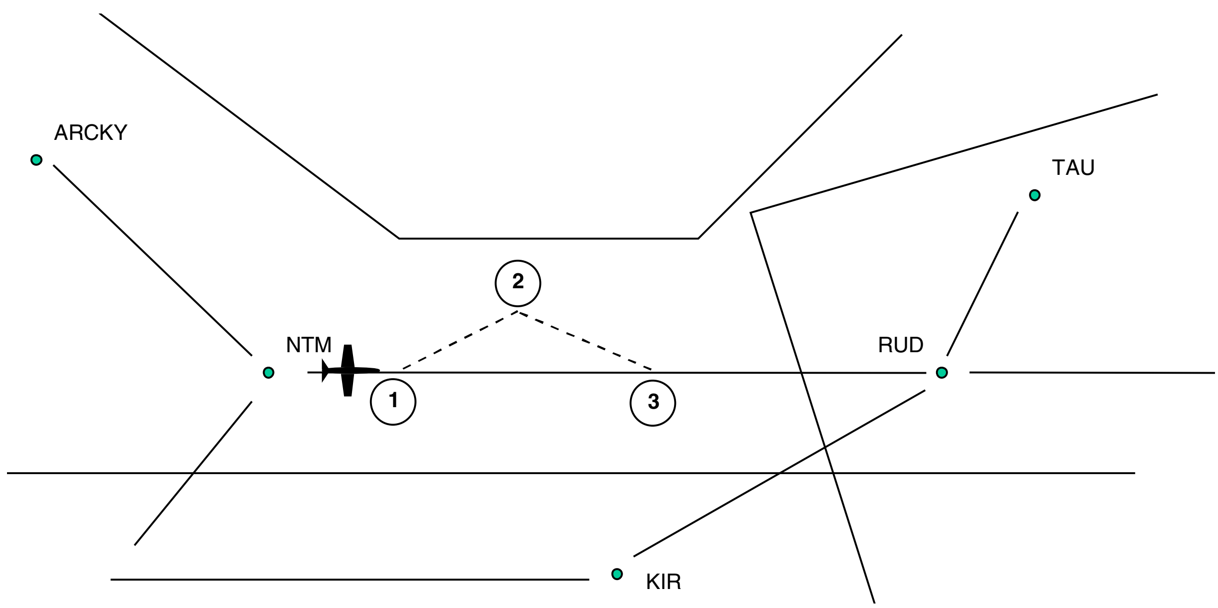


Figure 5-7 "Lineal holding" in WR1.

[17] The controller assistance system COMPAS (Computer Oriented Metering, Planning, and Advisory System) generates an optimized arrival sequence and time proposals for the handover between sectors. COMPAS has been in operational service at Frankfurt area control center since 1989.

aircraft is advised to turn left by 30 degrees at position 1, turns right again by 60 degrees at position 2 and joins the route to RUD again at position 3.

Vertical control
In order to prevent loss of separation, the controller often advises the second aircraft to descend to a flight level above the cleared flight level of the first aircraft, thus maintaining vertical separation even if the aircraft would for some reason approximate laterally. If, for instance, a communication failure or a failure of the radar system would occur, a standard procedure for the aircraft would be to enter the holding pattern at RUD. In this case a vertical separation of at least ten flight levels must be maintained. Of course, a third aircraft may again be cleared to a higher flight level. Whether this strategy is applied depends on the distance between the aircraft, their speed, and the controller's individual preferences.

Aircraft generally fly at constant Mach number or constant indicated airspeed. The speed above ground depends not only on the indicated airspeed, but also on the wind velocity and the air pressure which itself depends on the altitude. Aircraft flying at a higher altitude at the same indicated airspeed are therefore flying with a higher speed above ground. Neglecting the wind, the ground speed decreases when the aircraft is in a descent. This effect has to be taken into consideration when descents are advised for aircraft flying with little lateral separation.

Speed control
Aircraft typically enter the sector at an indicated airspeed of 280 to 320 knots. Speed reduction is required in order to be able to deliver the aircraft to the arrival sector with an indicated airspeed of 250 knots according to the handover agreement. At what point a speed reduction is advised depends on the overall traffic situation: on the one hand the controller tries to permit the aircraft to fly with high speed as long as possible, on the other hand he tries to avoid that trailing aircraft close up to the aircraft ahead. Irrespective of vertical separation, aircraft should be handed over to the arrival sector with a certain lateral separation to facilitate handling for the arrival controller. Most controllers consider lateral control more elegant than speed control.

Communication
Communication between pilot and controller is initiated when the aircraft enters the sector and the pilot issues an init call to announce its presence and provide information about its flight state. The controller responds to the init call confirming radar contact. When the aircraft approaches the sector boundaries to leave the airspace and if the handover conditions are met, it is advised to leave the frequency and contact the controller of the arrival sector on a specified radio frequency.

The strategies controllers have been observed to use most frequently are listed in Table 5-1 for each of the clearance categories, together with the conditions under which the strategies are typically applied and the estimated effect. These considerations are limited to conflict-free arrival traffic in WR1. Similarly, other control strategies have been identified for overflights in WR1.

	Strategy	**Conditions**	**Effect**
Lateral control			
	"direct to RUD" "direct to FFM"	inbound NTM	acceleration (30 - 60 sec)
	"left turn"	inbound NTM	acceleration (30 - 60 sec)
	"lineal holding"	inbound RUD or heading 090 east of NTM	delay (0-1 min)
	"holding at RUD"	inbound RUD	delay (4 - 6 min)
	"circle left/right"		delay (2 min)
	"heading 270"	inbound RUD or heading 090 east of NTM	delay (any)
Vertical control			
	"keep high level"	inbound NTM or inbound RUD and maintaining high level	acceleration (30 - 50 sec)
	"descent"	inbound NTM or inbound RUD and maintaining high level	delay (30 - 50 sec)
Speed control			
	"reduce speed"	inbound NTM or RUD and speed above 250 kts.	delay (30 - 60 sec)
	"increase speed"	inbound NTM or inbound RUD and moderate speed	acceleration (30 - 60 sec)
Communication			
	"confirm init call"	aircraft enters the sector and has issued an init call	-
	"contact arrival"	aircraft is overhead handover fix and handover conditions are met	aircraft leaves frequency

Table 5-1 Strategies applied for controlling arrival traffic in WR1.

The decision function estimates the likelihood of individual clearances in the actual situation. Each aircraft object generated by CCM possesses a uniform, non context-sensitive list of clearances which is generated when the aircraft object is constructed. The list includes all clearances that may be encountered at any point during the simulation and with common restrictions to clearance parameters[18] comprises about 450 clearance objects per aircraft[19]. Each clearance possesses a clearance type and a parameter. A clearance with the category "LEFT_HEAD" and the parameter "060", for instance, corresponds to the instruction to turn left to a heading of 060 degrees. Additionally, a weight parameter is assigned to each clearance, reflecting CCM's estimation about the likelihood that the concerned aircraft may receive this clearance in the actual situation. The clearance weight for each clearance is set to zero during initialization and then calculated in the subsequent steps of the decision function.

The major components of the decision function are depicted in Figure 5-8. In a first step the list of clearances is initialized for each aircraft and the clearance weights are set to zero. Then a set of rules is applied to each clearance of each aircraft in order to identify if this clearances at present appears feasible from a physical point of view. If so, a weight of one is assigned to the clearance and it is referred to as a possible clearance. After all possible clearances have been identified, another set of rules is applied to each possible clearance in order to identify clearances the Cognitive

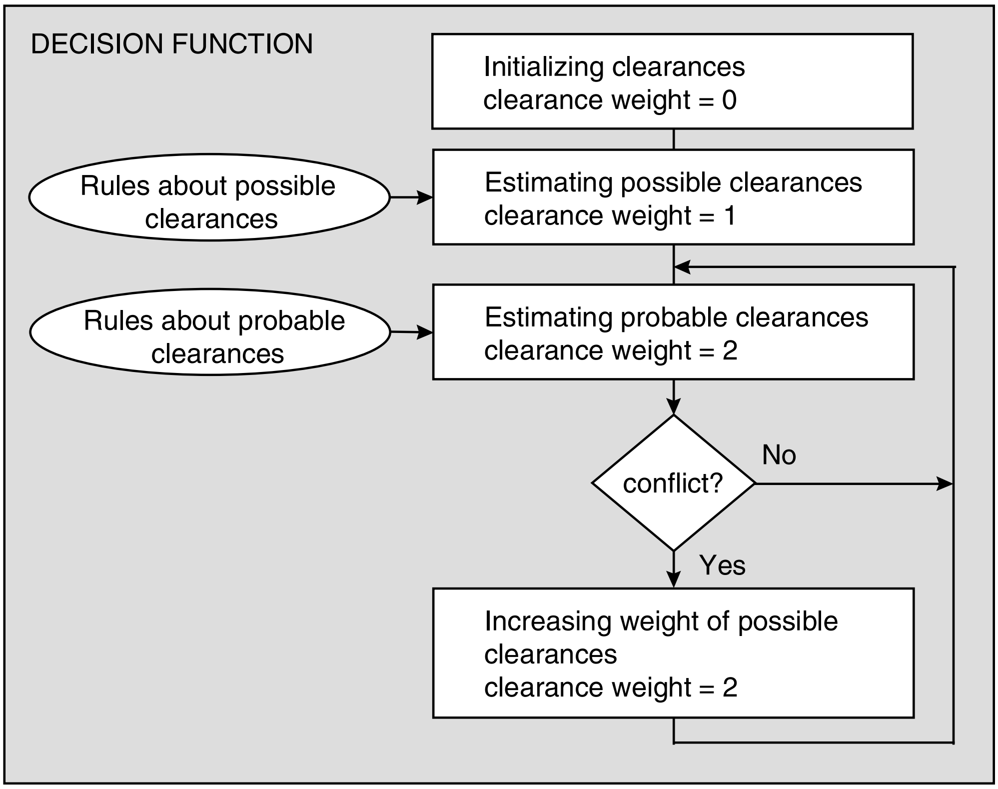


Figure 5-8 The decision function.

[18] For example airspeeds are commonly advised in multitudes of five or ten knots, headings in multitudes of five or ten degrees, etc.

[19] The list corresponds to the clearances a static syntax would comprise for each aircraft.

Controller Model considers likely in the actual situation. These clearances are assigned a weight of two and referred to as probable clearances. Whereas the set of possible rules is independent of airspace geometry and controller strategies, the probable rules imply sector-specific knowledge and represent the strategies that controllers have been observed to apply during their work in that airspace.

Conflicts occurred very seldom during the observed simulations and the mechanisms for conflict resolution are different and more complicated than those for routine situations, so that strategies for conflict resolution could not be identified and modeled. The scope of the Cognitive Controller Model is limited to routine situations in which standard procedures apply and no conflicts have to be solved (see chapter 5.1). To include a wide range of control actions in the predictions it seemed adequate to consider every physically possible clearance as probable if a conflict must be solved. If a pair of conflicting aircraft is detected during the conflict probe in the observation function, all possible clearances of both concerned aircraft are converted into probable clearances, i.e. their clearance weights are increased from one to two.

5.6 The Phraseology Function

After the controller has decided on appropriate instructions he or she must communicate with the pilots of the concerned aircraft. To ensure precise and fast communication with little risk of misunderstandings even under noisy conditions, the ATC phraseology has been standardized by the International Civil Aviation Organization (ICAO). The standards are assumed and, if necessary, adapted by the ATC agencies of the ICAO member countries. The standards published by the German Air Navigation Services (DFS) in the Aeronautical Information Publications (AIP) are mandatory for controllers and pilots during flights in Germany [AIP 97]. An excerpt from the AIP standards is depicted in Table 5-2.

Controllers often do not comply exactly with the standard phraseology. Instead, each controller seems to use a number of favorite phrases slightly deviating from the standards and although they are quite consistent in their preferred wording, the favorite phrases vary greatly between individuals. As speaking is a mostly unconscious function, concentrating on the use of specific phrases would require explicit attention, reducing the amount of attention that could be allocated to other tasks. Therefore it seemed likely that forcing controllers to use the ICAO standard phrases to interact with the ASR would have a negative effect on the simulation conditions.

A- Aircraft Radio Stations
G- Ground Radio Stations

7.32 Heading Instructions

G: **LEAVE** (position) **HEADING** (three digits) *e.g. AT (time)*
G: **CONTINUE HEADING** (three digits)
G: **CONTINUE PRESENT HEADING**
G: **FLY HEADING** (three digits)
G: **TURN LEFT / RIGHT** (figures) **DEGREES / HEADING** (three digits)
G: **MAKE A TREE-SIXTY LEFT/RIGHT** *(reason)*
G: **ORBIT LEFT/RIGHT** *(reason)*
G: **STOP TURN HEADING** (three digits)

Note: When it is necessary to specify a reason for the above maneuvers, the following phrases should be used:

- **FOR TRAFFIC**
- **FOR SPACING**
- **FOR SEPARATION**
- **FOR DOWNWIND / BASE / FINAL**

Table 5-2 Excerpt from Aeronautical Information Publication (AIP).

As the speech recognizer syntax contains the sentences, or sequences of words, the user is permitted to say, the wording of each ATC instruction must be determined. The communications recorded during simulations were analyzed in order to identify the most frequent deviations from the standards. This would permit to tailor an individual phraseology for each controller which would allow him to apparently "speak freely" while in reality he would follow his unconscious preferences. Design-

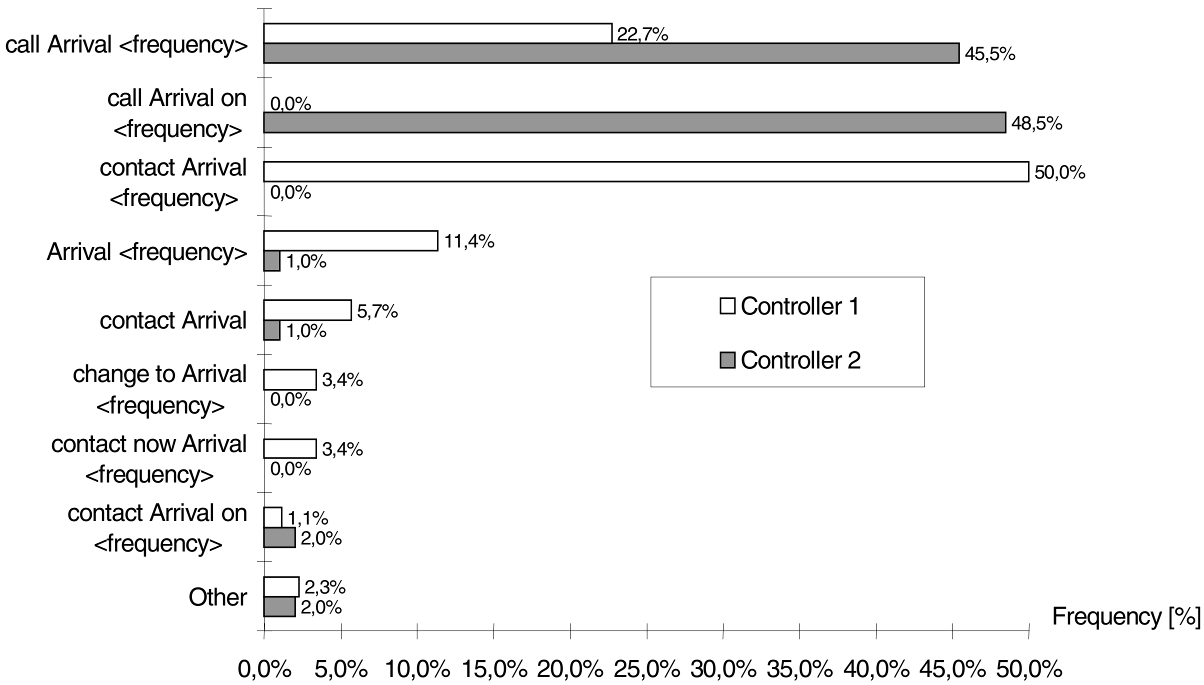


Figure 5-9 Phrases associated with the clearance to contact Arrival sector.

ing an individual syntax for each controller would cause an unacceptable effort. However, if the individual phraseologies of many individuals overlapped sufficiently, such a grammar could be designed for an entire controller population. Recordings of communications were therefore transcribed and statistically analyzed in order to identify the phrases used most commonly in each clearance category. Figure 5-9 depicts the phrases used most frequently for the clearance to contact the arrival controller. Controller 2 persistently uses the two phrases "call arrival on <frequency>" and "call arrival <frequency>", whereas controller 1 employs a broader set of phrases, including the ICAO standard "contact arrival <frequency>".

The transcriptions of 20 hours of simulations with two controllers were analyzed in this way. The most frequently spoken phrases per clearance category that in sum would account for 95 percent of the transmissions per category were collected for each of the two controllers. The respective numbers of phrases per category are depicted in Table 5-3. A syntax that could be used for both controllers would have to cover the greatest percentage of the phrases both controllers use which increases the size of the syntax even further. The number of phrases for 95 percent coverage of both controllers' utterances is given in the last column of Table 5-3.

Clearance Category	**Number of Phrases required for 95% coverage**		
	Controller 1	Controller 2	Controller 1 + 2
Response to init call	5	5	5
Contact Arrival	5	7	8
Contact Radar	4	6	8
Heading	1	8	8
Left/ Right to Heading	4	5	7
Direct to Fix	11	8	16
Left/ Right direct to Fix	8	6	10
Speed	5	11	13
Maintain Speed	7	3	9
Reduce Speed	11	16	21
Increase Speed	2	4	6
Circle Left/Right	3	1	4
Holding	5	0	5
Flight Level	6	12	17
Descend to Flight Level	3	2	4
Climb to Flight Level	2	1	3
Rate of Climb/Descent	6	13	18
SUM	**88**	**108**	**162**

Table 5-3 Most frequent clearances recorded during simulations.

The number of phrases required to cover the 95th percentile of the phrases of one controller in some cases is considerable when compared to the ICAO standard and increases further when two controllers are considered. It must be expected that the number increases for a greater population of controllers. The effect had to be scrutinized in more detail, i.e. by analysis of a greater number of transmissions involving a greater number of controllers before reliable predictions are possible. For the scope of this study, however, it seemed unreasonable to permit the subjects to speak completely unrestricted. Apart from the effort that lies in collecting and analyzing the data, a broader phraseology means a broader search space for the speech recognition process, resulting in lower recognition rates.

Therefore a different approach was chosen. A list of the ICAO standard phrases associated with the clearance categories applicable to air traffic control in the sector WR1 was collected [AIP 97]. The list was presented to air traffic controllers at Frankfurt area control center, asking them to write down those additional phrases they felt they also used frequently. About 20 controllers contributed to the list and the most frequently mentioned phrases were identified. The section of the ICAO standard phrases concerned with heading advisories is shown in Table 5-4 (the complete ICAO standard syntax can be found in Appendix A). The syntax containing the ICAO standard plus the additional phrases, from now on referred to as the extended phraseology, can be found in Appendix B. The section of the extended phraseology concerned with heading advisories is shown in Table 5-5.

Heading	<Callsign> cleared heading <Heading>
Left/ Right to Heading	<Callsign> turn left heading <Heading> <Callsign> turn right heading <Heading>
Maintain Heading	<Callsign> maintain present heading
Left/Right Turn by	<Callsign> turn left by <Degrees> degrees <Callsign> turn right by <Degrees> degrees

Table 5-4 Heading clearances (ICAO standard phraseology).

During the steps executed in the phraseology function, the sets of possible and probable clearances are identified, and sentences, i.e. sequences of words are generated with which the controller is expected to speak the clearances. Two syntaxes are generated in a format appropriate for use by the automatic speech recognizer, one comprising all possible clearances (possible.sts) and one comprising all probable clearances (probable.sts). The speech recognizer assumes both syntaxes as a basis for the recognition process (the speech recognition and the syntax compilation will be discussed in more detail in chapter 7). In a first step, the speech recognizer tries to identify the spoken utterance among the set of probable clearances. If this fails, possibly because the controller has decided upon a clearance CCM did not expect, the recognition process is repeated using the set of possible clearances.

Heading	<Callsign> cleared heading <Heading> <Callsign> pick up heading <Heading> <Callsign> roll out heading <Heading> <Callsign> continue heading <Heading> <Callsign> stop turn heading <Heading> <Callsign> fly heading <Heading> <Callsign> turn to heading <Heading>
Left/ Right to Heading	<Callsign> turn left (to) heading <Heading> <Callsign> left turn (to) heading <Heading> <Callsign> continue left heading <Heading> <Callsign> turn right (to) heading <Heading> <Callsign> right turn (to) heading <Heading> <Callsign> continue right heading <Heading>
Maintain Heading	<Callsign> maintain present heading <Callsign> maintain heading <Callsign> continue present heading
Left/Right Turn by	<Callsign> turn left by <Degrees> degrees <Callsign> left turn by <Degrees> degrees <Callsign> turn right by <Degrees> degrees <Callsign> right turn by <Degrees> degrees

Table 5-5 Heading clearances (extended phraseology).

Before starting the ATC simulation, the speech recognizer, and the Cognitive Controller Model the experimenter decides whether the ICAO standard phraseology or the extended phraseology shall be used throughout the simulation. CCM is then configured accordingly and started. Before the phraseology function converts the clearance objects into sentences, it reads the phraseology standards from a configuration file. The standards are then used when writing the syntax of possible clearances and the syntax of probable clearances, as depicted in Figure 5-10.

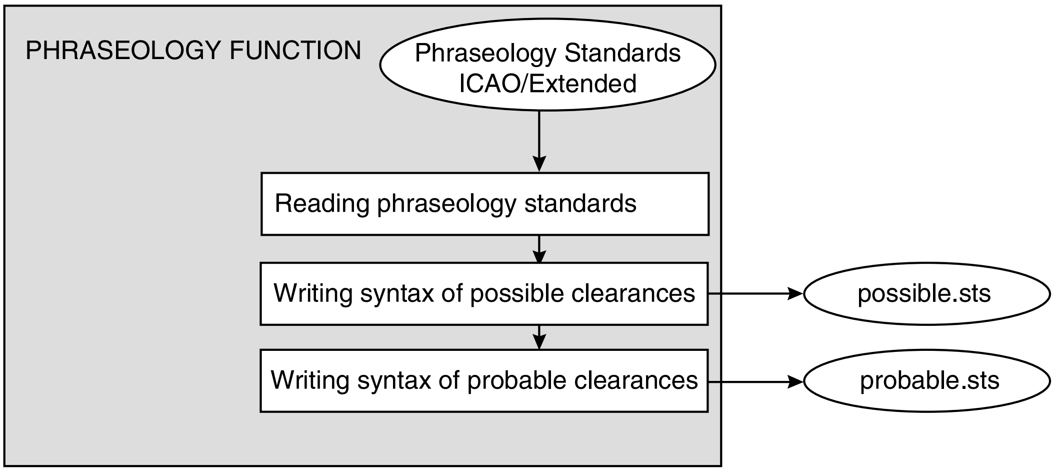


Figure 5-10 The phraseology function.

5.7 Summary

The Cognitive Controller Model (CCM) is proposed as a model of the cognitive processes during the work of an ATC controller, concerned with situation observation, making decisions about the most probable instructions, and choosing the associated phrases the controller may speak. Corresponding to existing cognitive user models, CCM consists of three functions for situation assessment, decision making, and phraseology selection. Different knowledge acquisition techniques have been applied to identify the relevant knowledge items. As this knowledge is to a large degree dependent on the airspace structure and sector-specific procedures, the investigation has been limited to the enroute sector WR1 in the vicinity of Frankfurt airport. The acquired knowledge for each of the three functions must now be implemented in an appropriate form to permit a runtime implementation of the Cognitive Controller Model.

6 Implementation of the Cognitive Controller Model

The Cognitive Controller Model (CCM) is implemented in a runtime program in order to generate a context-specific prediction which sentences the controller may speak. CCM is based on existing cognitive models of human behavior and consists of three modules: the observation module, the decision module, and the phraseology module. An object-based knowledge representation technique was chosen for the observation module, while production systems are used for the decision module. The phraseology module associates sentence structures to the clearances and generates a speech recognizer syntax. Performance tests with CCM, based on data recorded during simulations, indicate that 96.5 percent of all recorded clearances were correctly included in the predictions generated by CCM. At the same time, the number of clearances in the search space was only 2.4 percent of that of a static syntax.

6.1 Methods of Knowledge Representation

Once knowledge about human behavior has been acquired, it can be structured and implemented in a model. Several methods of knowledge representation exist that vary according to the characteristics of the task and the aim of the model. For example, tasks such as continuous control, classification and diagnosis, or problem solving require different representations of knowledge. In some cases, knowledge about user behavior is available in an implicit form, so that it can be used for the training of autonomously learning systems. In other cases, knowledge is available explicitly so that it can be implemented in production rules. The requirements for the implementation itself may also vary: in some cases a continuously changing knowledge data base must be maintained, whereas in other cases it is necessary to reproduce and understand the inference process.

One approach to classify knowledge representation techniques is to assess the appropriateness of each technique for modeling different levels of cognitive activity. A classification of knowledge representation techniques according to the classification of human performance as either skill-based, rule-based, or knowledge-based behavior as presented by Rasmussen is discussed by Ruckdeschel [Rasmussen 83, Ruckdeschel 97]. As discussed above, CCM is limited to standard ATC situations, for which rule-based behavior is most relevant. Methods that are considered convenient for modeling rule-based behavior include:

- fuzzy logic and fuzzy control
- finite state machines, statecharts, and augmented transition networks (ATN)
- semantic nets and frames

- scripts
- petri nets
- production systems.

Fuzzy Logic and Fuzzy Control

Based on the fuzzy set theory proposed by Zadeh, fuzzy logic provides an extension of the classical logic theory to systems whose behavior can be described by continuous parameters rather than by the logical values TRUE or FALSE [Zadeh 65]. Parameter value ranges are converted into discrete classes so that actual parameters can be described by a membership to each class, commonly in an interval between 0 and 1. For instance, the temperature may be described by the classes hot, warm, and cold and the membership value for each of the three classes is a function of the temperature. An example of the temperature described by three membership functions (cold, warm, hot) in industrial founding has been described by Brause and depicted in Figure 6-1 [Brause 95].

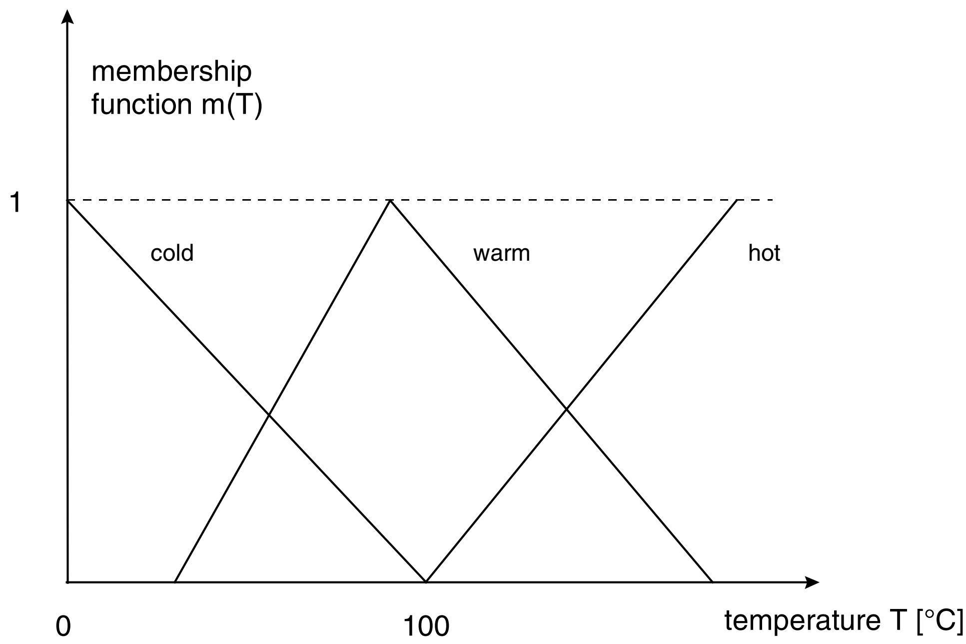


Figure 6-1 Fuzzy membership functions for temperature.

The application of the theory of fuzzy logic on problems of guidance and control is known as fuzzy control. The discipline of fuzzy reasoning is concerned with the application of fuzzy logic on knowledge representation and rule- and knowledge-based problem solving [Ruckdeschel 97]. Fuzzy set theory can be used in classic problems of many-valued logic where parameters are determined, stochastically distributed or partially unknown. It can also be applied in domains where the truth values, i.e. the membership functions themselves are uncertain and must therefore be represented as fuzzy sets. However, doubts have been raised about the benefits of the latter approach. For instance, Rasmussen states that:

> the basic advantage of the fuzzy set approach seems to be its compatibility with ambiguous verbal statements [Rasmussen 86].

Finite State Machines, Statecharts, and Augmented Transition Networks (ATN)

The theory of finite state machines models the activities of human operators or technical systems as transitions between discrete states. It is based on the assumption that the behavior can be described by discrete steps and that only a limited number of well-defined states exist. Finite state machines are graphically displayed in transition networks where states are depicted by circles connected by arrows symbolizing the transitions. Finite state machines can be described by the states, the input vectors and the output vectors of the system plus two functions, one mapping the system states to input vectors and one mapping the output vectors to the system states [Ruckdeschel 97]. A refinement of classic state machines in order to permit information flow between parallel processes leads to the development of statecharts. Another type of transition networks are augmented transition networks, transition networks extended by so-called registers, i.e. subsystems that store memory items that can be retrieved and modified by other components of the system. Figure 6-2 depicts an example statechart describing lane changes of car drivers [Kopf 94].

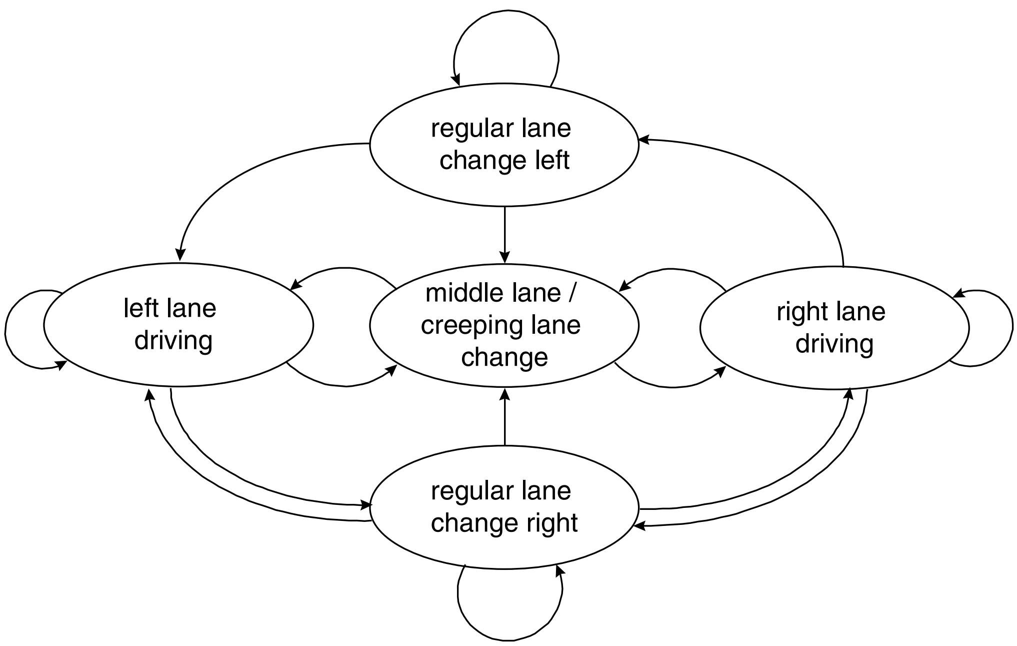


Figure 6-2 Statechart of driver behavior (lane change).

Semantic Nets and Frames

Semantic nets have originally been implemented as raw models of the human memory. Information about objects is implemented in nodes connected by relations of different types, such as "is-a" or "has-a". Semantic nets basically serve to model the relations between objects or distinct knowledge structures and are often combined with techniques for the representation of the objects themselves. A classification of automobiles as an example for semantic nets is depicted in Figure 6-3 [Kraiss 93].

Frames have been proposed by Minsky in order to model "data structures for representing stereotyped situations that are organized as a network of nodes and relations" [Rasmussen 86]. Frames can be considered as object-type knowledge structures which contain slots for the description of different aspects of the object, usually parameters or attributes. Procedures can also be associated with the slots and executed when a specific access to the data in the slot is performed (e.g. "if-added" procedure, "if-needed" procedure). A slot may contain another frame, so that one object can completely or partially be composed from other objects. Moreover, the attributes of one frame can be transmitted to a child frame, so that hierarchical knowledge structures can be implemented [Minsky 75]. However, Rasmussen doubts the adequacy of the frame theory for representing human memory and thinking and states in [Rasmussen 86]:

> Minsky's use of one single concept - the frame theory - to model the human representation of the environment that are active for sensory perception, for physical and verbal interactions with environments, and for symbolic reasoning, leads to unnecessary simplification.

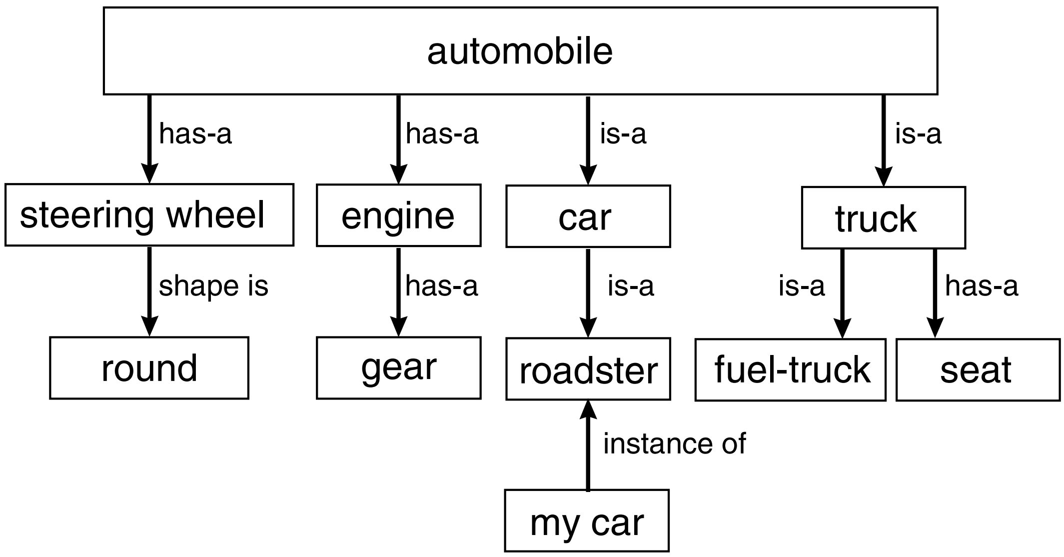


Figure 6-3 Semantic net description of automobiles.

He further argues that representations consisting only of objects and relations, are somewhat static and therefore inappropriate for modeling goal-driven behavior or reasoning:

> Sequential scene analysis and verbal reasoning based alone on semantic nets or frame systems defined as a system of nodes and relations will lack the basis for the overall "direction" in the process. It will be like walking in a city without a map, only aware of the immediate neighborhood.

Scripts

Scripts have been proposed as a means for the analysis of natural language and can be considered as a form of frames that are particularly appropriate for the representation of behavioral procedures [Schank & Abelson 77 in Ruckdeschel 97]. They contain structured sequences of actions that operators may perform in order to achieve a given goal. A script can be part of another script, so that a decomposition of behavioral modules is possible. Scripts are appropriate for representing procedures but less suitable for representing object-like knowledge structures. The script of a person dining in a restaurant is presented in Table 6-1 [Barr & Feigenbaum 81 in Ruckdeschel 97].

Props:	(Restaurant, Money, Food, Menu, Tables, Chairs)
Roles:	(Hungry-Persons, Wait-Persons, Chef-Persons)
Point-of-View:	(Hungry-Persons)
Time-of-Occurrence:	(Times-of-Operation of Restaurant)
Place-of-Occurrence:	(Location of Restaurant)
Event Sequence:	
first:	Enter-Restaurant Script
then:	if (Wait-To-Be-Seated-Sign or Reservations) then Get-Mâitre-d's-Attention Script
then:	then Please-Be-Seated Script
then:	Order-Food Script
then:	Eat-Foot Script unless (Long-Wait) then Exit-Restaurant-Angry Script
then:	if (Food-Quality was better then Palatable) then Compliments-to-the-Chef Script
then:	Pay-for-it Script
finally:	Exit-Restaurant Script

Table 6-1 Script for dining in a retaurant.

Petri Nets

According to a theory proposed by Petri discrete system behavior can be described by situations and events [Petri 62]. Events transfer one situation into another and only occur in certain situations. Dependencies between situations and events are described by local causal relations so that petri nets support the modeling of parallel processes. In a graphical representation, situations are symbolized by circles while events are depicted by bars. Events and situations are connected by arcs, input arcs connecting situations to events and output arcs connecting events to situations. The present system state is marked by marks symbolizing active situations. Figure 6-4 depicts a sample petri net describing a person entering a room. The bar symbolizes the procedure of entering the room, while the connections between the state and the bar symbolize necessary conditions (arrow) and inhibitory conditions (line with circle). The dot refers to the actual state of the system at a given time.

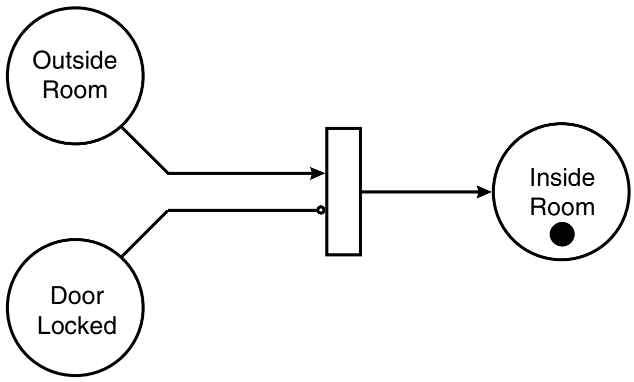


Figure 6-4 Sample Petri Net.

Production Systems

Productions have been introduced by Newell & Simon as a hierarchical structure of actions or conclusions correlated to conditions [Newell & Simon 72]. Production systems consist of three major components: the long term memory, the short term memory, and the inference engine [Ruckdeschel 97]. The long term memory contains production rules and static data while the short term memory contains dynamic data. The inference engine (also known as rule interpreter) decides which productions are executed and updates the data in the short term memory which is modified by external events or by the application of productions. The production rules themselves consist of conditions (IF-part) and assertions (THEN-part), which are executed if the conditions are met. If the conditions of more than one production rule are met, the inference engine decides which rule will be executed, for instance on the basis of priorities assigned to the production rules.

According to the type of inference, forward-chaining and backward-chaining production systems can be distinguished. Forward-chaining, also called data-driven inference, refers to the successive execution of all productions whose conditions are confirmed, either by the data or the assertions of productions that have been executed before. The inference terminates after a specific conclusion has been found or if no further productions can be executed. During backward-chaining, also called goal-driven inference, a conclusion is tested by identifying a production rule that leads to that conclusion and testing all conditions in that rule. Often, the conditions of that rule are assertions of other rules, so that the process continues with testing these rules. The inference stops if either a given hypothesis (the conclusion) is validated or if no further productions can be confirmed.

The Implementation of CCM

For the generation of data-structures such as aircraft, waypoints and clearances, an object-based notation, similar to frames, appears appropriate. It seems to match the controller's mental representation of the static and dynamic data and supports a hierarchical composition of the objects using features such as inheritance and instantiation. Production rules seem appropriate for the representation of decision making in the decision module. Controllers often provide explanations for their decisions in the form of if/then combinations, so that production rules seem to match the mental structure of the knowledge relevant for routine decision making. Besides, evidence has been found that routine decision making can be classified as rule-based behavior and Onken states that "rule-based operator behavior can often be modeled excellently by production systems" [Onken 91].

The object-oriented programming language C++ was chosen for the implementation of the Cognitive Controller Model. C++ permits the construction of objects and class structures together with many helpful features such as inheritance and instantiation. It also allows the representation of production rules.

6.2 Object Representation in the Observation Module

During the steps executed in the observation module, CCM updates its representation of the air traffic situation. The observation module uses a hierarchical class structure for the representation of all relevant objects. A class serves as a template for the instantiation of objects, each object representing relevant data in a specific structure. For each aircraft in the sector, an aircraft object is constructed containing the relevant parameters and attributes of that specific aircraft. The aircraft objects are derived from the class Aircraft. The structure of the class Aircraft is depicted in Figure 6-6. The structure of the classes Position, Waypoint, and Flightplan can be

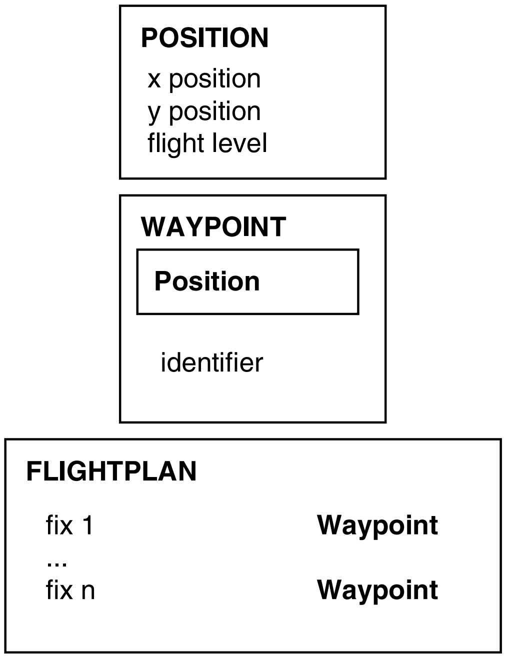


Figure 6-5 The classes Position, Waypoint and Flightplan.

found in Figure 6-5. The complete structure of the major classes within CCM is given in Appendix C.

The class Position consists of the parameters x position, y position and flight level. For each object derived from the class Position, the parameters are filled with the corresponding data. Position objects are used in a variety of other classes. For example, the class Waypoint has been implemented to represent navigational aids. Using the feature of inheritance, the class Waypoints possesses all properties of the class Position plus an identifier for the name of the navigational aid. The class Flightplan possesses a list of fixes, each instantiated from the class Waypoint.

Figure 6-6 depicts the class Aircraft. Aircraft inherits from the classes Position and Flightplan, i.e. an instance of each class is assigned to Aircraft, so that the aircraft possesses a unique position with the properties x position, y position and flight level and a flight plan, consisting in a list of waypoints. Apart from that, the aircraft object possesses a number of other parameters and attributes. The callsign is the aircraft identification code, consisting of the airline designator and flight number (such as DLH1905). Aircraft type specifies the aircraft model which is required for performance and speed calculations. The dynamic state of the aircraft is specified not only by its position, but also by its heading, indicated airspeed (IAS), ground speed (GS), and rate of climb/descent (ROCD). For those parameters that may be advised by the air traffic controller, Aircraft possesses additional properties to store the cleared figures. The property cleared fix is an instance of the class Waypoint and refers to the navigational aid the aircraft is flying to, provided its lateral status is

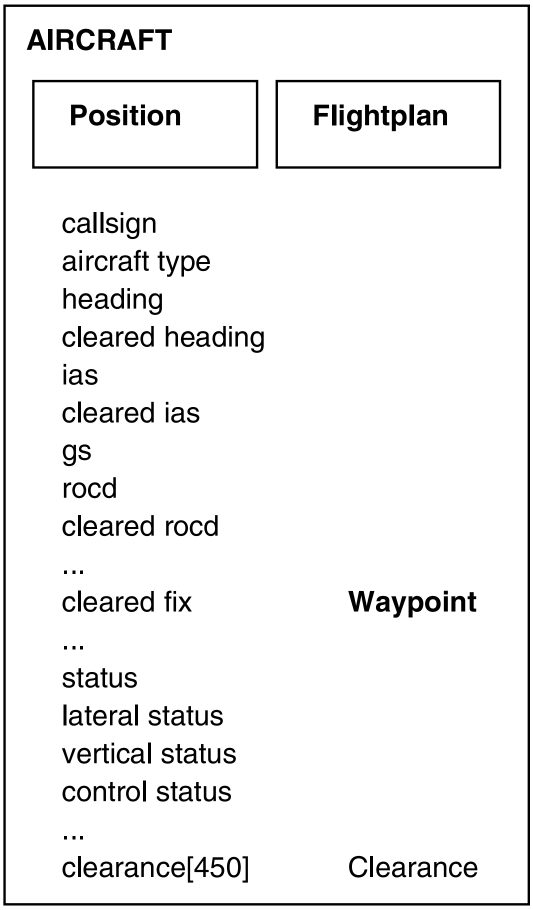


Figure 6-6 The class Aircraft.

"TOFIX". The status parameters lateral status, vertical status, control status and status are used to classify the aircraft according to a mental scheme controllers have been observed to apply (status parameters have already been discussed in chapter 5.4). The class Aircraft also possesses a list of instantiations of the class Clearance. Each Clearance corresponds to one specific instruction the air traffic controller might assign to an aircraft. The structure of the class Clearance is depicted in Figure 6-7. A clearance possesses the properties type (reflecting the kind of clearance, e.g. "heading"), parameter (the clearance parameter, e.g. "250") and weight. The weight reflects CCM's estimation of the likelihood that the ATCO might decide upon this specific instruction in the actual situation. For each clearance of each aircraft the parameter weight is calculated continuously in the decision module.

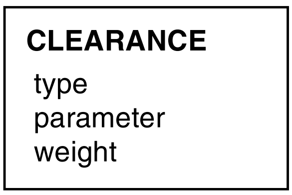


Figure 6-7 The class Clearance.

The information about the aircraft are taken from the simulation data file. Each aircraft object is constructed and initialized with the corresponding information from the simulation data file, such as the aircraft flight plan. This information is written to the simulation data file prior to the aircraft entering the airspace. After initialization, an aircraft position update is written to the file every four seconds and the aircraft object is updated accordingly. The parameters that can be accessed directly from the file are written to the aircraft object and other parameters and properties, such as the states, are calculated and the properties of the object adapted accordingly.

After one second has elapsed and all aircraft objects in the sector have been updated, a conflict check is performed in order to identify pairs of two or more aircraft for which a violation of the separation minimum must be expected during the near future. In a first step, pairs of aircraft are identified that, according to their present flight state, will be less than six nautical miles apart laterally at some point within the next two minutes. For these aircraft, the vertical separation is calculated for each moment in the future at which the lateral separation is less than the required six miles. If the vertical separation is less than 10 flight levels at any such time, the aircraft are marked as conflicting and a list of possible conflicts is updated by CCM.

6.3 Production Rules in the Decision Module

The decision module assesses which instructions the air traffic controller might decide upon in the actual situation. During its initialization a complete list of clearances is assigned to each aircraft object, regardless of the feasibility of each of these clearances in the actual situation. The decision module assigns a value to the property clearance weight for each clearance object of each aircraft. During initialization or updating of the aircraft objects in the observation module the clearance weight is set to zero and then assessed in the decision module. After all rules in the decision module have been applied the clearance weight may possess one of three values according to Table 6-2.

clearance weight	**explanation**
0	clearance is physically not possible
1	clearance is physically possible
2	clearance is probable from CCM’s point of view

Table 6-2 Clearance weights.

In a first step those clearances are identified that appear possible from a physical point of view. The parameter range of possible clearances is limited by the aircraft’s present dynamic state. For example, a clearance to climb to a certain flight level is only feasible if a parameter higher than the aircraft’s present flight level is assigned. A set of rules about physically possible clearances is applied and the possible clearances are assigned a clearance weight of 1. The rules about possible clearances are dependent neither on the airspace geometry nor on controller strategies but reflect physical considerations. As an example, Figure 6-8 depicts a rule from the set of possible rules limiting the parameter range of clearances to reduce the indicated airspeed[20]. On the one hand it is only feasible to reduce the speed to a value less than the present speed, on the other hand the range of possible speeds is limited by the minimum speed specified for the aircraft type[21]. If the clearance parameter lies between present speed and minimum speed, the clearance is considered possible and a clearance weight of one is assigned to it.

IF	type of clearance equals "REDUCE IAS"
	AND parameter of clearance is less than airspeed of aircraft
	AND parameter of clearance is greater or equal minimum airspeed of aircraft type of aircraft
THEN	set weight of clearance to 1

Figure 6-8 Rule to reduce airspeed (possible clearances).

IF	type of clearance equals "DIRECT TO"
	AND status of aircraft equals "ARRIVAL"
	AND x position of aircraft is less or equal to x position of waypoint "NTM"
	AND distance of aircraft to waypoint "NTM" is less or equal 15 NM
	AND lateral status of aircraft equals "TOFIX"
	AND next but one waypoint of flightplan of aircraft equals "RUD"
	AND parameter of clearance equals "RUD"
THEN	set weight of clearance to 2

Figure 6-9 Rule to proceed direct to Rüdesheim (probable clearances).

After all possible clearances have been identified another set of rules is applied in order to detect clearances that appear probable from CCM’s point of view. During this assessment, only those clearances are taken into consideration that have previously been marked as possible. The rules in this set are dependent on the sector geometry and reflect the strategies that controllers have been observed to apply most frequently during conflict-free ATC operations in Frankfurt WR1 (compare

[20] The indicated airspeed is the relevant speed parameter for operating an aircraft, because it reflects the aerodynamic conditions. Controllers, therefore, generally advise the indicated airspeed.

[21] In an enroute sector this is typically the minimum clean speed, i.e. the minimum speed with which the aircraft can be operated in „clean“ configuration, i.e. without flaps.

chapter 5.3 and 5.5). Clearances that are estimated as probable are assigned a clearance weight of two.

Figure 6-9 depicts a rule from the set of probable rules. Controllers often reduce the remaining flight distance for arrival traffic flying inbound the waypoint Nattenheim (NTM) by advising to proceed direct to waypoint Rüdesheim (RUD) (compare Figure 5-6, page 70). If the aircraft either flies inbound cleared fix NTM and its position is west of NTM and its distance to NTM is less than 15 nautical miles (in order not to enter the military TRA sector in the north) and the succeeding waypoint in the flightplan after NTM is RUD: then it is probable that the aircraft may be advised to proceed direct to RUD.

As the focus of this study lies on conflict-free traffic in WR1, no explicit rules for problem solving in case of conflicts were implemented. However, the estimation of probable clearances must contain all clearances the ATCO could decide upon if a conflict might be detected. Therefore, if a conflict between two or more aircraft was anticipated for the next two minutes, all possible clearances for the concerned aircraft are converted into probable clearances, i.e. their respective clearance weights increased from one to two.

The decision module assesses the clearance weight of each clearance of each active aircraft in the following manner: the first clearance from the first aircraft is analyzed by applying the first rule from the set of possible rules to it. At that time the clearance weight possesses the value zero as assigned by the observation module. If the conditions in the first rule are fulfilled, the clearance is classified as "possible" and the clearance weight is raised to one. In that case the decision module continuous by analyzing the second clearance of the first aircraft. Otherwise, if the rule does not fire, the second rule from the set of possible rules is applied to the first clearance. The application of rules to the clearance continuous either until a rule does fire or until all rules have been tested. Then the next clearance is tested. After all clearances of the first aircraft have been tested, the decision module switches to the second aircraft which is treated in a similar manner. The set of possible rules comprises about 35 rules. The complete set of possible rules can be found in Annex D.1.

After all clearances of all aircraft have been classified as either possible (clearance weight equals one) or not possible (clearance weight equals zero) the decision module applies the rules about probable clearances in a similar manner. As the controller will only decide upon physically possible clearances, the set of probable clearances is a subset of possible clearances. Therefore, only possible clearances are taken into consideration when probable clearances are identified. After all clearances have been analyzed using the probable rules, each clearance has been classified as either not possible, possible, or probable and assigned a clearance weight of zero, one, or two. The set of probable rules comprises about 75 rules. The complete set of probable rules can be found in Annex D.2.

In a subsequent step the possible clearances of aircraft that have been detected to be involved in a future separation violation are converted into probable clearances by increasing their clearance weights from one to two. Thereafter, the decision module cycle is completed and the phraseology module generates speech recognizer syntaxes for the probable clearances and the possible clearances.

6.4 The Phraseology Module

The phraseology module generates two syntaxes that the automatic speech recognizer uses to decode the ATCO's spoken utterance: the syntax possible.sts contains the clearances that appear possible from a physical point of view (possible.sts comprises the clearances that have been classified as possible by the decision module) whereas probable.sts comprises the clearances CCM considers most probable (corresponding to those clearances classified as probable). As the entire loop consisting of observation module, decision module, and phraseology module is executed once per second, two new syntaxes are generated every one second. The format of the syntax is dependent on the ASR that is used. In the context of this study, the Phonetic Engine PE500 by Speech Systems Inc. has been used; the syntax format, accordingly, has been defined by the manufacturer[22].

The phraseology module generates two lists of the clearances classified as possible and probable, respectively. These lists are then processed with regard to possible and probable parameters each clearance type may possess for each of the aircraft. If a combination of aircraft and clearance type possesses one or more possible/ probable parameters, an entry is made to the syntax, defining the parameter or parameter range.

Figure 6-10 depicts an excerpt from a syntax the phraseology module generated in a simulation run. The syntax is a set of branching rules describing how sentences are constructed. The first line, starting with '#', contains information about the starting point of the branching marked by the symbol Clearance. The legal sentences are then described by associating to Clearance a sequence of symbols, using the ' ->'

[22] Some manufacturers of automatic speech recognition systems use standardized syntax formats, such as the Backus-Naur Form (BNF). This facilitates the comprehension of the syntax structure as well as the re-usability of the syntax when the ASR is replaced with another system. In the context of this study, however, a proprietary format was required.

expression. Parentheses embed obligatory choices whereas brackets embed optional choices. The corresponding syntax probable.sts is written in the same format, only the parameters of the clearances are different.

```
#start Clearance
...
Clearance -> +DLH1905 +REP_HDG
...
Clearance -> +SAB513 + DOWN_FL {+60|+70|+80|+90|+100|+110|
+120|+130|+140|+150}
...
+DLH1905 -> DLH 1 9r 0 5
+SAB513 -> SAB 5 1 3t
...
DLH -> loofthunsa
SAB -> sabena
AFR -> air fronce
...
+DOWN_FL -> {cleared down (to)|descend (to)|continue
descent to} (flight) level
+STOP_DESC -> {stop descent (at)|level off (at)}
(flight) level
...
+ REP_HDG -> {report|what is your} heading
...
9r -> niner
3t -> tree
...
+030 -> 0 tree 0
...
+70 -> 7 0
+80 -> 8 0
+90 -> niner 0
+100 -> one hundred
```

Figure 6-10 Excerpt from a syntax possible.sts (extended phraseology).

The first clearance defined in Figure 6-10

```
Clearance -> +DLH1905 +REP_HDG
```

applies to the aircraft DLH1905 and specifies that the aircraft may receive a clearance to report its heading. After applying the definitions at the bottom of the syntax, the clearance could be spoken in two different wordings:

```
loofthunsa one niner zero five report heading
loofthunsa one niner zero five what is your heading.
```

Similarly, the next clearance

```
Clearance -> +SAB513 + DOWN_FL {+60|+70|+80|+90|+100|+110|
+120|+130|+140|+150}
```

defines the wording with which a clearance for aircraft SAB513 to descend to a certain flight level may be spoken. The range of possible parameters for this clearance, flight levels between 50 and 150, is given in brackets.

6.5 Performance and Calibration

In order to calibrate the Cognitive Controller Model and to obtain a measure of its performance, protocols of earlier simulation sessions in ATMOS were used. During a replay CCM observed and analyzed the simulation and generated estimations about probable and possible clearances. It was then tested whether the instructions the controller had actually given were included in the syntaxes CCM had generated.

Two electronic transcripts were available that provided a detailed picture of the simulation: the simulation data file and the pseudo pilot protocol[23]. The simulation data file contains all relevant data generated by the ATMOS simulation kernel, including flight plans of the aircraft and aircraft parameters such as position, flight level, speed, and heading. As the aircraft parameters change dynamically, updated parameters are written to the simulation data file every four seconds.

```
...
36051 timetick
36052 timetick
36053 timetick
36053 radar AZA462 51.6517 9.4331 210.00 0 404.0 234 4403
36053 radar DLH69 49.2376 11.1657 200.00 0 397.0 300 4404
36053 radar DLH1713 49.2193 11.2137 190.00 0 390.0 302 4406
36054 timetick
36054 flplan DLH1713 ARR B737 M ALB2A   ALB   36050 PSA   36906 390.000 3D
36054 route DLH1713  ----- ----- ----- ----- ALB   WUR   PSA   FPS   25LDF DF25L
        FW1   FW2   CHA   25LDF
36054 quali DLH1713 -     -     -     -     Q     A     S     T
36054 speed DLH1713      0     0     0     0  2900  2500  2500  2300  1800  1300
        2000  2100  2200  1800
36054 altit DLH1713      0     0     0     0 19000 17000  8000  7800  4000   300  4000
        4000  4000  3000
36054 times DLH1713      0     0     0     0 36050 36604 36906 37083 37236 37495
...
```

Table 6-3 Excerpt from a simulation data file.

[23] The instructions identified by the speech recognizer or entered via mouse are written to the simulation data file in the ATC simulation environment that will be used for the evaluation of CCM and discussed in chapter 7. In ATMOS the pseudo pilot entries are written to a separate file.

Table 6-3 depicts an excerpt from a simulation data file. The first column contains the synchronized simulation time in seconds, followed by a label that specifies the category of the entry. The entry radar for example tags a line providing the dynamic parameters required to generate the aircraft blip on the radar screen. The first radar entry in Table 6-3 at simulation time 36053 refers to the aircraft with the callsign AZA462 (Alitalia flight 462) and specifies the latitude (51.6517°) and longitude (9.4331°), the flight level (FL 210), the rate of climb/descent (0 feet per minute), the ground speed (404 knots) and the heading (234°). The last column specifies the transponder code (4403) which is used for identification.

The pseudo pilot protocol contains the clearances that had been entered into the pseudo pilot terminals. The relevant data includes the time the clearance was entered, the aircraft callsign, the clearance category and the clearance parameter plus a reference to the sector the pseudo pilot worked in. Table 6-4 gives an excerpt from a pseudo pilot protocol. The protocol uses the same simulation time as the simulation data file. The second column refers to the aircraft callsign, followed by the pseudo pilot terminal number (which permits to identify the operator responsible for the aircraft), the clearance category and parameters. The first line in Table 6-4, for instance, corresponds to a clearance the aircraft with the callsign AZA462 received from pseudo pilot number 4. The aircraft was cleared to flight level 60. As a rate of descent has not explicitly been entered, the last column contains the digit zero.

```
...
37083   AZA462    4 LEVEL     60    0
37089   DLH1775   2 SPEED     270
37096   DLH1713   3 HEADING   340
37110   DLH1713   3 LEVEL     50    0
37117   DLH1713   3 OVER TO   FEEDER
...
```

Table 6-4 Excerpt from a pseudo pilot protocol.

The instructions spoken by the controller are not available in an electronic transcript. However, apart from occasional pseudo pilot errors and the delay of the input, the clearances in the pseudo pilot protocols equal the controller's instructions. As both protocols use the same simulation time, clearances in the pseudo pilot protocol can directly be related to the simulation data file.

In a first step, the pseudo pilot protocols were analyzed in order to isolate input errors. In many cases it was obvious that an error had occurred. If, for example a clearance parameter outside of the legal range was entered (e.g. a heading of 2500 was advised) an input error appeared most likely. Often, inputs were corrected a few seconds later, so that probably the earlier entry was erroneous. In some cases, input errors could only be identified when the entire simulation was analyzed, e.g. by visualizing the traffic situation at the time a clearance was logged.

In order to measure the delay between the moment the controller would speak an instruction and the moment the pseudo pilot would complete entering it, audio tape protocols of the pilot controller communication were analyzed. It was presumed that the pseudo pilot would enter the clearance into the system at the same moment he would complete the readback which is common among pseudo pilots because it permits to use the clearance parameters, which are then stored and displayed in an input line as an aid for the readback. The delay depends on the number of instructions per transmission. The average delay measured in three simulation runs is depicted in Table 6-5. As the greatest percentage of instructions involved only one instruction per transmission, the mean delay was found to be about 10 seconds.

Mean Pseudo Pilot Response Time (Standard Deviation) [sec]			
No. of Instructions per transmission	Simulation 1	Simulation 2	Simulation 3
1	7.1 (2.2)	6.9 (2.0)	7.8 (1.9)
2	11.6 (3.5)	12.6 (2.5)	12.8 (2.1)
3	11.0 (3.0)	16.3 (2.1)	20.0 (-)

Table 6-5 Mean pseudo pilot input delay.

The Cognitive Controller Model was configured to read the simulation data file successively and to generate a forecast of probable and possible clearances once per second. CCM then accessed the pseudo pilot protocol and, provided that a clearance was recorded in the one second elapsed since reading it for the last time, tested whether this clearance was included in the set of probable clearances. This permitted to test the accuracy of the predictions CCM had generated. Pseudo pilot entry errors were labeled as such and not considered for the calibration. A compensation of ten seconds was used to eliminate the input delay.

A total of 11 simulations was analyzed, each lasting about 90 minutes. In total, 1,447 instructions had been recorded. 3.0 percent of the clearances were tagged as invalid due to obvious pseudo pilot input errors, the remaining instructions were used for the tests. 96.5 percent of the valid clearances were included in the predictions of probable clearances.

The mean numbers of clearances in the syntaxes probable.sts and possible.sts for all simulation runs were calculated and compared to the number of clearances a static syntax would contain. These figures describe the reduction in the speech recognition search space CCM accomplishes. The syntax probable.sts contained an average number of 273 clearances (2.4 percent of the static syntax) while the syntax possible.sts contained an average number of 798 clearances (6.9 percent of the static syntax).

6.6 Summary

The Cognitive Controller Model (CCM) has been introduced in order to generate two situation-specific speech recognizer syntaxes: probable.sts comprises the most probable sentences while possible.sts contains all sentences that are currently possible. According to cognitive models of human operators, CCM consists of three functions. The observation function generates an internal representation of the traffic situation. An object-based knowledge representation has been chosen for the observation function. The decision function provides an estimation of possible and most probable clearances. Its structure is based on production rules. The phraseology function translates the clearances into sentences and writes them to the syntaxes probable.sts and possible.sts in a speech recognizer-adapted format. The three functions are continuously executed, so that new syntaxes are generated once per second.

Performance tests proof a tremendous reduction of the speech recognition search space: the set of probable clearances contains only 2.4 percent of the clearances in a static syntax while correctly predicting 96.5 percent of all clearances recorded during simulations in DLR's ATMOS. The Cognitive Controller Model must now be integrated into an ATC simulation and speech recognition environment in order to assess the effect the context-sensitive syntax has on the recognition performance. The ATC simulator and the speech recognizer will be discussed in chapter 7.

7 The Simulation and Speech Recognition Environment

After analyzing the requirements in the ATC simulation domain a commercially available automatic speech recognition system has been chosen and integrated into an air traffic control simulation environment so that the simulated aircraft can be controlled by means of voice. The speech recognizer analyzes the spoken instructions and transmits the relevant pieces of information to the ATC simulation process whereas a speech synthesis system generates pilot responses. Therefore, the same functions are performed that would otherwise require pseudo pilots, i.e. init calls are generated when the aircraft enter the sector, clearances are executed and confirmed and the speech recognizer responds to controller inquiries, supplying the requested information. The Cognitive Controller Model is also integrated into the simulation environment so that the speech recognizer can be configured to use the context-sensitive syntaxes generated by CCM. For comparison purposes, the speech recognizer can also be configured to use a static syntax.

7.1 The Speech Recognition Engine

The development of a speech recognition interface typically focuses on the integration of an existing speech recognition engine to the application. The recognition engine comprises the internals of the recognition process, such as the A/D conversion, the pattern matching process, and mathematical models of speaking behavior and their variations. These algorithms are integrated in a software or hardware system and made available to the integrator via a specified and documented interface. For reasons of competition, the internals of the ASR are usually not disclosed by the system manufacturer.

Function calls to the recognition are usually integrated in a computer program which uses the recognition results to control the application. The function calls are available as a part of the speech recognizer interface, for instance in a library. Due to the wide range of domains, a variety of speech recognition engines exists, each more or less tailored to a specific domain. After analyzing the requirements a choice has to be made about an appropriate recognition engine.

In air traffic control simulation, continuous speech recognition is required, permitting the user to speak in the same way he or she would speak to a pilot or pseudo pilot without breaks between words (compare chapter 3.2). A speaker-independent system is very desirable because it greatly reduces the effort when training a new user to work with the system. A high recognition performance is required because slow or unreliable recognition would not only annoy the user but also adversely affect the simulation itself. The use of a deterministic syntax appears more desirable than the use of a probabilistic syntax because it permits more flexibility in adapting the syntax. In order to be able to use a dynamic syntax as generated by the Cognitive Controller Model, the recognition engine must also possess a feature to change syntax and dictionary during runtime.

After comparing a number of commercially available recognition engines, the Phonetic Engine PE500 by Speech Systems Inc. was chosen [SSI 97]. PE500 comprises a PC card (Interactive Speech Card, ISC) and software drivers. The ISC includes an analogue/digital (A/D) converter, a digital signal processing chipset (DSP) and an analogue interface to connect to a microphone. The recognizer is activated by means of a push-to-talk button which is connected to the ISC and must be pressed while speaking. As current recognition applications do not use dynamic syntaxes, existing ASR systems do generally not provide the feature to change the syntax and the dictionary during runtime. Speech System agreed to develop this feature and made it available in the latest software release [SSI 97]. The functions to control the recognition engine are accessible via an application programmer's interface (API) containing libraries with function calls which can be included in Microsoft Visual C++ and Visual Basic programs on a Microsoft Windows 95 computer.

Figure 7-1 depicts the functional structure of the Phonetic Engine PE500. The user speaks into a noise-cancelling microphone connected to the speech card. The voice input is transferred to the acoustic processor which converts the analog pattern into digital signals and extracts a set of speaker-independent acoustic features typical of human speech. The phonetic encoder compresses the acoustic features supplied by the acoustic processor and generates a speaker-independent phonetic stream, i.e. a sequence of phonetic codes that indicate likely phonemes in the input. The phonetic decoder generates the final phonetic transcription by matching the phonetic stream to the sequences specified in the application syntax and dictionary.

The syntax is a set of rules defining legal sentences, i.e. sequences of words, while the phonetic dictionary specifies acceptable pronunciations for the words in the syntax. The speaker models describe characteristics of the human voice under specified acoustic conditions. As the Phonetic Engine PE500 is speaker-independent, two speaker models belong to the speech recognition software, one describing the female voice and one describing the male voice. Depending on the user's gender, one of the speaker models must be loaded when launching the phonetic engine. The application software communicates with the phonetic engine run-time system via the phonetic decoder interface (PDI), typically by including function calls from the PDI library in the application software.

7.2 The Simulation and Speech Recognition Environment

The speech recognition application must provide all functions required to control air traffic by means of voice, which means that it must respond to the controller's spoken instructions in exactly the same way as a pseudo pilot. The central requirements are:

- Generation of init calls: An init call must be executed by means of speech synthesis as soon as a new aircraft enters the sector, announcing the aircraft's presence and readiness to receive clearances and supplying information about its present state.
- Execution and response to ATC clearances: The speech recognition application must respond to control advisories by isolating the relevant clearance parameters and transmitting them to the ATC simulator so that the respective aircraft executes the clearance. The pilot's readback, confirming the clearance, must be generated by means of speech synthesis.
- Response to controller inquiries: Aircraft must respond to questions concerning their present state by supplying the desired information via speech synthesis.

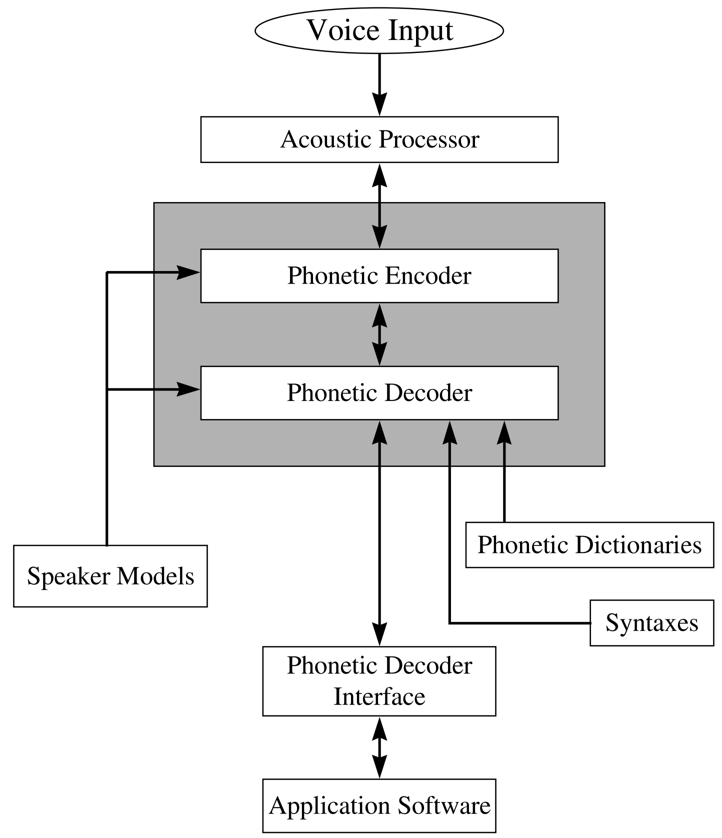


Figure 7-1 Structure of the Phonetic Engine PE500 [SSI 97].

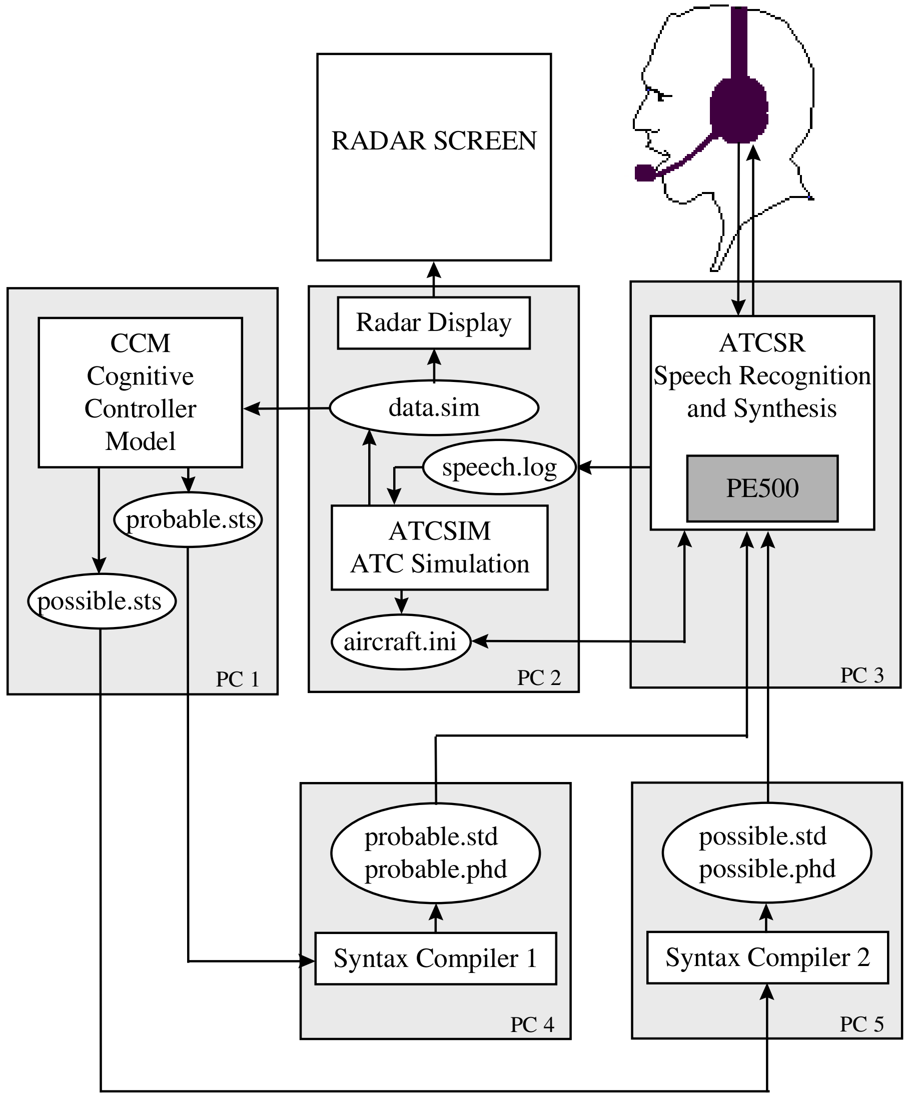


Figure 7-2 The ATC simulation and speech recognition environment.

Figure 7.2 gives an overview of the processes involved in the ATC simulation and speech recognition environment. There are basically four major processes, each hosted on a separate personal computer (PC):

- The ATC Simulation (ATCSIM) generates dynamic aircraft states and positions in the simulated airspace. The Radar Display associated with ATCSIM converts the aircraft parameters and data about the airspace structure into a graphical image displayed on the simulated radar screen. ATCSIM can either be operated via the speech recognition interface or as a standalone system. In the latter case, the control advisories are entered by means of mouse input. ATCSIM and the Radar Display are hosted on a Linux PC.
- The speech recognition and synthesis application ATC Speech Recognizer (ATCSR) controls the speech recognition process executed on the Phonetic Engine PE500. It responds to the controller’s spoken instructions and synthesizes

the pilot's responses. The ATC Speech Recognizer is hosted on a personal computer operated under Windows 95[24].

- The Cognitive Controller Model (CCM) generates two situation-dependent speech recognizer syntaxes, one comprising the clearances CCM considers probable in the actual situation (probable.sts) and one, more extensive, that comprises possible clearances (possible.sts) and is used for a second decode, if no successful decode is available on the basis of probable.sts. Both syntaxes are generated in ASCII format. CCM is hosted on a PC operated under Linux.
- The Syntax Compiler converts the context-sensitive syntaxes generated by CCM into the binary format required by the speech recognizer. During compilation, a situation dependent dictionary is also generated for each syntax. The Syntax Compiler processes are hosted on Windows 95 PCs. For performance reasons, two separate computers are used, each hosting one compiler process.

The communication between the four processes is based on shared files, i.e. one or more processes write data to a file that can be read by one or more other processes:

- The simulation data file data.sim is generated by ATCSIM and contains all simulation data, such as aircraft positions and parameters, flight plans, clearances, etc. Data.sim contains all information required for a complete replay of a simulation.
- The protocol speech.log contains the clearances the speech recognizer has identified. ATCSIM continuously reads speech.log and uses the entries to determine the behavior of the aircraft for which a clearance has been received. To provide a complete description of the simulation in the simulation data file, ATCSIM also transfers the clearances to data.sim.
- The file aircraft.ini contains a list of the aircraft presently in the control sector together with their flight parameters, such as altitude, heading, airspeed, etc. Aircraft.ini is generated and continuously updated by ATCSIM and used by the speech recognizer to respond to controller inquiries. ATCSR also writes to the file to keep track whether an aircraft has already issued an init call.
- The syntaxes probable.sts and possible.sts are generated by CCM and contain a selection of clearances that CCM presently considers probable or possible. The syntaxes are written in ASCII notation and updated every one second.
- The binary syntaxes probable.std and possible.std are generated by the Syntax Compiler and then transmitted to ATCSR as soon as the compilation is completed. The Syntax Compiler also generates the dictionaries probable.phd and pos-

[24] The API routines to control the Phonetic Engine PE500 are only available for Windows 3.11 and Windows 95. Otherwise, a Unix-based implementation would have been favored for reasons of higher performance and reliability.

sible.phd that contain the words that are used in the syntaxes. The dictionaries are also transmitted to the speech recognizer.

```
#start Clearance
...
Clearance -> +DLH1905 +REP_HDG
...
+DLH1905 -> DLH 1 9r 0 5
...
DLH -> loofthunsa
...
+ REP_HDG -> {report|what is your} heading
...
9r -> niner
+90 -> niner 0
...
```

Figure 7-3 Excerpt from a syntax possible.sts (extended phraseology).

Figure 7-3 depicts an excerpt from a syntax (compare Figure 6-10 on page 94). Every symbol used in the declaration of the sentences is specified again either as another sequence of symbols or as a sequence of words, so that by applying all the declarations, every symbolic expression can be transferred into a sequence of words. For example, the declaration

`Clearance -> +DLH1905 +REP_HDG`

means that a clearance is described by the sequence of the expressions +DLH1905 and +REP_HDG, which themselves are symbolic expressions as declared by

```
+DLH1905 -> DLH 1 9r 0 5
DLH -> loofthunsa
9r -> niner
+REP_HDG -> {report heading|what is your} heading.
```

By successively inserting the declarations into the expression, the sentence reads:

`"loofthunsa one niner zero five report heading"`

or optionally:

`"loofthunsa one niner zero five what is your heading?"`

Often words are not part of the standard dictionary supplied with the Phonetic Engine, so that they must be constructed explicitly. The Phonetic Engine provides a tool that converts written words into a phonetic description by reasoning from the spelling of the word about its pronunciation in American English. Non-standard words in the syntax must therefore be spelled in such a way that the tool can construct the appropriate pronunciation. The German airline Lufthansa therefore reads "loofthunsa" in the syntax.

Some of the symbols in the syntax start with a '+'-sign and are referred to as so-called parse-tags. The Phonetic Engine can be configured either to return the complete sentence as the decode or just to return the parse-tags, so that this mechanism can be used to sort relevant from less relevant information. If, for instance, the speech recognizer returns

```
+SAB513 + DOWN_FL +90
```

the decode contains the relevant information that the aircraft with callsign SAB513 has been cleared to descend to flight level 90. At this point it appears to be of little interest which words the controller used to express the clearance, because they are of no relevance for the simulation. Parse-tags provide a powerful tool to facilitate the processing of the speech recognition decode for controlling the simulation.

7.3 The ATC Speech Recognizer

The ATC Speech Recognizer (ATCSR) has been implemented as a Microsoft Visual C++ program for Windows 95. The functions to control the Phonetic Engine are included as pre-compiled routines in dynamic link libraries (DLL) and can be accessed in the program code after linking the DLLs to the program executable. ATCSR possesses a graphical user interface (GUI) which permits to start, configure and control the recognition and which provides information about its present state and the last decode. A variety of parameters can be modified via the GUI to adapt ATCSR to different simulation and recognition modes. While the experimenter uses the GUI to start and control ATCSR, the ATC controller does not need to interact with it. The controller wears a headset with a microphone and presses a push-to-talk button in when speaking a clearance while his or her eyes remain focused on the radar screen.

ATCSR has been configured to return the syntax parse tag as the decode of a spoken utterance. Otherwise, if the recognition returned the sequence of spoken words, the decode would have to be analyzed to obtain the meaning of the words, a process referred to as language-parsing (compare chapter 3.1). By using parse tags and appropriately designing the syntax, language parsing has been avoided completely because every parse tag unambiguously corresponds to a specific clearance. Therefore, the decode contains all information required to control the simulation and need not be analyzed further. The parse tags are written to speech.log and used to control the simulation and generate a pilot response by means of speech synthesis.

The pilot responses are generated from pre-recorded sound files that are stored on the computer hard disk. A sequence of segments is concatenated and output via the personal computer's audio card and loudspeakers. The sound files have been generated by recording pseudo pilot responses and isolating appropriate segments in such a way that all necessary responses can be constructed from a limited number of segments. If for, instance, the ATC clearance

`"Lufthansa one two three descend flight level one two zero"`

had been received, the correct pilot response would be

`"Lufthansa one two three descending flight level one two zero".`

The sentence can be divided into three segments:

- the aircraft callsign (`Lufthansa one two three`),
- the clearance category (`descending flight level`),
- the clearance parameter (`one two zero`).

The first segment, referring to the aircraft callsign, can be used for all responses of that aircraft. The second segment can be used to synthesize a response to any descent clearance by concatenating any other parameter. The third segment can be used for other clearances with the same parameter, such as a clearance to turn to a heading of 120. About one hundred segments, i.e. sound-files plus an additional file for each aircraft callsign and each waypoint in the sector have been recorded that permit to generate every necessary pilot response and init call. A concatenation of recorded speech events sounds more natural than a synthetic voice and controllers find it more agreeable and less exhausting to listen to this mode of readback.

The central requirements for the speech interface

- Generation of init calls
- Execution and response to ATC clearances
- Response to controller inquiries

have already been listed in chapter 7.2. How ATCSR provides these functions will be discussed below.

Generation of init calls

When entering an ATC sector aircraft pilots announce their presence by issuing a so-called init call providing:

- the station that is called (the ATC sector's designator)
- the station that is calling (the aircraft callsign)
- the actual flight level; in some cases the position is also provided
- courtesy phrases, such as "good morning".

The file aircraft.ini contains a list of all aircraft in the sector together with the relevant aircraft parameters and a flag that indicates whether the aircraft has already executed an init call. ATCSR continuously checks for the presence of new aircraft in the file aircraft.ini and, if a new aircraft is encountered, an init call is generated by outputting a sequence of sound-files. The sound files correspond to

- the radar sector WR1, referred to as `"Frankfurt Radar"`
- the aircraft callsign
- a file saying `"flight level"`
- a parameter file associated with the actual flight level
- a file saying `"good morning"`.

The init call of DLH1905, entering the sector at flight level 230, would be:

`"Frankfurt Radar, Lufthansa one niner zero five, flight level two three zero, good morning".`

The controller would typically confirm the init call by saying

`"Lufthansa one niner zero five, radar contact".`

Execution and response to ATC clearances

After a spoken clearance has been analyzed the corresponding parse tags are returned by the recognition engine. As they unambiguously describe the meaning of an instruction, parse tags are used to control the simulation and to generate the pilot response via speech synthesis. The clearance that ATCSR has identified is written to the file speech.log together with the simulation time at which it has been received. ATCSIM continuously checks for new clearances in speech.log and uses the clearances to control the aircraft behavior. If, for example, the controller said:

`"Sabena one two three, turn left heading zero five zero"`

and the ASR had correctly analyzed the utterance the decoded parse tags would be:

`+SAB123 +LEFT_HEAD +050.`

The decode contains all relevant information: the aircraft, the clearance category and the clearance parameter. The decoded sentence is then written to the file speech.log and read by ATCSIM which initiates a left turn to the cleared heading for aircraft SAB123. Figure 7-4 depicts an excerpt from the file speech.log.

The parse tags are also used to generate the pilot's response. A specific sound segment is associated to each parse tag so that by sequentially outputting the concerned sound files the correct pilot response is generated. The association between parse tags and sound files are:

```
+SAB123 -> "Sabena one two three"
+LEFT_HEAD -> "turning left heading"
+050 -> "zero five zero".
```

concatenated to the response

```
"Sabena one two three turning left heading zero five zero".
```

```
...
37368  +DIORA    +STOP_DESC     +130
37386  +DIORA    +RIGHT_HEAD    +90
37423  +SWR517   +IAS           +200
37478  +SAB111   +REP_HDG
37537  +SAB111   +LEFT_HEAD     +350
...
```

Figure 7-4 Excerpt from the file speech.log

Response to controller inquiries

Sometimes the controller seeks information about aircraft parameters such as heading or airspeed by asking the pilot who then returns the desired information. ATCSR responds to controller inquiries for dynamic aircraft parameters which are stored in the file aircraft.ini. By continuously updating aircraft.ini ATCSIM ensures that the current parameters are always available. If an inquiry has been decoded by ATCSR, a parse tag commencing with '+REP_' is returned and the desired aircraft parameter is read from the file aircraft.ini as depicted in Figure 7-5. For example, the controller could ask the aircraft SWR538 for its present airspeed saying:

```
"Swissair five tree eight, report airspeed"
```

corresponding to the parse tag

```
+SWR538 +REP_IAS.
```

Provided the aircraft is presently in the sector, a section in the file aircraft.ini is associated with the aircraft SWR538. In this section the actual value of the indicated airspeed IAS is associated with the parse tag +REP_IAS so that ATCSR can provide the correct information. If the current airspeed is 250 knots, the response reads:

```
"Swissair five tree eight, present airspeed is two five zero knots indicated".
```

During the recognition process the Phonetic Engine compares the spoken utterance to every sentence in the syntax, dynamically constructing hypotheses about the best match. A measure of confidence is determined for the best match reflecting the conformity between the spoken utterance and the decoded sentence, i.e. the Phonetic

Engine's confidence that the decode is correct. On the one hand, due to background noise as well as individual and dynamic variations in the characteristics of the voice, the confidence measure will seldom be maximum; on the other hand very poor decodes must be rejected. ATCSR permits to configure a rejection threshold so that decodes with a confidence measure below the required minimum are rejected, in which case the user is prompted to speak the sentence again. A sound file is then output which prompts "say again".

```
[AIRCRAFT]
0 = +DLH1775
1 = +SWR538
...
[+DLH1775]
STATUS      = +INIT
+REP_IAS    = 250
+REP_HDG    = 300
+REP_FL     = 90
+REP_ROC    = 2000
+REP_ROD    = 0

[+SWR538]
STATUS      = +INIT
+REP_IAS    = 250
+REP_HDG    = 300
+REP_FL     = 200
+REP_ROC    = 0
+REP_ROD    = 1000
...
```

Figure 7-5 Excerpt from the file aircraft.ini.

ATCSR can be configured to use a second syntax for the decode. The syntax probable.sts contains all the sentences that the Cognitive Controller Model considers probable in the present context. The performance tests discussed in chapter 6.5 indicate that the majority of the clearances are included in probable.sts. The remaining clearances would result either in non-existent or incorrect decodes. However, these sentences are included in the file possible.sts. Therefore, the second syntax is used as a means of fall-back. In case that the recognition does not return a successful decode on basis of probable.sts, i.e. a measure of confidence below the rejection threshold is assigned to the best match, the decode is repeated with the syntax possible.sts. If this recognition does not return an acceptable decode either, the controller is prompted to repeat the utterance. Otherwise the second decode is accepted.

ATCSR uses either a dynamic or a static syntax, the latter containing all clearances for all aircraft crossing the control sector at any time during the simulation session. The static syntax is compiled once so that a binary syntax and a dictionary are loaded when launching ATCSR and remain unchanged during the simulation. If ATCSR uses the dynamic syntaxes probable.sts and possible.sts, the ASCII syntaxes generated by the Cognitive Controller Model must continuously be compiled at simulation runtime. The Syntax Compiler checks for the availability of new syntaxes and compiles them into a binary format, also generating a context-specific dictionary for each syntax (the Syntax Compiler will be discussed in chapter 7.4). ATCSR continuously checks for updated versions of the binary syntaxes and the dictionaries. If new versions are available on the hard disk, ATCSR unloads the older versions and exchanges them for the newer versions.

As discussed in chapter 6.4, two phraseologies have been implemented: the ICAO standard phraseology which only allows for the official standards and the extended phraseology which also permits the most frequent deviations from the standard. The Cognitive Controller Model can be configured to write the syntaxes in either of the two phraseologies. Different phraseologies are implemented by different associations between parse tags and sequences of words, while the structure of the parse tags themselves remains unchanged. For example, the sequence of parse tags

```
+AFR15 + STOP_DESC +90
```

corresponds to a clearance to aircraft Air France 15 to stop its descent at flight level 90. The association between the parse tag `+STOP_DESC` and legal sequences of words are different in both phraseologies. In the ICAO standard the association is

```
+STOP_DESC -> stop descent flight level
```

whereas in the extended phraseology it reads

```
+STOP_DESC -> {stop descent (at)|level off (at)} (flight) level
```

so that the legal expression for the clearance in the ICAO Standard phraseology is:

```
"air france one five, stop descent flight level niner zero"
```

whereas the Extended phraseology permits to use one of the following expressions:

```
"air france one five, stop descent flight level niner zero"
"air france one five, stop descent at flight level niner zero"
"air france one five, stop descent level niner zero"
"air france one five, stop descent at level niner zero"
"air france one five, level off flight level niner zero"
"air france one five, level off at flight level niner zero"
"air france one five, level off level niner zero"
"air france one five, level off at level niner zero".
```

However, the decode the Phonetic Engine provides remains unchanged for both phraseologies because it only comprises the parse tags:

```
+AFR15 + STOP_DESC +90
```

so that the ATC Speech Recognizer does not have to be modified if the phraseology is changed.

7.4 The Syntax Compiler

The Syntax Compiler is also implemented as a Microsoft Visual C++ program for Windows 95. It has the sole purpose of continuously compiling the situation-dependent syntaxes that the Cognitive Controller Model generates. The Syntax Compiler continuously checks whether the ASCII syntaxes probable.sts and possible.sts have been updated since the moment the last compilation was started. If so, the compilation is triggered and a binary syntax (extension .std) plus a context specific dictionary (extension .phd) are generated and written to the hard disk.

The compilation itself requires considerable processing capacity, so that for performance reasons the compilation is not executed on the same computer on which the ATC Speech Recognizer is running. Furthermore, each Syntax Compiler process is hosted on a separate computer to reduce compilation time. Depending on the size of the syntax that has to be compiled, i.e. the number of sentences in the syntax, the compilation takes between one and four seconds on a Pentium PC.

7.5 Summary

The ATC Speech Recognizer (ATCSR) has been developed as the voice interface between an air traffic control simulation environment and the controller. ATCSR analyzes the spoken utterances, transmits the relevant information to the ATC simulation environment, and simulates a pilot response by means of speech synthesis. ATCSR generates init calls, executes and confirms ATC clearances and responds to controller requests. It uses the dynamic syntaxes probable.sts and possible.sts the Cognitive Controller Model generates after they have been transformed into a digital format by the Syntax Compiler. For comparison purposes, the speech recognizer can also be configured to use a static syntax. Therefore, the Cognitive Controller Model, the ATC Simulation, the ATC Speech Recognizer and the Syntax Compiler provide a simulation environment that permits to evaluate the benefits of context-sensitive speech recognition in the ATC simulation domain.

8 Experimental Evaluation

Experiments in an air traffic control simulation environment have been designed in order to quantify the effects the dynamic syntax generated by CCM has on the recognition performance. Furthermore, two different phraseologies were used, the ICAO standard phraseology and the extended phraseology. Instructors from the German Air Navigation Services Academy participated in the simulations, during which they controlled the air traffic in the enroute sector Frankfurt Westradar 1 by means of voice. The speech recognizer processed the clearance and controlled the aircraft behavior accordingly. The pilot's response was generated by means of speech synthesis. All relevant data was logged and audio recordings were generated and transcribed for later analysis. The operator's subjective workload was also recorded.

8.1 Objectives

Experiments were designed to measure and quantify the effects the use of the dynamic syntax has on the recognition performance and the operator's workload, when compared to the use of the static syntax. Also, the effect of using the extended phraseology, compared to the ICAO standard phraseology, was analyzed. Three hypotheses have been formulated and experiments designed to confirm or reject them. Hypothesis A is concerned with the effect that the use of the dynamic syntax has on the recognition error rate, compared to the use of the static syntax:

HA-0:	**The use of the context-sensitive syntaxes probable.sts and possible.sts dynamically generated by the Cognitive Controller Model does not result in a reduced recognition error rate, as compared to the use of the static syntax.**

The second and third hypothesis are concerned with the effects that the use of the extended phraseology has on recognition performance and operator's workload:

HB-0:	**The use of the extended phraseology, compared to the use of the ICAO standard phraseology, does not have a negative effect on the recognition error rate.**
HC-0:	**The use of the extended phraseology, compared to the use of the ICAO standard phraseology, does not result in a reduced subjective workload of the controllers.**

8.2 Experimental Design and Test Subjects

During the simulations the test subjects controlled air traffic in the enroute sector Frankfurt Westradar 1 (WR1). The clearances were spoken in the same manner as in operational air traffic control or in simulations with pseudo pilots, however, the test subjects had to use the phrases included in the ICAO standards or in the extended phraseology. A headset with microphone and a push-to-talk button were used to enter the clearances into the speech recognizer. A radar screen and electronic flight strips were presented to the test subjects.

Six traffic scenarios were designed in order to avoid learning effects. All scenarios were equal in terms of traffic load and aircraft mix and involved 31 aircraft during a simulation of ca. 70 minutes duration, 26 arrivals with destination Frankfurt (85 percent) and 5 overflights with other destinations (15 percent). The participants were asked to control aircraft with destination Frankfurt such that the handover agreement with the adjacent sector Frankfurt Arrival was met. The handover agreement states that aircraft should be instructed to contact Frankfurt Arrival over the fix Rüdesheim at flight level 90 with an indicated airspeed of 250 knots (see chapter 5.2, page 60).

Aircraft announced their presence with an init call when entering the sector, providing callsign and flight level. Each aircraft in the sector executed and confirmed the instructions received via the speech recognizer and also responded to controller inquiries by providing the desired information. The radar screen of Frankfurt Westradar 1 as used during the simulations is depicted in Figure 8-1.

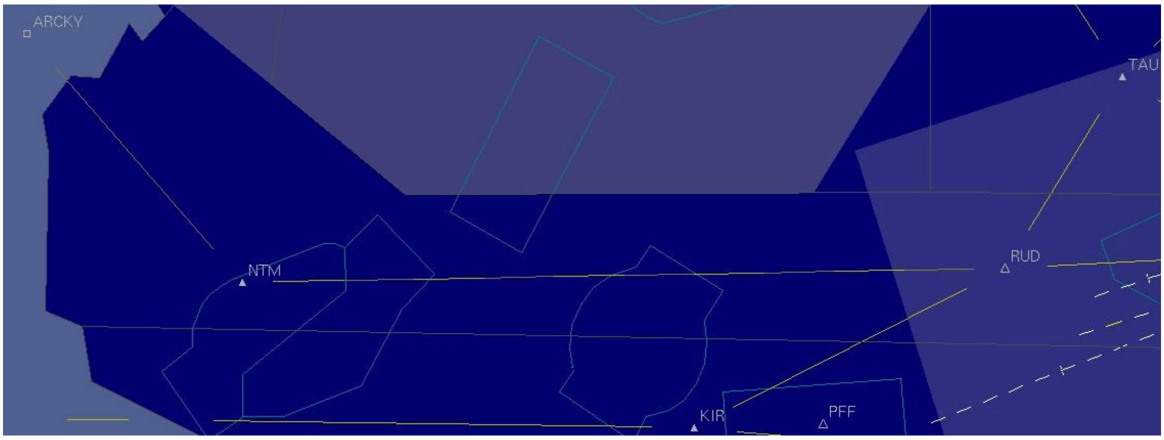


Figure 8-1 Radar screen of the sector Frankfurt Westradar 1.

Clearances were only executed correctly, i.e. according to the test subjects intentions, if the speech recognizer decoded the spoken utterance correctly. Otherwise the recognition process either provided no decode and a synthetic voice saying "say again" prompted the operator to repeat the instruction, or an incorrect decode was

Figure 8-2 Aircraft symbol with label on the radar screen.

returned. In the latter case the aircraft executed the incorrectly decoded instruction and thus reacted in an unwanted way. During the experiments, three methods were available to correct misrecognitions:

- By saying the aircraft callsign, followed by "disregard" the test subject would advise the aircraft to ignore the last clearance and return to the previous clearance state. Thereafter the misrecognized instruction had to be repeated.
- The test subject could explicitly advise the cleared state prior to the misrecognized instruction thus undoing its effect, and then speak the clearance again. However, as this is more time-consuming and repeated clearances often resulted in another misrecognition, the test subjects were discouraged to use this method.
- The clearance could be entered with a mouse. Each aircraft label on the radar screen was equipped with pulldown menus for the relevant parameters (heading, flight level, airspeed, and rate of climb or descent). An aircraft symbol together with the label as it appeared on the radar screen is depicted in Figure 8-2 (Air France 15 at flight level 163, descending to flight level 100 with a ground speed of 280 knots; the arrow indicates that the aircraft is descending).

Two conditions were varied in the simulations: simulations using the dynamic syntax generated by CCM were compared to simulations using the static syntax. Furthermore, the use of the ICAO standard phraseology was compared to the use of the extended phraseology which produced four experimental conditions:

- dynamic syntax, ICAO standard phraseology,
- static syntax, ICAO standard phraseology,
- dynamic syntax, extended phraseology,
- static syntax, extended phraseology.

For reasons of limited availability of the participants, only two experimental simulations were executed per test subject. As the comparison of dynamic and static syntax was the major point of interest, it was decided that each test subject should attend one simulation with a dynamic syntax and one with a static syntax while the phraseology would remain unchanged, either ICAO standard or extended. This permitted an inter-individual comparison of dynamic and static syntax, while the effect of the phraseology could be determined by means of intra-individual comparison between the two groups of test subjects that used either phraseology. The experiments with each participants comprised the following steps:

- The experiments commenced with a briefing and a demonstration of the simulation environment and the speech recognizer. The methods and objectives of the experiments were explained and questions were answered.
- For training purposes, a complete simulation was executed during which the test subjects controlled the traffic via voice in order to become familiar with the sector structure and the handling of the speech recognizer. The conditions equaled those in the succeeding experimental simulations, but no data was logged.
- Two experimental simulations were executed, during one of which the dynamic syntax generated by CCM was used while during the other simulation the static syntax was used. The sequence was varied in order to balance learning effects. Each test subject used either the ICAO standard phraseology or the extended phraseology throughout all simulations. A list of the phrases associated with each clearance was available during the experiments.
- After each of the two experimental simulations the participant was asked to provide his or her subjective workload according to the NASA Task Load Index (TLX) method (for an explanation of TLX see chapter 8.3).
- After all simulations were completed, the test subjects filled in a questionnaire dealing with the usability of the simulation and the speech recognizer (see Appendix F for the questionnaire). During the debriefing session questions were answered and suggestions for improvements were collected.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	mean / sum
age	46	47	45	53	54	36	57	56	45	56	35	54	55	**49,2**
male	X		X	X	X		X	X	X	X	X	X	X	**11**
female		X				X								**2**
ATC controller and instructor	X		X	X	X		X	X	X	X		X	X	**10**
pseudo pilot		X				X					X			**3**
experience as controller [years]	13		22	30	27		30	39	24	39		27	29	**28,0**
experience as instructor [years]	4		10	8	2		2		20	38		22	23	**14,3**
experience in WR1							X							**1**

Table 8-1 Overview of the test subjects.

13 test subjects participated in the experiments, eleven male and two female. Ten of the test subjects were licensed air traffic controllers who worked as instructors at the German Air Navigation Services ATC Academy. Only one test subject had previously worked in the sector WR1. Three test subjects were pseudo pilots. Table 8-1 gives an overview on the test subjects.

test subject	phraseology	first experimental simulation		second experimental simulation	
		syntax	traffic scenario	syntax	traffic scenario
1	ICAO	static	1	dynamic	2
2	ICAO	dynamic	3	static	4
3	extended	static	5	dynamic	6
4	extended	dynamic	1	static	2
5	ICAO	static	3	dynamic	4
6	ICAO	dynamic	3	static	4
7	extended	static	5	dynamic	6
8	extended	dynamic	1	static	2
9	ICAO	static	3	dynamic	4
10	ICAO	dynamic	5	static	6
11	extended	static	1	dynamic	2
12	ICAO	static	5	dynamic	6
13	extended	dynamic	3	static	4

Table 8-2 Sequence of experimental and traffic scenarios per test subject.

8.3 Logged Data

During the experiments every relevant action of test subject and simulation environment was logged to analyze the performance and usability of the speech recognizer and to study types and frequencies of misrecognitions. The most important log files are simulation data file and speech recognizer decode file. The verbal communications between controller and speech recognizer were recorded on audio tapes.

The simulation data file

The simulation data file data.sim is generated by the ATC Simulation and used as a shared file for the communication with other software components such as the Cognitive Controller Model and the ATC Speech Recognizer. Data.sim contains all relevant simulation data such as aircraft parameters, flight plans, controller actions, and decoded clearances. The file permits statistical analysis and a complete replay of the entire simulation (for a description of the simulation data file see chapter 7.2).

The speech recognizer decode file

The ATC Speech Recognizer writes the decoded clearances to the file speech.log which is read by the ATC Simulation to control the aircraft behavior. Speech.log contains the simulation time and the parse tags of the decoded clearance, i.e. aircraft callsign, clearance type and clearance parameter (see chapter 7.2). More detailed information about the results of each recognition are logged in the decode log file decode.log, providing the simulation time, the response time, i.e. the time needed for decoding the utterance and generating a pilot response, the recognition confidence, and the exact decode i.e. the sequence of words the recognizer has transcribed. An excerpt from a decode log file is presented in Appendix E.

Audio tape protocols

The voice transmissions between controller and speech recognizer were recorded on audio tapes. While the synthetic pilot response is bound to the recognition decode, the utterance the test subject has actually spoken is not available in an electronic protocol. The transcription of the spoken utterance and its comparison to the decoded utterance permits the identification and classification of recognition errors.

8.4 The NASA Task Load Index (TLX)

To avoid interference with the simulation, a technique that measures the subjective workload after completion of the simulation was preferred over a technique that continuously measured the workload. The NASA Task Load Index (TLX) was chosen in order to quantify the operator's subjective workload throughout the experiments. NASA TLX has been developed for flight deck applications and successfully used in air traffic control environments [NASA 86, PD/2 98]. NASA TLX assesses the subjective workload in different dimensions, so that six subscales were identified. The subscales mental demand, physical demand and temporal demand are concerned with the characteristics of the task. Effort and performance reflect behavioral aspects and frustration level is concerned with individual characteristics. Considerable individual differences in how the subscales contribute to the overall workload were observed, so that a technique of individually weighting the scales has been developed.

NASA TLX is raised in a two step process: during the rating phase the test subject is asked to quantify his or her workload in each dimension along a scale between 0 and 100. During the weighting phase all 15 pairs of dimensions are successively presented to the test subject who chooses the dimension which he felt had contributed stronger to his overall workload. The six scales are then ranked and a weighting factor between 5 and 0 is assigned to each subscale. The TLX measure is calculated as the sum of the individual ratings multiplied by their corresponding weightings.

Dimension	Description
Mental Demand	How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	How much time pressure did you feel due to the rate or pace at which the task or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Effort	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Performance	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Frustration Level	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the tasks.

Table 8-3 Definitions of the NASA TLX Rating scales.

8.5 Statistical Analysis

As it provides the most detailed information about the results of each recognition, the file decode.log served as a basis for the identification and classification of recognition errors. In a first step, the audio protocols were transcribed and the exact wording of each spoken utterance was added to decode.log. Every spoken utterance was then classified as belonging to one of the clearance categories in Table 8-4. The purpose of this classification was to test whether recognition errors would occur particularly frequently with instructions of specific categories.

The comparison of the spoken and the decoded sentences allowed to classify the recognition as either successful or erroneous. The test subjects occasionally spoke invalid sentences, such as incomplete or interrupted instructions or unintentionally pressed the push-to-talk button. Sometimes, the test subjects repeated an instruction the speech recognizer had decoded incorrectly, or the speech recognizer did not return a decode, asking the user to repeat the sentence. All decodes were therefore classified according to the categories depicted in Table 8-5.

Category	Explanation
Init/HO	response to init calls and instruction to change to the frequency of the next ATC sector
FL	instruction concerning the altitude / flight level
Hdg	instruction concerning the heading
Fix	instruction to proceed to a navigation fix
IAS	instruction concerning the airspeed
ROCD	instruction concerning the rate of climb / descent
Other	other transmission, e.g. inquiries

Table 8-4 Categories of instructions.

Category	Explanation
Correct	utterance was decoded correctly at first speaking
Error	utterance was decoded incorrectly at first speaking
Repeat	incorrectly decoded utterance was repeated
Say Again	recognition did not return a decode and controller was prompted to repeat the sentence
Invalid	an invalid sentence was spoken

Table 8-5 Decode categories.

Invalid utterances were eliminated from the analysis. Further, as a decode should be classified as erroneous even if repeating the sentence would return a correct decode, repeated sentences were also not taken into consideration. The recognition error rate was defined as the ratio of incorrect decodes and the sum of correct and incorrect decodes:

$$\text{Recognition Error Rate} = \frac{\text{Number (Error)}}{\text{Number (Correct)} + \text{Number (Error)}}$$

If the decoded sentence deviated from the spoken utterance in the exact wording but still produced the intended reaction, i.e. if the correct parse tags were returned, then the recognition was classified as successful, because the wording is of little relevance for the simulation. If, for example, the following clearance had been spoken:

`"Swissair five tree eight descend flight level niner zero"`

and the speech recognizer had decoded

`"Swissair five tree eight descend` **`to`** `flight level niner zero"`

the parse tags for both sentences would be

`+SWR538 +DESC_FL +90`

and the aircraft would execute the desired maneuver.

A recognition error could be due to the misrecognition of the callsign, the clearance type or the clearance parameter. Also, more than one item could be decoded incorrectly. According to the kind of misrecognition, incorrect decodes were classified as belonging to one of the categories depicted in Table 8-6.

	Error Category	**Explanation**
PE	Parameter Error	incorrect recognition of clearance parameter while aircraft callsign and clearance type had been decoded correctly. e.g. DLH123 descend flight level 190 instead of DLH123 descend flight level 90
IE	Instruction Error	incorrect recognition of clearance while the aircraft callsign had been decoded correctly. e.g. DLH123 turn left heading 130 instead of DLH123 descend flight level 90
CE	Callsign Error	incorrect recognition of aircraft callsign while clearance parameter and clearance type had been decoded correctly. e.g. SAB123 descend flight level 90 instead of DLH123 descend flight level 90
TE	Total Error	incorrect recognition of aircraft callsign and clearance type and / or clearance parameter e.g. SAB123 turn left heading 130 instead of DLH123 descend flight level 90

Table 8-6 Categories of recognition errors.

The experiments with each test subject included one scenario with a static syntax and one scenario with a dynamic syntax. Therefore, the effect of using the dynamic syntax can be analyzed by inter-individual comparison in order to validate or reject hypothesis HA-0, i.e. the assumption that the recognition error rate can not be reduced when the dynamic syntax is used instead of the static syntax (see chapter 8.1). Both the simulations with ICAO standard phraseology and those with extended phraseology were analyzed separately, so that two sets of matched pairs were found.

As recognition error rates below zero percent will not occur, a Gaussian distribution can not be expected. Besides, the small number of samples (six resp. seven for each of the four conditions) appears insufficient to test whether the actual distribution equals a Gaussian distribution. To test matched pairs of a non Gaussian distribution, the nonparametric Wilcoxon-Test for matched pairs was applied. This test first ranks the differences between the pair's scores without regard to sign and then affixes the signs. In case of a random distribution, which is the null hypothesis, a balanced order of signs can be expected, whereas a directional order of the signs indicates that an alternate hypothesis may be true.

As the aim of the test was to either confirm or reject hypothesis HA-0, a directional test was performed on the counter hypothesis HA-1, i.e. the hypothesis that the error rate can be reduced by using the context-sensitive syntax [Siegel 50, Bortz 85]. By means of the Wilcoxon test, the one-tailed probability that HA-1 is true was calculated and the hypothesis HA-1 was assumed if the error probability was less than five percent. By assuming HA-1, HA-0 would be rejected.

The comparison of experiments with ICAO standard phraseology and extended phraseology did not permit inter-individual comparisons as each test subject used one phraseology throughout all simulations, so that an intra-individual comparison was required to test hypothesis HB-0, i.e. the assumption that the recognition error rate would not be increased by using the extended phraseology instead of the ICAO standard phraseology. Equally, testing hypothesis HC-0, concerned with the effect the phraseology has on the subjective workload, also required intra-individual comparison. The tests were carried out separately for experiments with dynamic syntax and experiments with static syntax. As a Gaussian distribution was not expected for the above mentioned reasons, the nonparametric Mann-Whitney U Test was used. The Mann-Whitney U Test ranks the scores of two independent sets respecting the sign. Then a value is calculated for each set by summing up the number of scores of the other set preceding each score of the first set. In case of a random distribution of the two sets, i.e. if the null hypothesis is true, similar values can be expected for the two sets.

The Mann-Whitney U-Test was also applied at a level of error probability of 5 percent [Bortz 85]. The recognition error rate was compared for the two phraseologies in order to prove or reject hypothesis HB-0 (see chapter 8.1). Therefore, as HB-0 is the null hypothesis, the alternate hypothesis that the extended phraseology would result in a higher recognition error was tested, so that a directional test was applied. The comparison of the subjective workload ratings permitted to test for hypothesis HC-0 using the Mann-Whitney U-Test. Both tests were carried out separately for scenarios with dynamic syntax and scenarios with static syntax.

8.6 Summary

Experiments have been designed in order to study the effect that the use of the context-sensitive syntax has on the recognition performance, compared to the use of the static syntax. The effect of using the ICAO standard and the extended phraseology on recognition performance and workload was another point of interest. The experimental environment comprised an air traffic control simulator with a speech recognition and speech synthesis interface. The test subjects controlled air traffic in a typical simulation by speaking the instructions the same manner as in simulations with pseudo pilots. All relevant pieces of information were recorded during the simulations in order to support a detailed analysis of recognition errors.

9 Results of the Experiments

More than 4,100 transmissions during 26 simulations were recorded, transcribed, and analyzed. It was observed that the recognition error rate was about 50 percent lower in experiments in which the context-sensitive dynamic syntax was used instead of the static syntax. When CCM was active and the ICAO standard phraseology was used, a recognition rate of 93 percent was achieved. The recognition error was slightly higher for experiments with extended phraseology than for those with ICAO standard phraseology, but this effect was not significant. The controllers' subjective workload showed no significant effect, i.e. it neither varied with the phraseology nor depended on whether static or dynamic syntax are used. Debriefings and questionnaires revealed that the improvements in the recognition performance due to the dynamic syntax were perceived as improvements by the test subjects.

9.1 Data Material

The audio protocols of 26 simulations were transcribed, each lasting about 70 minutes. The transcriptions of the spoken sentences were then added to the decode protocols to permit a comparison between the spoken and the decoded sequences of words. In total 4,112 sentences were spoken which were then classified into the categories Correct, Error, Repeat, Say Again, or Invalid as discussed in chapter 8.5. Table 9-1 lists the number of sentences in each category.

Category	**Number**	**Explanation**
Correct	2963	utterance was decoded correctly at first speaking
Error	586	utterance was decoded incorrectly at first speaking
Repeat	344	incorrectly decoded utterance was repeated
Say Again	63	recognition did not return a decode and controller was prompted to repeat the sentence
Invalid	156	an invalid sentence was spoken
Sum	**4112**	

Table 9-1 Number of sentences per decode category.

As discussed in chapter 8.5, only the categories Correct and Error were taken into consideration for the calculation of the recognition error rate. The sentences in these categories were classified with regard to the instruction category (see Table 8-4 in chapter 8.5). The frequency of the clearances of each type are listed in Table 9-2.

Type	Number	Explanation
Init/HO	1246	response to init calls and instruction to change to the frequency of the next ATC sector
FL	919	instruction concerning the altitude / flight level
Hdg	130	instruction concerning the heading
Fix	297	instruction to proceed to a navigation fix
IAS	416	instruction concerning the airspeed
ROCD	108	instruction concerning the rate of climb / descent
Other	433	other transmission, e.g. inquiries
Sum	**3549**	

Table 9-2 Frequency of clearance types.

9.2 Recognition Error Rate

Figure 9-1 depicts the overall recognition error rates for experiments with the ICAO standard phraseology and for experiments with the extended phraseology. In both cases the recognition error rate is about 50 percent lower for experiments in which the context-sensitive syntax was used instead of the static syntax. The recognition error rate is reduced by 47.1 percent from 13.3 percent to 7.0 percent for the ICAO standard phraseology and by 51.2 percent from 24.4 percent to 13.3 percent for the extended phraseology. This effect is statistically significant for both phraseologies so that hypothesis HA-0 is rejected[25].

The use of the situation-dependent syntaxes dynamically generated by the Cognitive Controller Model results in a reduced recognition error rate, compared to the use of the static syntax.

Hypothesis HB-0 states that a higher recognition error rate would not occur if the extended phraseology was used instead of the ICAO standard phraseology. A higher error rate can be observed, however, as this effect is statistically non-significant, no evidence is found to refute hypothesis HB-0[26].

The use of the extended phraseology, compared to the use of the ICAO standard phraseology, does not have a negative effect on the recognition error rate.

[25] Wilcoxon-Test for matched pairs, one-sided, level of error probability 5%
[26] Mann-Whitney U-Test, one-sided, level of error probability 5%

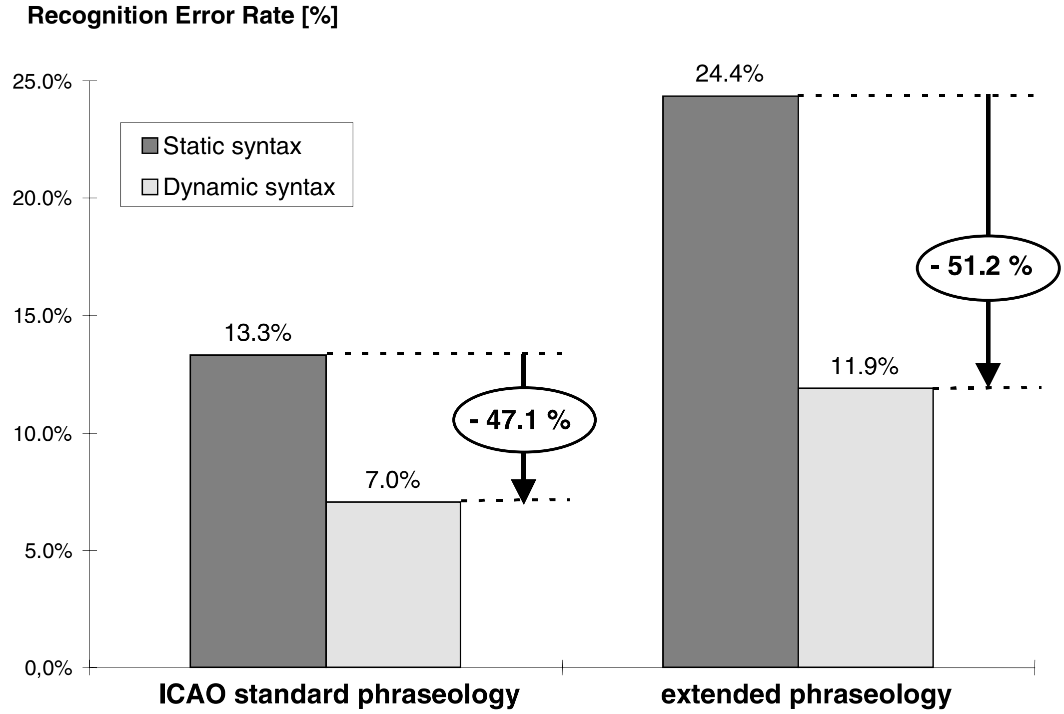


Figure 9-1 Recognition error rates.

Error Categories

The recognition error rates were calculated separately for each of the error categories Parameter Error (PE), Instruction Error (IE), Callsign Error (CE), and Total Error (TE) as discussed in chapter 8.5 (see Table 8-6, page 120). The recognition error rates per error category are and depicted in Figure 9-2 and listed in Table 9-3.

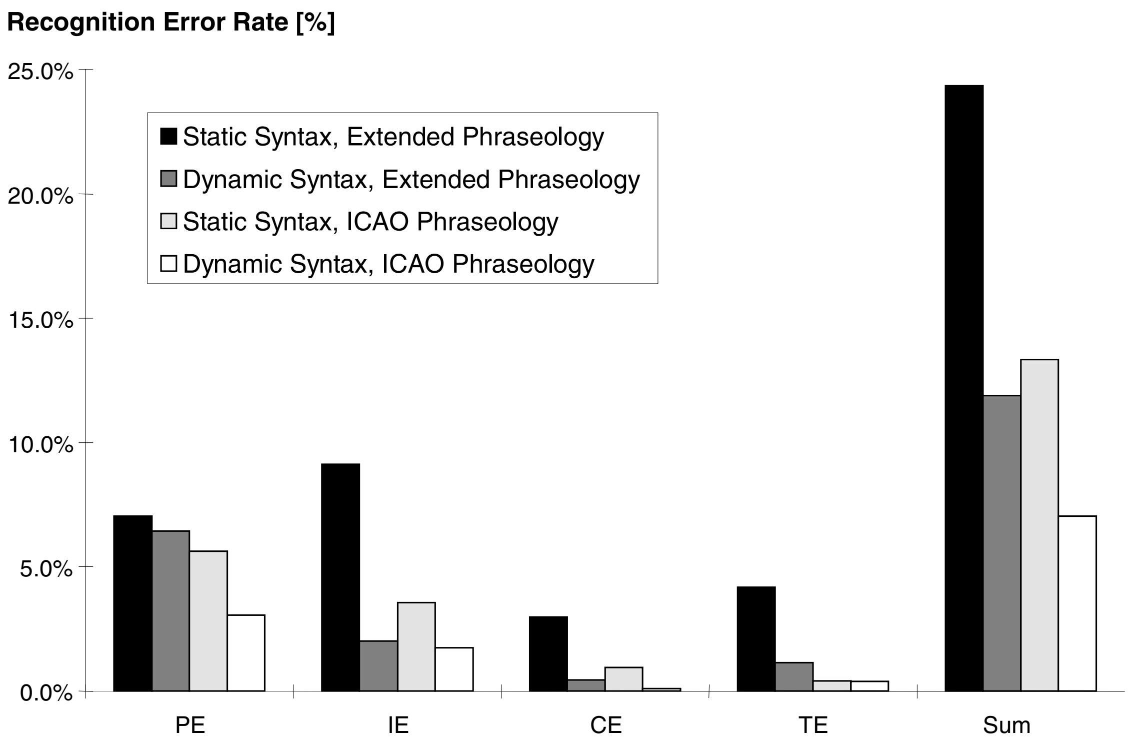


Figure 9-2 Recognition error rate per error category.

	ICAO standard phraseology		sign.	extended phraseology		sign.
	static syntax	**dynamic syntax**		**static syntax**	**dynamic syntax**	
PE	5.6%	3.1%	*	7.0%	6.4%	
IE	3.5%	1.8%	*	9.1%	2.0%	*
CE	1.0%	0.1%		3.0%	0.5%	
TE	0.4%	0.4%		4.2%	1.15%	
Total	**13.3%**	**7.0%**	*	**24.4%**	**11.9%**	*

Table 9-3 Recognition Error Rate per error category.

The error rate in each error category equals the average of the corresponding rates over all test subjects. Therefore, the sum of the rates does not necessarily equal the total error rate. Asterisks in the column sign. mark error categories for which the reduction in the recognition error rate is statistically significant. In a combined analysis of both phraseologies, significance was found for all categories but TE.

Recognition Error Rate per Clearance Type

The recognition error rates were analyzed according to the type of clearance that had been recognized incorrectly. Again, this analysis was carried out separately for both phraseologies. The results for the ICAO standard phraseology are depicted in Figure 9-3 and listed in Table 9-4. The results for the extended phraseology can be found in Figure 9-4 and Table 9-5. Again, significant effects are marked by asterisks.

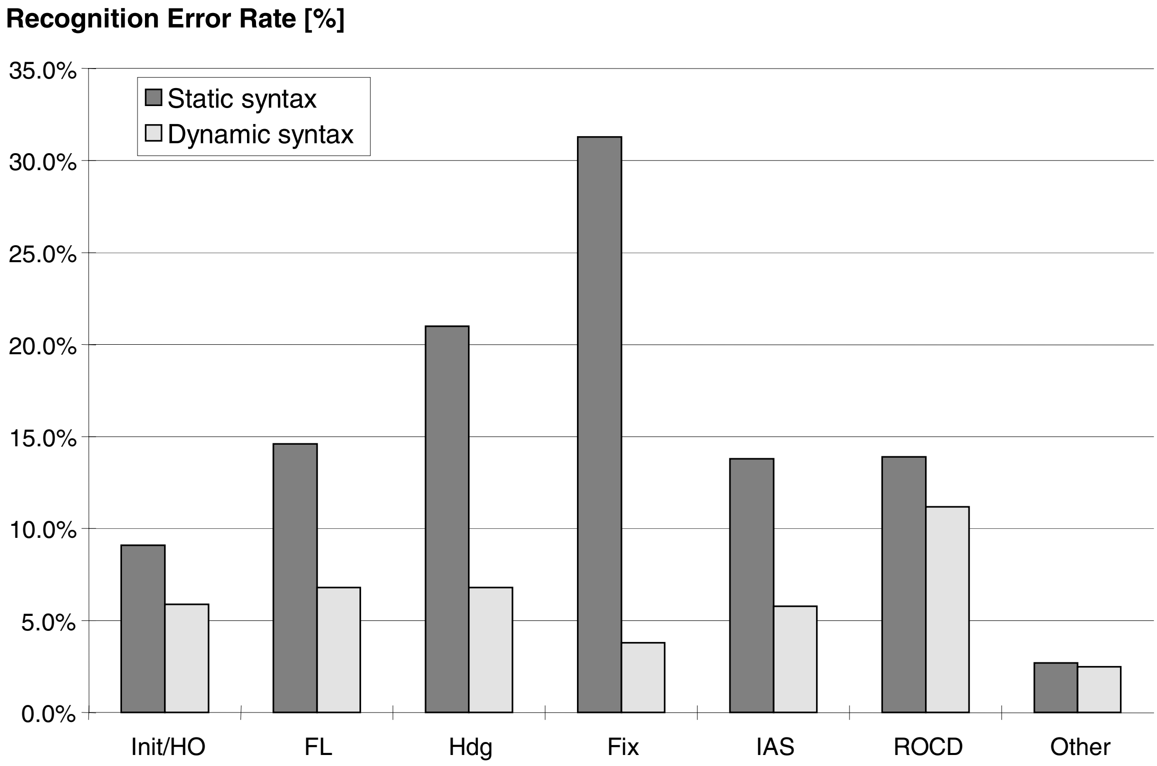


Figure 9-3 Error rate per clearance type - ICAO standard phraseology.

clearance type	recognition error static syntax	recognition error dynamic syntax	difference
Init/HO	9.1%	5.9%	-35.2%*
FL	14.6%	6.8%	-53.4%*
Hdg	36.8%	11.9%	-67.7%
Fix	31.3%	3.8%	-87.9%*
IAS	13.8%	5.8%	-58.0%*
ROCD	16.2%	11.2%	-30.9%
other	3.2%	3.0%	-6.3%
mean	**13.3%**	**7.0%**	**-47.1%***

Table 9-4 Error rate per clearance type - ICAO standard phraseology.

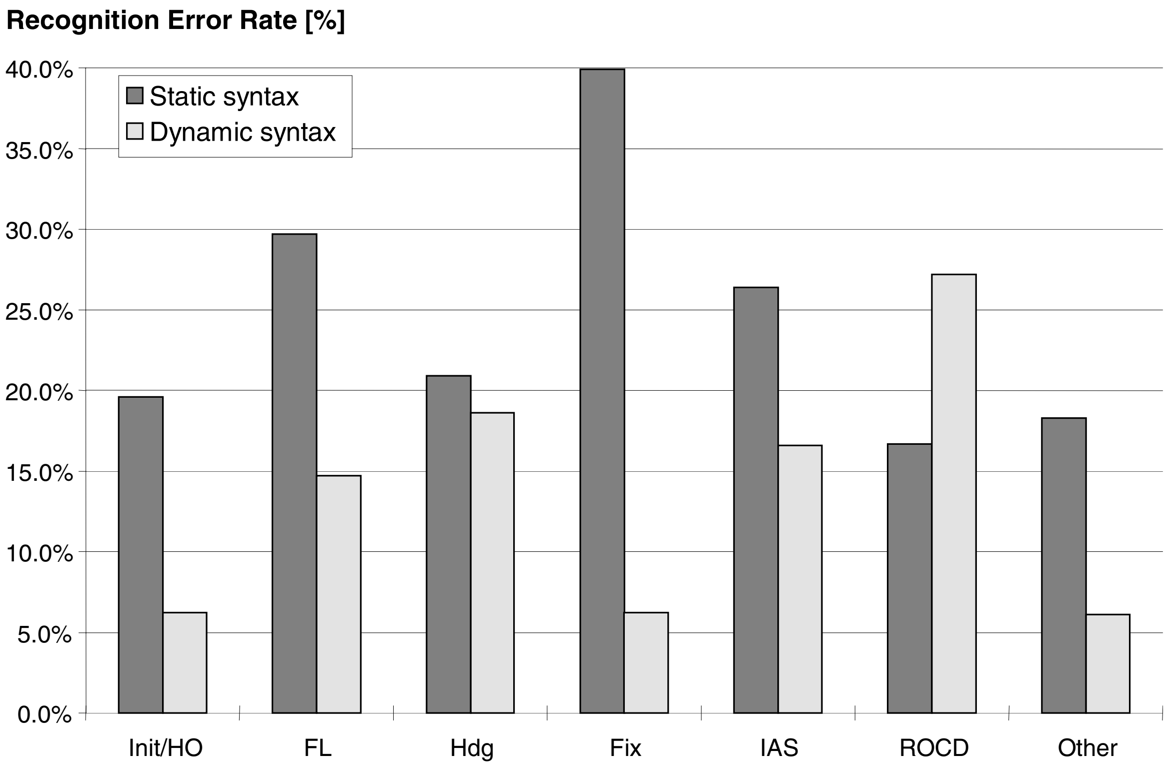


Figure 9-4 Error rate per clearance type - extended phraseology.

clearance type	recognition error static syntax	recognition error dynamic syntax	difference
Init/HO	19.6%	6.2%	-68.4%
FL	29.7%	14.7%	-50.5%*
Hdg	20.9%	18.6%	-11.0%
Fix	39.9%	6.2%	-84.5%*
IAS	26.4%	16.6%	-37.1%*
ROCD	16.7%	27.2%	62.9%
Other	18.3%	6.1%	-66.7%
mean	**24.4%**	**11.9%**	**-51.2%***

Table 9-5 Error rate per clearance type - extended phraseology.

The effects of using the context-sensitive, dynamic syntax instead of the static syntax are different for each clearance type. The different reductions are due to the fact that the Cognitive Controller Model cannot equally well restrict the search space for all clearance types. For example, it is easy to restrict the number of waypoints the controller might clear an aircraft to by just using the next three fixes in the flight plan. However, it is much more complicated to predict which rate of climb or descent the controller may instruct. Accordingly, a strong, significant reduction can be observed for the clearance type FIX, while the effects for the clearance type ROCD are non-significant. By jointly analyzing the data of both phraseologies, a significant reduction of the recognition error rate can be observed for all types but ROCD and Other.

Recognition Error Rate per Test Subject

The recognition error rate was also analyzed per test subject, again separately for both phraseologies. While a positive effect of the context-sensitive syntax was observed for every individual participant, the absolute recognition error rates vary considerably. The reduction also varies between the test subjects. However, the statistical relevance of this effect must not be overestimated. The recognition error rates per test subject are presented in Figure 9-5 for the ICAO standard phraseology and in Figure 9-6 for the extended phraseology.

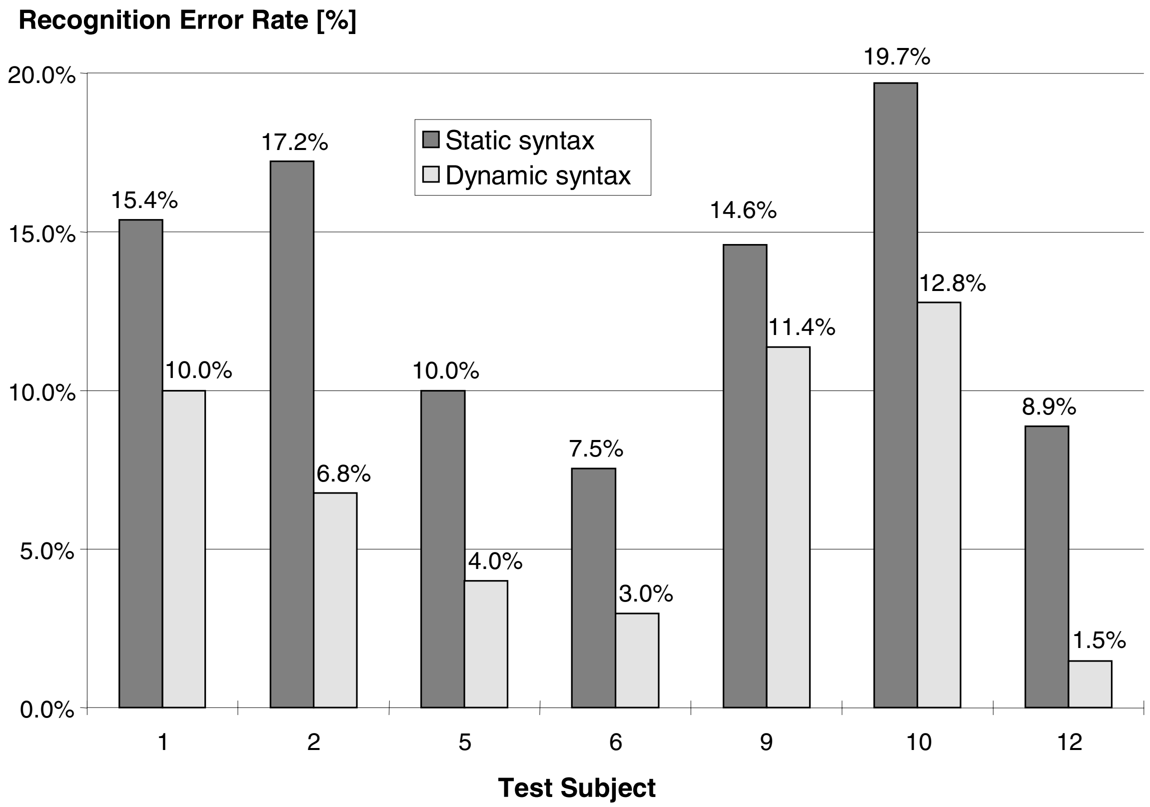


Figure 9-5 Error rate per test subject - ICAO standard phraseology.

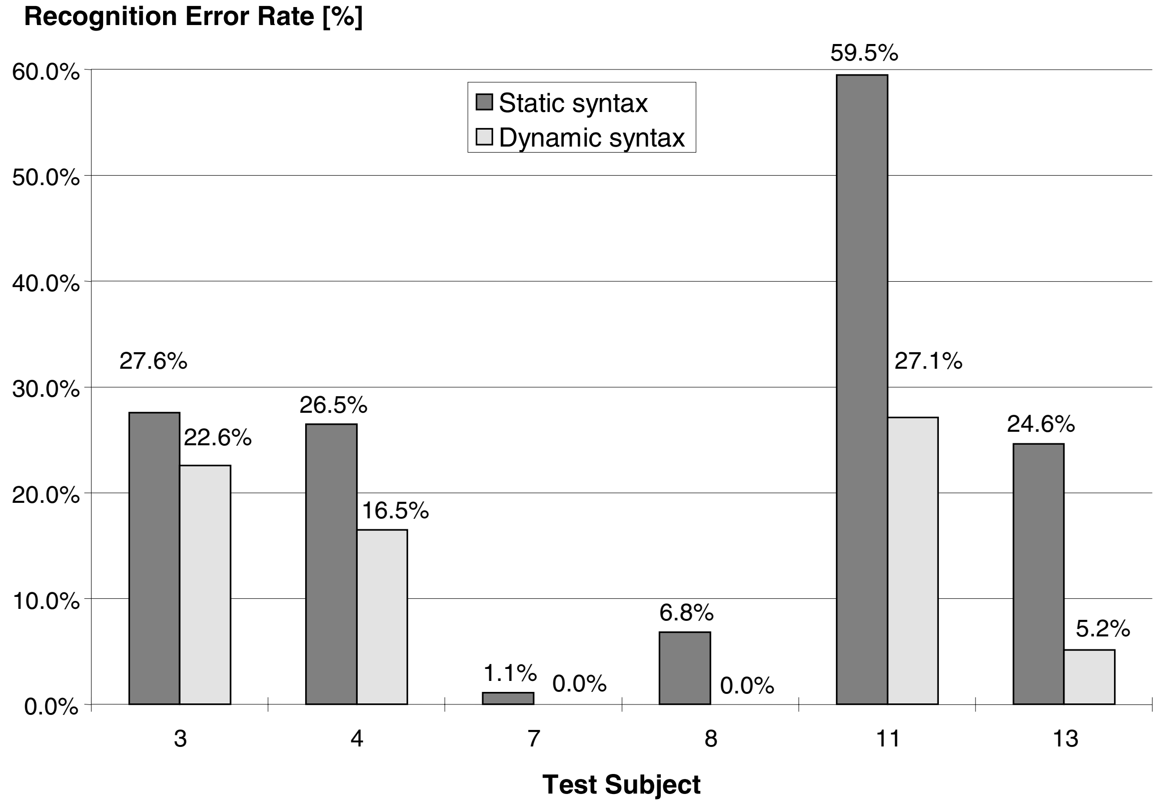


Figure 9-6 Error rate per test subject - extended phraseology.

9.3 Subjective Workload

The NASA TLX scores of the simulations with ICAO standard phraseology are depicted in Figure 9-7. Figure 9-8 depicts the scores for simulations with extended phraseology. Statistical analysis revealed no significant difference between simulations with static syntax and simulations with dynamic syntax for both phraseologies[27]. Whether the static or the dynamic syntax is used seems to be of little relevance for the workload the test subjects perceived. A comparison of simulations with ICAO standard phraseology and simulations with extended phraseology does also not reveal any statistically significant differences[28]. The perceived workload does apparently not depend on the phraseology. It was supposed that due to learning effects the perceived workload would decrease with the time the test subject would use the speech recognizer. The workload scores for the second experimental simulation were therefore compared to the scores for the first experimental simulation. However, statistical analysis revealed no difference in the NASA TLX scores between first and second experimental simulation. The perceived workload seemed not to decrease for the second simulation.

[27] Wilcoxon-Test for matched pairs; one-side significance; level of error probability 5%

[28] Mann-Whitney U-Test, one-side significance; level of error probability 5%

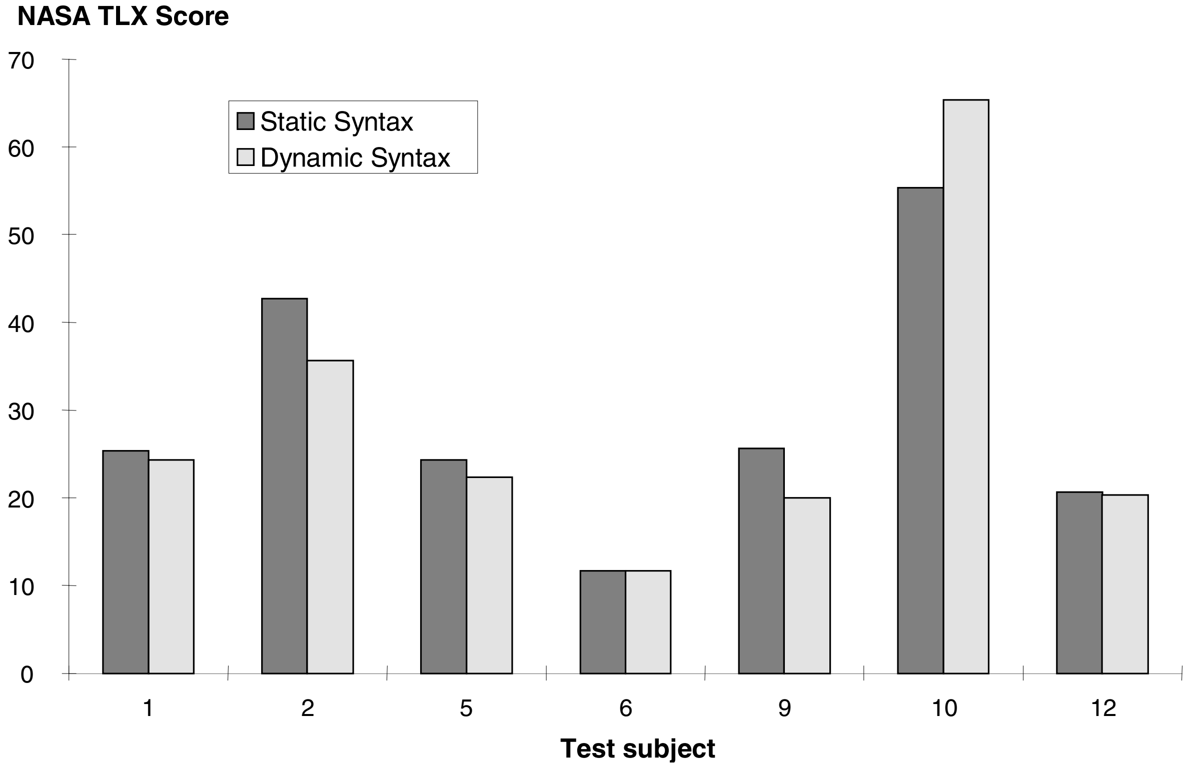


Figure 9-7 NASA TLX scores - ICAO standard phraseology.

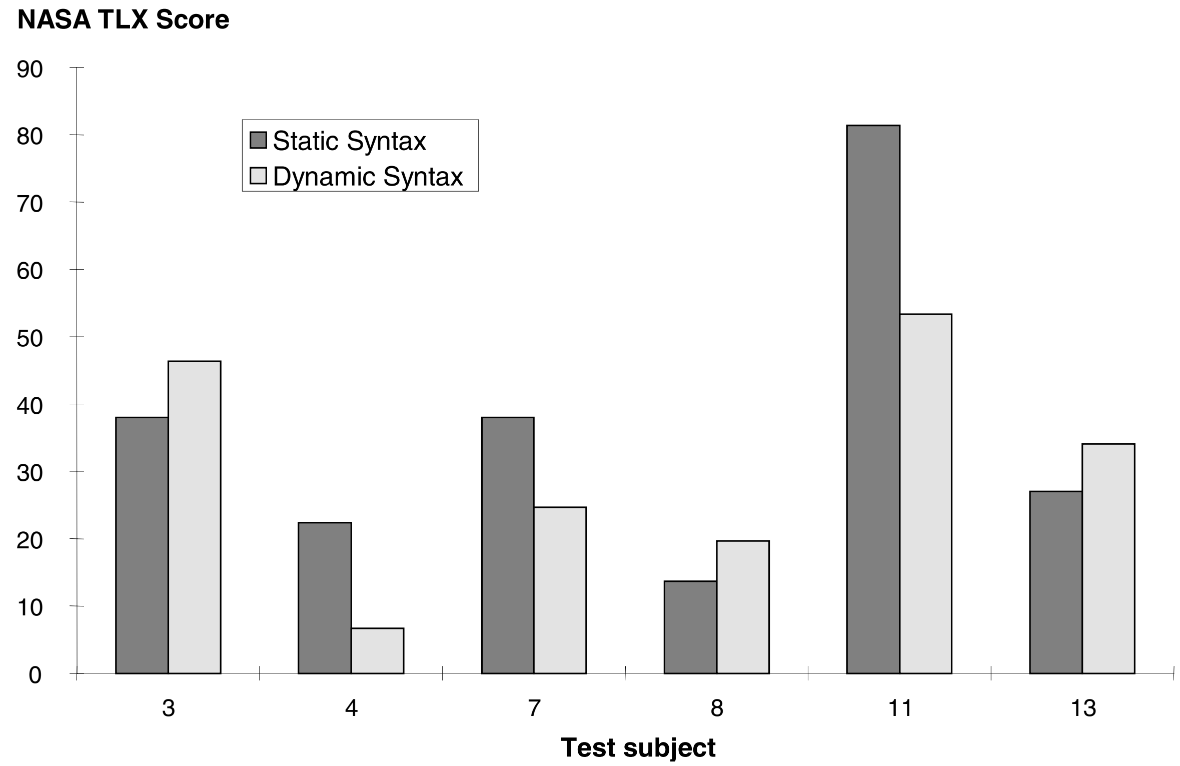


Figure 9-8 NASA TLX scores - extended phraseology.

Although the mean NASA TLX score for all simulations with extended phraseology (mean: 33.8; standard deviation: 19.2) is higher than the mean for simulations with ICAO standard phraseology (mean: 29.0; standard deviation: 15.1) no statistically significant difference can be proven. However, it was found that the subjective workload rates correlate with the recognition error rates (correlation coefficient of 0.65). Recognition errors seem to be a major contributor to perceived workload. Still, hypothesis HC-0 must be accepted, as it claimed that the perceived workload would not decrease with the use of the extended phraseology:

The use of the extended phraseology does not result in a reduced subjective workload of the controllers when compared to the use of the ICAO standard phraseology.

9.4 Questionnaires

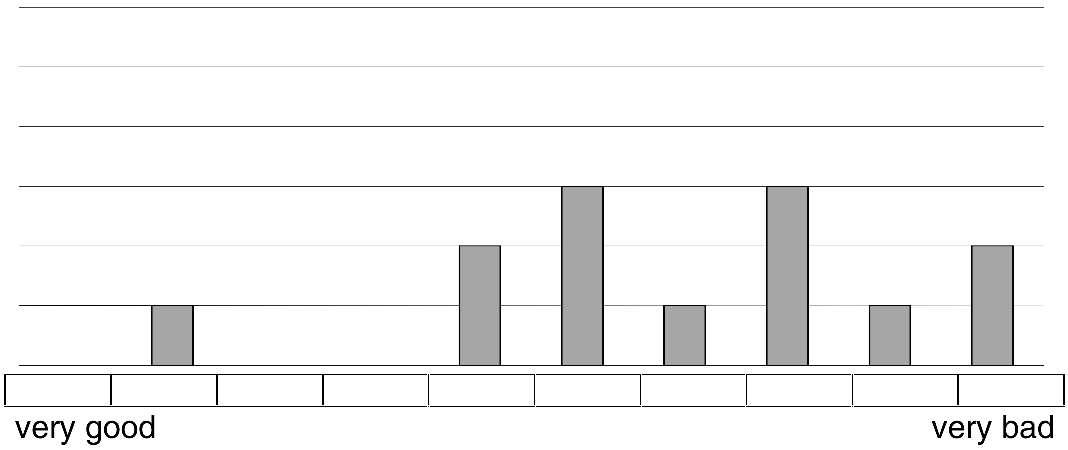
After they had completed all simulations the test participants were asked to fill in a questionnaire about the usability of the simulation environment and the speech recognizer (the original German questionnaire together with the English translations of the questions can be found in Appendix F). The questionnaires included questions and a 10-scale check-box with semantic differentials in which the test subjects marked a box they considered appropriate to answer the question[29]. In the figures below the frequency with which each box was chosen is depicted as a bar above the corresponding box.

As a means to interpret the answers, a binomial test was performed for each question. The null hypothesis was checked, i.e. it was presupposed that the responses would follow a random distribution among the response fields. In order to test the null hypothesis two categories of responses were constructed, each comprising the responses closer to one of the two sides of the check-box so that the distribution of the responses was transferred to a binomial distribution. Then the binomial probability, i.e. the probability that the presumption of a random distribution is valid was tested. Provided that the binomial probability was less than five percent, the null hypothesis was refuted. In this case, the responses provided a statistically safe interpretation towards the label on either the one or the other side of the check-box. With 13 participants responding to the questions, it is required that the responses of at least 9 subjects belong to one of the two categories in order to refute a random distribution with a level of error probability of less than five percent [Siegel 50].

[29] Neutral responses may not only reflect a neutral attitude but also be due to undecisiveness or lack of motivation to answer the question. Eliminating the possibility of neutral responses, an even number of discriminations in the scale was preferred over an uneven number.

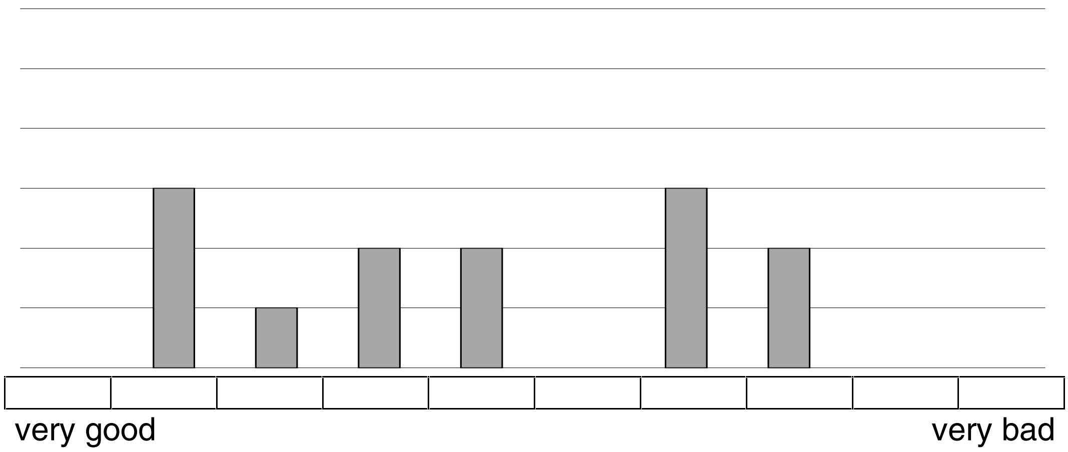
The first question was concerned with impression the participants had of the ASR recognition rate during experiments in which the Cognitive Controller Model was not active, i.e. the static syntax was used. 10 out of 13 participant judged the recognition rate as "bad" rather than "good". The responses show significantly that the recognition rate was felt as being rather bad when CCM was not active.

How do you judge the recognition rate of the ASR during simulations without the Cognitive Controller Model?



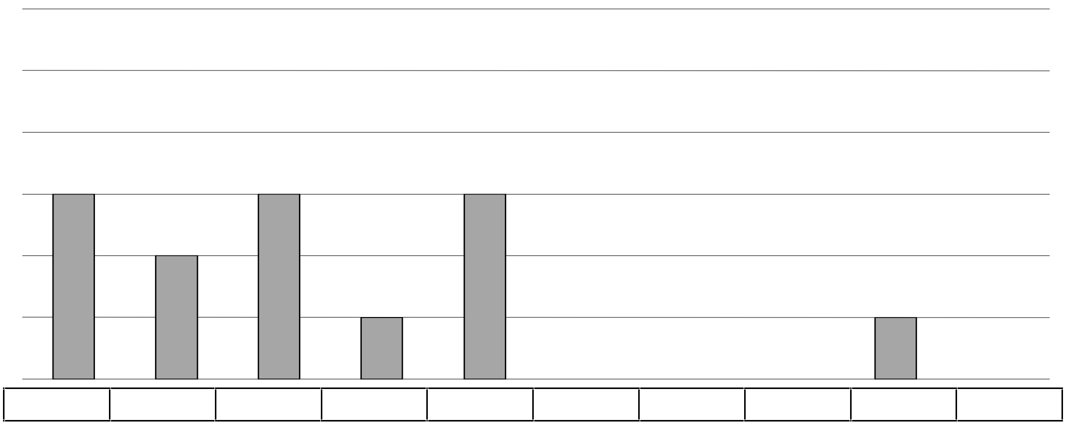
The next question was concerned with the recognition rate during experiment in which the ASR used the dynamic syntax generated by the Cognitive Controller Model. Compared to the responses to the previous question, the rating appears to be more favorable, however does not permit a significant interpretation as only 8 out of 13 persons judged the recognition rate as "good" rather than "bad".

How do you judge the recognition rate of the ASR during simulations with the Cognitive Controller Model?



When the test participants were asked about the response times of the simulated pilots, i.e. how fast they felt the speech synthesis responded to their instructions and requests, 12 out of 13 persons felt that the responses were "quick" rather than "slow". As this distribution is significantly tending towards the left side, it can be concluded that the subjects had the impression of favorable response times.

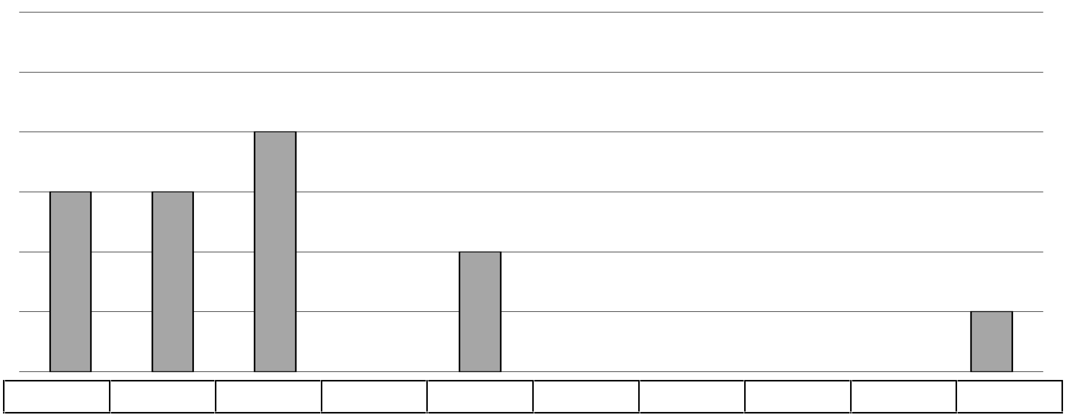
How do you judge the response times of the simulated pilots?



very quick very slow

The quality of the speech synthesis was judged equally well. 12 out of 13 test participant found that the quality was "good" rather than "bad". As this results is also significant it can be concluded that test participants had a favorable impression of the quality of the speech synthesis.

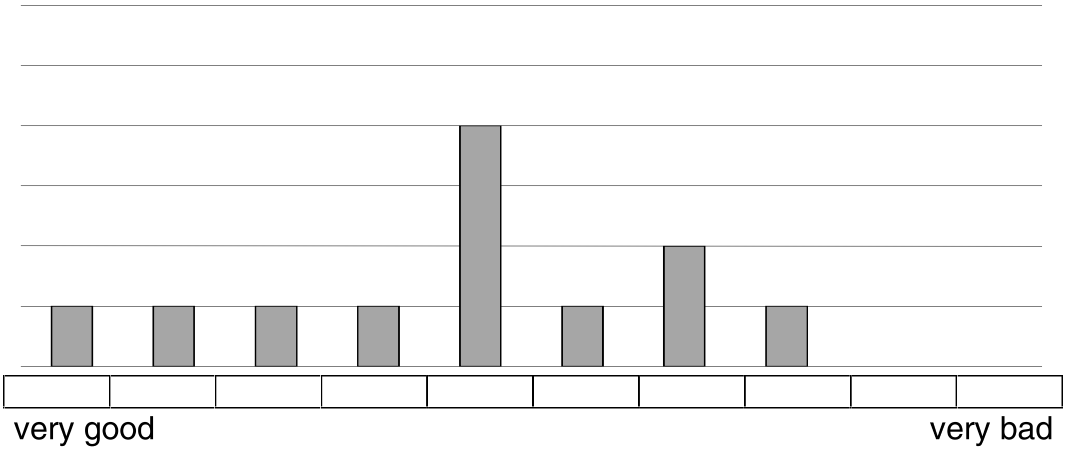
How do you judge the quality of the speech synthesis?



very good very bad

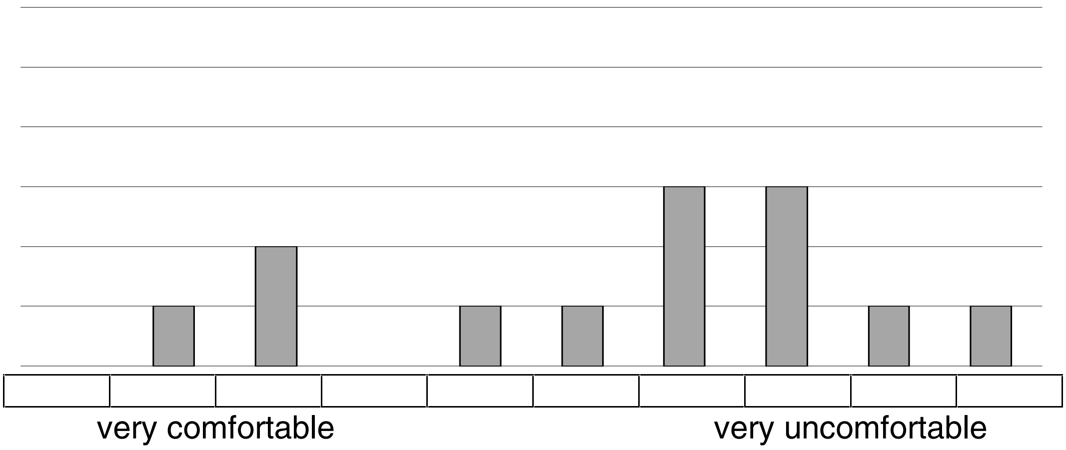
When the test subjects were asked how easily they felt they were able to correct misrecognitions of the speech recognizer, the responses were less uniform. Although the majority of the participants judged the feature as "good" this effect is not significant.

How easy is it, in your opinion, to correct misrecognitions of the speech recognizer?



When asked how comfortable they found headset and push-to-talk button, most participants said these devices were rather "uncomfortable". Again, the responses do not permit a significant interpretation.

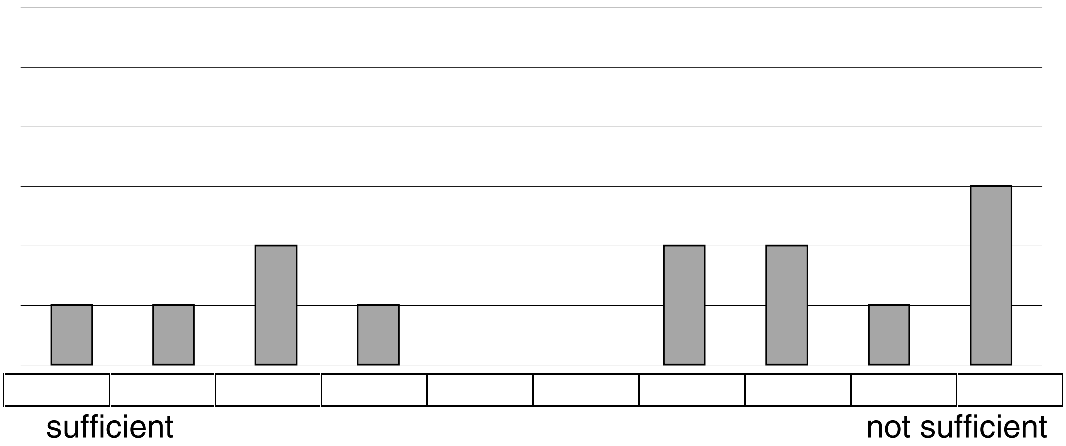
How do you judge the handling of headset and push-to-talk button?



The final question was concerned with possible fields of application of the speech recognition system. The controllers were asked whether they considered the performance of the ASR sufficient for its use in ATC controller training. No significant distribution can be identified among the responses: 5 test subjects stated that using the ASR for controller training would be possible, while 8 subjects responded in the negative.

The distribution of the responses permits one possible interpretation: as there are many fields where the application of speech recognition technology appears imaginable in ATC controller training, the question "Do you think the performance of the speech recognizer is sufficient for its use it in ATC controller training?" may be interpreted as: "Do you think the performance of the speech recognizer is sufficient for its use it in some fields of ATC controller training?" or as: "Do you think the performance of the speech recognizer is sufficient for its use it in all fields of ATC controller training?". Accordingly, some test subjects may have answered the latter question in the affirmative while the rest replied in the negative to the first question. This impression is supported by the results of the debriefing, during which the participant were explicitly asked where they found ASR technology could be applied in the ATC controller training context [Schäfer & Emmermann 98].

Do you think the performance of the speech recognizer is sufficient for its use it in ATC controller training?



The responses to the questionnaires permit the interpretation that the interaction with the speech recognition environment was fairly convenient, i.e. the response times and the quality of the speech synthesis were rated as acceptable although most of the test subjects found using headset and push-to-talk button less convenient. The recognition rate appeared poor to most test participants during simulations that did not involve the context-sensitive syntax. The rating was much more favorable for simulations in which the Cognitive Controller Model was active. Still, a further increase of the recognition rate appears to be desirable from the test participant's point of view.

9.5 The Recognition Confidence

During the recognition process, a measure of conformity between the spoken utterance and the decoded sentence is determined by the Phonetic Engines, reflecting its confidence that the decode is correct. The ATC Speech Recognizer refuses all decodes with a recognition confidence less than a specified rejection threshold and prompts the user to repeat the sentence by saying "say again". According to the possible range of the recognition confidence, a rejection threshold between zero and

900 can be chosen and entered to the ATC Speech Recognizer in a parameter editor (compare chapter 7.3). After initial tests prior to the experiments a rejection threshold of 600 was chosen.

The recognition confidence of all correct and incorrect decodes was analyzed. Figure 9-9 depicts the number of correct and incorrect decodes in confidence intervals of ten. The confidence for incorrect decodes averages by 690, whereas the confidence for correct decodes averages 730. Below a confidence of 650 a similar number of correct and incorrect decodes occurred. Refused sentences, i.e. decodes with a confidence measure below 600 are not included in Figure 9-9. However, Table 9-1 (page 123) reveals that only 63 out of 4,112 sentences were refused whereas 586 sentences were decoded incorrectly.

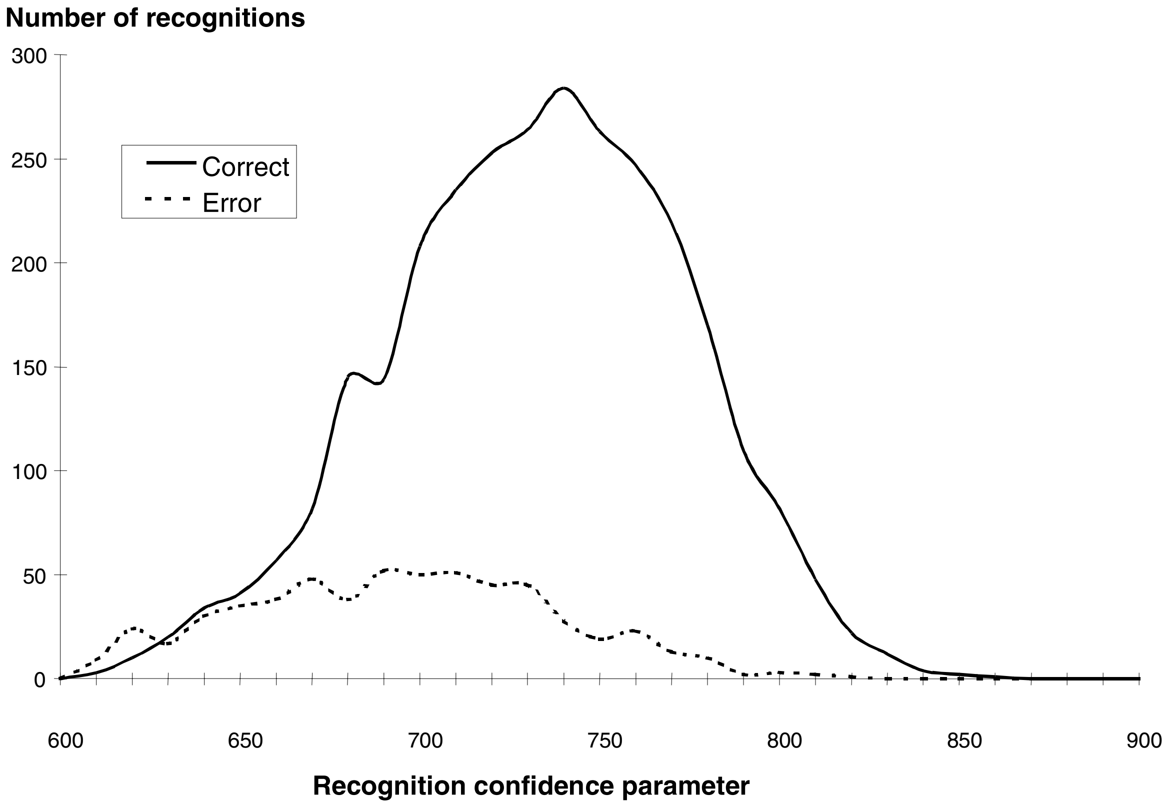


Figure 9-9 The recognition confidence of correct and incorrect decodes.

Less effort and time is required to repeat an instruction than to undo the effects of incorrect recognition, so that it appears desirable to increase the number of refused decodes if that equally reduces the number of misrecognitions. This has also been recognized and proposed by some of the test subjects. By raising the rejection threshold to 650 a similar number of incorrect and correct decodes would be refused. However, as an appropriate threshold depends on many parameters correlated to the simulation environment and individual speaker, it may be necessary to repeatedly analyze the recognition confidence in each environment in which the speech recognizer shall be used.

9.6 Discussion

Context-sensitive speech recognition holds the potential of greatly enhancing the performance of automatic speech recognition systems in the ATC simulation. Experiments proved that by using the context-sensitive syntax generated by the Cognitive Controller Model, the recognition error can be reduced by 50 percent when compared to simulations in which a non context-sensitive syntax is used. Controllers who worked with the system noticed and appreciated the improved recognition performance. The response times and the quality of the speech synthesis were also rated favorable. The reduction in the size of the pattern matching search space for the speech recognition process is dramatic. The number of sentences in the context-sensitive syntax probable.sts is only 2.4 percent of the sentences in the static syntax a non context-sensitive speech recognition system would use (compare chapter 0).

A great advantage of the concept of dynamic syntaxes is that it does not interfere with other approaches to improve the recognition performance and can be integrated into existing systems. Still, lessons learned in the experiments indicate that further improvements are possible. A few considerations concerning the Cognitive Controller Model, the ATC Speech Recognizer, the phraseology, and the usability of the entire simulation environment for research and training are presented below.

The Dynamic Syntaxes generated by CCM

Analysis revealed that both the recognition error and the improvements achieved by using a context-sensitive syntax are different for each instruction category (compare Table 9-4, page 127 and Table 9-5, page 127). The reason is that for some categories predictions limiting the parameter ranges are more accurate and powerful than for others. The frequencies with which instructions of each category have been issued (compare Table 9-2, page 124) give a hint where approaches for improvements are particularly rewarding: instructions concerning init call and handover together with flight level and speed clearances accounted for nearly 73 percent of all transmissions in the experiments.

Two kinds of recognition errors can be distinguished (compare Figure 4-2, page 42): error due to lack of sentence means that the syntax did not include the spoken sentence whereas error due to confusion of sentence means that the spoken sentence was included in the syntax but confused with a phonetically similar sentence during the decoding process. As the static syntax contained all instructions that had to be expected at any point in time during the simulation, all recognition errors during experiments with the static syntax were due to confusion of sentence. On the contrary, a considerable percentage of misrecognitions seemed to be due to lack of sentence during the simulations with the context-sensitive syntaxes. The logged data did not permit to study this effect in detail, but it was felt that extending the predictions of probable clearances could help to reduce the overall recognition error because a slightly broader search space could help to reduce the frequency of errors due to lack of sentence while only slightly increasing errors due to confusion of sentence.

The speech recognizer currently uses the sector-specific predictions of probable clearances to decode the spoken sentence. However, a non sector-specific syntax would be very desirable, as it would permit to use the context-sensitive speech recognizer in any airspace without adapting the Cognitive Controller Model. At present, the sector-specific syntax probable.sts is used for the decoding process whereas the second syntax possible.sts is only used as a means of fallback in case that the recognition should fail with the first syntax. However, possible.sts is not sector-specific and still results in a tremendous reduction of the search space (6.9 percent of the static syntax, see chapter 0). A simple solution is to use possible.sts as the main syntax. Of course, it must be expected that the recognition performance is not as good as demonstrated with probable.sts, but the improvements when compared to the use of a non context-sensitive syntax may still be considerable. This effect should be studied in experiments during which possible.sts is used as the main syntax.

The ATC Speech Recognizer

Whereas a reduction in the recognition error rate of about 50 percent when using the context-sensitive syntax has been observed quite consistently for all test participants, the absolute error rates of individual speakers varied greatly (the recognition error rates per test subject are depicted in Figure 9-5 on page 128 and Figure 9-6 on page 129). For the extended phraseology for example, the recognition error rate ranged from 60 percent to 1 percent for experiments in which the static syntax was used and from 28 percent to zero for experiments with dynamic syntax. Often, specific misrecognitions were observed that occurred frequently with individual speakers. In some cases for example the digits "two" and "four" were confused, while in other cases "five" and "niner" were confused. Besides, it seemed that test subjects speaking with an American accent demonstrated better results than subjects speaking with a German accent. This in not surprising, because the Phonetic Engine's speaker model is based on American English. As the characteristics of German controllers speaking English deviates from the average American speaker, some improvements could be achieved by adapting the ASR speaker model. As this requires the collection and analysis of large quantities of speech samples of German controllers, this is a costly process.

Additional improvements in the recognition performance can be achieved when raising the rejection threshold as discussed in chapter 9.5. Together with the above discussed refinements in the ATC Speech Recognizer and the predictions of the Cognitive Controller Model, a further improvement in the recognition performance is expected and a sentence recognition rate of above 95 percent seems within reach.

The Phraseology

Each participant used either the ICAO standard phraseology or the extended phraseology throughout the entire experiment. Therefore the data does not permit a subjective comparison of the two phraseologies. However, it was felt that the extended phraseology provided a flexibility that was well appreciated by the test subjects because they did not have to concentrate on the phrases associated with the ICAO standard. The recognition error rate was somewhat higher than for experiments in which the ICAO standard phraseology was used, though this effect was statistically not significant. Repeated tests with a larger number of participants could help to clarify whether the difference in the error rate is statistically relevant.

A detailed analysis of the phrases that had actually been spoken can be used to further refine the extended phraseology. Phrases that have rarely been used may be removed from the phraseology while others can be added. Another possible field of use of the speech recognition environment, apart from research and development, is the training of controllers. One training objective being to learn the use of the standard, it is necessary to forbid any deviation from the ICAO standard phraseology during training simulations. It therefore seems very desirable to make both phraseologies available to the instructor or supervisor who, prior to starting a simulation, chooses which phraseology shall be used.

Usability Considerations

The majority of the test participants were licensed ATC controllers who worked as instructors at the German Air Navigation Services ATC Academy. When asked about possible fields of application of the speech recognition environment, most of the test subjects said that an application in the initial training of controller students and computer-based training (CBT) would be possible and beneficial. For more complex simulations however, as they are required in more advanced training phases or in research and development, the performance of the speech recognizer at present appeared not sufficient.

Apart from the recognition error, another limitation was often mentioned as inhibitory to using the ASR in more advanced simulation environments: the user is presently limited to issue only one clearance per transmission. The reason is, that combining several clearances per transmission would dramatically increase the size of the syntax. The compilation time required by the Syntax Compiler would equally increase so that the compiled syntax cannot be made available to the ATC Speech Recognizer fast enough. As the compilation time depends on the performance of the central processing unit (CPU) of the host computer, this problem is hardware-related, so that with more powerful computers the syntax can be extended to include more than one instruction per transmission.

9.7 Summary

When using the dynamic and context-sensitive syntax generated by the Cognitive Controller Model the recognition error rate can be reduced by about 50 percent. The improvements were statistically significant as well as perceptible by the controllers who participated in the simulation experiments. Whereas the recognition error rates varied considerably among individuals, the effect that using the dynamic syntax instead of the static syntax had on the error rate was more or less constant and averaged at 50 percent. A mean recognition error rate of only 7 percent has been demonstrated in simulations using context-sensitive speech recognition and the ICAO standard phraseology. With some refinements of the Cognitive Controller Model and the ATC Speech Recognizer, a recognition rate above 95 percent seems to be attainable.

The ICAO standard phraseology was compared to the extended phraseology, containing the most frequent deviations from the official standards. While the recognition error rate was slightly higher for simulations in which the extended phraseology was used, this effect is statistically non-significant. The workload that the test subjects perceived during the simulations was also analyzed. It was hypothesized that using the extended phraseology would reduce the subjective workload, as the user did not have to concentrate on using the ICAO standards. However, this could not be confirmed statistically. Rather, the subjective workload correlates with the recognition error rate.

10 Summary and Conclusions

10.1 Summary

Air traffic control simulation is playing an increasingly important role both in the training of ATC controllers and in research and development because it permits to simulate and reproduce every desired air traffic situation without causing safety hazards to human operators and machines. As ATC simulators typically do not involve real aircraft but display the movements of artificial aircraft symbols on a radar screen, the communication between controllers and pilots is mostly simulated using the so-called pseudo pilot concept. Auxiliary personnel is responsible for the maneuvers of the simulated aircraft, entering the controllers' clearances to the simulation computer and confirming the instructions. However, as the required personnel makes simulations very expensive, the introduction of automatic speech recognition (ASR) systems is considered as a promising alternative.

The speech recognition system must be designed in such a manner that it understands and executes the controller's spoken commands and generates a pilot response by means of speech synthesis. As the quality of simulation environments depends on the degree of realism they provide, the controller must be able to communicate with the speech recognizer in the same way he communicates with pilots or pseudo pilots. The ASR must understand continuously spoken ATC instructions in a speaker-independent fashion with little response time. Moreover, the recognition error rate, i.e. the percentage of incorrectly decoded utterances, must not exceed that of human listeners. Unfortunately, present state-of-the-art speech recognition systems are not capable of meeting these requirements, and approaches to improve the recognition performance are necessary.

The superior performance of human listeners is not only due to the more complex sensory apparatus that humans posses or the use of non-verbal information, such as gesture. Humans also posses a broad source of contextual knowledge that permits them to anticipate which words and sentences their opposite may possibly speak. The structure of the language, the subject of the conversation, the dispositions of the conversant, the present situation and the dialogue history are pools of information that permit humans to distinguish probable and less probable verbal statements. Humans, therefore, are capable of interpreting even ambiguous and partially omitted utterances with superior reliability.

Compared to humans, automatic speech recognition systems use little information about the subject of the dialogue. Usually, valid sentences are defined once when integrating the ASR into the application and a dictionary and a syntax are generated. While the dictionary contains the acoustic properties of the relevant words, the syntax specifies which sequences of words are considered as valid sentences. Unlike their human counterparts, current automatic speech recognition systems do not use contextual information to discriminate between probable and less probable sentences. However, both the recognition time and the reliability of an ASR system would benefit from such a discrimination because the sentences that the user may speak in a specific situation are only a fraction of all sentences comprised in the syntax. An increase in the recognition performance may be obtained if the speech recognizer would use a syntax tailored to the actual situation.

This approach of context-sensitive speech recognition would require a module that, after carefully analyzing the present situation, provides and continuously updates a prediction about sentences the user may be expected to say. The prediction could then be used to generate a dynamic and context-sensitive syntax, more restricted than the static syntax conventional speech recognizers use. Accordingly, the recognition error rate of context-sensitive speech recognition systems which use a dynamic syntax is supposed to be small when compared to non context-sensitive systems using a static syntax. The success of this approach, however, depends very much on the quality of the predictions that are used to construct the context-sensitive syntax.

Due to the tremendous complexity of air traffic control, it is impossible to classify a limited number of distinct situations in each of which a specific syntax-subset would apply. A more powerful approach seems to be to identify the mental processes involved in the controller's decision making and to implement these in a computer-based model. Although the mental processes involved in air traffic control have been subject of research for many years, no model exists that is capable of predicting what an air traffic controller could be expected to do in specific situations. This is partly due to the enormous complexity of the tasks and cognitive activities involved in air traffic control and the difficulties in correlating user actions to the situation. It is also due to the fact that each situation can be treated in various manners and it is a question of expertise and individual preferences how each individual controller will actually react.

To fill this gap, the Cognitive Controller Model (CCM) has been developed. CCM is a mental model of the controller's activity which analyzes the traffic situation and assesses which instructions the controller may be expected to issue in that situation, quite similar to a person looking over the controller's shoulder. The architecture of CCM is based on existing models of human problem solving. The decision processes and strategies implemented in CCM have been derived by observing and questioning ATC controllers during extensive simulations and were calibrated using data logs from simulation runs. CCM consists of three major modules: The observation module is concerned with developing a mental representation of the actual context by observing and classifying the present air traffic situation. The decision module aims at predicting which instructions a controller could issue under the given circumstances. The phraseology module translates the instructions into sentences, i.e. sequences of words, and generates a context-sensitive syntax. As the controllers' decisions are to a large degree dependent on the airspace geometry, the implementation of CCM is specific to the ATC sector.

The Cognitive Controller Model has been implemented as a runtime software in order to quantify the effects which the use of a context-sensitive dynamic syntax would have on the recognition performance. A different methodology of knowledge representation was found to be adequate for the three different modules of CCM. An object-based structure was chosen for the observation module, whereas the controller strategies in the decision module were implemented as production rules. In order to generate the syntaxes, the phraseology module maps phraseology items to the more symbolic descriptions of the ATC clearances used within CCM. Combining the requirements the three modules posed, the object oriented programming language C++ was chosen for the implementation of CCM.

Data material recorded during simulations in DLR's ATC simulation facility was used in order to calibrate CCM and test its performance. During these tests, CCM was able to restrict the number of clearances to less than three percent of the static syntax, while more than 97 percent of the clearances given by controllers were correctly included in CCM's predictions of probable clearances. CCM produces two dynamic syntaxes: the syntax containing the most probable instructions as considered by CCM is used as the primary means for decoding the spoken utterance. If for some reason the decode should fail, possibly because the controller decided on a strategy CCM could not anticipate, the decoding process is repeated using a syntax containing all instructions that are physically possible in the actual situation. Both syntaxes are generated once per second.

CCM was integrated into an ATC simulation environment equipped with a speech recognition and speech synthesis interface. The ATC simulation environment permits to control simulated aircraft by means of voice, speaking the instructions in the traditional way and also provides a pilot read-back of the instructions. The speech recognizer can be configured to use either the static syntax or the context-sensitive syntaxes generated by CCM.

Generally, the communication between pilots and controllers is scheduled by international regulations which include the wordings of clearances. These standards were implemented in the ICAO standard phraseology. However, controllers often use phrases that deviate slightly from the official standards and it was presumed that by compelling them to use the standard phrases, they would have to draw additional attention to the process of speaking. This would be a perturbation of the experimental conditions and impede the transfer of simulation results to reality. Therefore, the most frequent deviations from the official standards were collected and implemented in the extended phraseology. CCM was implemented with a feature permitting the operator to choose whether the syntax shall be generated in the ICAO standard phraseology or in the extended phraseology.

Simulation experiments with experienced ATC controllers were carried out in order to assess the performance of the context-sensitive speech recognition system. Each participant controlled the traffic in an enroute sector by means of voice during two simulations, during one of which the speech recognizer used the dynamic syntax generated by CCM, whereas in the other simulation the static syntax was used. The effect of the phraseology on the recognition error rate and the subjective workload was also under investigation. Therefore half of the test subjects used the ICAO standard phraseology whereas the others used the extended phraseology.

The experiments revealed that the recognition error rate was reduced by 50 percent when the context-sensitive syntax was used instead of the static syntax. Obviously, CCM has the potential of greatly enhancing the speech recognition process. A recognition rate of 93 percent was achieved when the dynamic syntax and the ICAO standard phraseology were used. The recognition error was slightly higher when the extended phraseology was used, however, this effect was statistically not significant. Besides, it was found that variations in the recognition error rate between the individual test subjects were considerable. The subjective workload did not change when the extended phraseology was used instead of the ICAO standard phraseology and the subjective workload seemed to correlate primarily with the recognition error rate.

10.2 Conclusions

Using a dynamic, context-sensitive syntax generated by a cognitive model of the air traffic controller appears to be a powerful tool to increase the performance of automatic speech recognition in the ATC simulation. Within the context of this study, a reduction of the percentage of incorrectly decoded sentences of 50% has been proven. As the recognition error rate can be reduced significantly using contextual knowledge, a recognition rate of 95 percent under operational conditions is within reach if additional enhancements in other system components are envisaged. Once such a recognition rate is achieved, ASR could widely be used in the ATC simulation domain, supporting research and development as well as controller training.

A drawback of the present configuration of the speech recognizer is that, due to hardware limitations, it is currently only possible to speak one instruction per transmission whereas in reality controllers often include two or more instructions in one transmission. Restrictions in the usability of the ATC simulation and speech recognition environment that are caused by the hardware will probably be overcome by using new, faster computers and different speech recognizer hardware. Controllers and ATC instructors stated that such a system would be a powerful tool for computer-based training of controller disciples. With further experience it will be possible to continuously improve CCM and the speech recognizer, so that the performance will permit to use speech recognition in more advanced simulations. As soon as this new technology has given proof of its performance and reliability, questions about its use in operational ATC may be raised.

This work has demonstrated that the performance of automatic speech recognition systems in the air traffic control simulation can be improved considerably when a context-sensitive syntax is used. Compared to traditional, non context-sensitive speech recognizers, the recognition error rate can be reduced by about 50 percent. The response time and the handling of the speech recognizer have been judged agreeable and it seems very probable that speech recognition will play a vital role in future ATC training and simulation systems.

Acknowledgments

The work presented in this book would have been impossible without the assistance that I have received from various people. I wish to thank Prof. Dr. Reiner Onken and Prof. Dr. Heinz Winter for their extremely helpful contributions to this endeavor and their friendly way of coaching me. I am particularly indebted to Ralf Beyer for his wise assistance and his critical review of this book.

It is wonderful when colleagues become friends and friends become colleagues: I wish to thank Dr. Dietrich Härtl and Dr. Stephan Romahn for their critical and constructive review of the manuscript and for many helpful advises. I further wish to single out the substantial contributions I received from Frank Emmermann, Bernd Engelhardt, Dr. Marc Gerlach, and Dr. Fred Schick.

I am further indebted to Günter Meyer and Dr. Karin Haese for a critical review of the manuscript and to Georg Reichelt (Romeo Tango) for thrilling insights into the work of ATC controllers. My wife Andrea was extremely helpful in providing professional as well as emotional support whenever necessary. Thank you.

The work presented in this book has been sponsored by the German Aerospace Center (DLR) and was carried out at the DLR Institute of Flight Guidance in Braunschweig, Germany.

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Appendix A: ICAO Standard Phraseology

Response to Init Call	<Callsign> (Frankfurt Radar) identified
Report State	<Callsign> report heading <Callsign> report airspeed <Callsign> report rate of climb <Callsign> report rate of descent
Heading	<Callsign> cleared heading <Heading>
Left/ Right to Heading	<Callsign> turn left heading <Heading> <Callsign> turn right heading <Heading>
Maintain Heading	<Callsign> maintain present heading
Left/Right Turn by	<Callsign> turn left by <Degrees> degrees <Callsign> turn right by <Degrees> degrees
Speed	<Callsign> cleared (air)speed <IAS> knots (indicated)
Reduce Speed	<Callsign> reduce (air)speed to <IAS> knots (indicated)
Increase Speed	<Callsign> increase (air)speed to <IAS> knots (indicated)
Maintain Speed	<Callsign> maintain present (air)speed
Flight Level	<Callsign> cleared flight level <FL>
Descend to Flight Level	<Callsign> descend (to) flight level <FL>
Stop Descent	<Callsign> stop descent flight level <FL>
Climb to Flight Level	<Callsign> climb (to) flight level <FL>
Stop Climb	<Callsign> stop climb flight level <FL>
Maintain Flight Level	<Callsign> maintain present flight level
Rate of Climb/Descent	<Callsign> descend at <ROC> feet per minute (or more, or less) <Callsign> climb at <ROD> feet per minute (or more, or less) <Callsign> maintain present rate of descent <Callsign> maintain present rate of climb
Direct to	<Callsign> proceed direct to <FIX> <Callsign> turn left direct to <FIX> <Callsign> turn right direct to <FIX>
Circle Left/Right	<Callsign> make a tree-sixty to the left <Callsign> make a tree-sixty to the right

Contact Arrival	<Callsign> contact (Frankfurt) arrival (on) 120.8 (1 2 0 decimal 8)
Contact Radar	<Callsign> contact (Frankfurt) radar (on) 129.67 (1 2 niner decimal 6 7)
Holding	<Callsign> enter the <FIX> holding

Appendix B: Extended Phraseology

Response to Init Call	<Callsign> (Frankfurt Radar) identified <Callsign> (Frankfurt Radar) radar contact
Report State	<Callsign> report heading <Callsign> what is your heading <Callsign> report airspeed <Callsign> what is your airspeed <Callsign> report rate of climb <Callsign> what is your rate of climb <Callsign> report rate of descent <Callsign> what is your rate of descent
Heading	<Callsign> cleared heading <Heading> <Callsign> pick up heading <Heading> <Callsign> roll out heading <Heading> <Callsign> continue heading <Heading> <Callsign> stop turn heading <Heading> <Callsign> fly heading <Heading> <Callsign> turn to heading <Heading>
Left/ Right to Heading	<Callsign> turn left (to) heading <Heading> <Callsign> left turn (to) heading <Heading> <Callsign> continue left heading <Heading> <Callsign> turn right (to) heading <Heading> <Callsign> right turn (to) heading <Heading> <Callsign> continue right heading <Heading>
Maintain Heading	<Callsign> maintain present heading <Callsign> maintain heading <Callsign> continue present heading
Left/Right Turn by	<Callsign> turn left by <Degrees> degrees <Callsign> left turn by <Degrees> degrees <Callsign> turn right by <Degrees> degrees <Callsign> right turn by <Degrees> degrees
Speed	<Callsign> cleared (air)speed <IAS> knots (indicated) <Callsign> speed <IAS> knots (indicated) <Callsign> maintain <IAS> knots (indicated) <Callsign> keep <IAS> knots (indicated) <Callsign> speed not above <IAS> knots (indicated) <Callsign> speed not below <IAS> knots (indicated)
Reduce Speed	<Callsign> reduce (air)speed to <IAS> knots (indicated) <Callsign> speed back to <IAS> knots (indicated) <Callsign> slow (to) <IAS> knots (indicated) <Callsign> start speed reduction to <IAS> knots (indicated)
Increase Speed	<Callsign> increase (air)speed to <IAS> knots (indicated) <Callsign> speed up to <IAS> knots (indicated)

Maintain Speed	<Callsign> maintain present (air)speed <Callsign> maintain (air)speed <Callsign> keep (air)speed <Callsign> keep up (air)speed <Callsign> keep high (air)speed <Callsign> keep up high (air)speed <Callsign> do not reduce (air)speed
Flight Level	<Callsign> cleared (flight) level <FL> <Callsign> cleared to (flight) level <FL> <Callsign> maintain (flight) level <FL>
Descend to Flight Level	<Callsign> descend (flight) level <FL> <Callsign> descend to (flight) level <FL> <Callsign> cleared down (flight) level <FL> <Callsign> cleared down to (flight) level <FL> <Callsign> continue descent (flight) level <FL> <Callsign> continue descent to (flight) level <FL> <Callsign> down to (flight) level <FL>
Stop Descent	<Callsign> stop descent (flight) level <FL> <Callsign> stop descent at (flight) level <FL> <Callsign> level off (flight) level <FL> <Callsign> level off at (flight) level <FL>
Climb to Flight Level	<Callsign> climb level <FL> <Callsign> climb to (flight) level <FL> <Callsign> cleared up (flight) level <FL> <Callsign> cleared up to (flight) level <FL> <Callsign> continue climb to (flight) level <FL> <Callsign> continue up to (flight) level <FL>
Stop Climb	<Callsign> stop climb (flight) level <FL> <Callsign> stop climb at (flight) level <FL> <Callsign> level off (flight) level <FL> <Callsign> level off at (flight) level <FL>
Maintain Flight Level	<Callsign> maintain present (flight) level <Callsign> maintain (flight) level <Callsign> continue present (flight) level
Rate of Climb/Descent	<Callsign> descend at <ROC> feet per minute (or more, or less) <Callsign> climb at <ROD> feet per minute (or more, or less) <Callsign> rate of climb <ROC> feet per minute (or more, or less) <Callsign> rate of descent <ROD> feet per minute (or more, or less) <Callsign> maintain rate of climb <Callsign> maintain your rate of climb <Callsign> maintain present rate of climb <Callsign> maintain your present rate of climb

	<Callsign> maintain rate of descent <Callsign> maintain your rate of descent <Callsign> maintain present rate of descent <Callsign> maintain your present rate of descent
Direct to	<Callsign> proceed direct to <FIX> <Callsign> proceed on course to <FIX> <Callsign> turn left direct to <FIX> <Callsign> turn right direct to <FIX> <Callsign> direct to <FIX> <Callsign> cleared to <FIX> <Callsign> set course to <FIX> <Callsign> on course to <FIX> <Callsign> turn left to <FIX> <Callsign> turn right to<FIX> <Callsign> set heading to<FIX>
Circle Left/Right	<Callsign> make a tree-sixty to the left <Callsign> tree-sixty to the left <Callsign> make a left tree-sixty <Callsign> circle to the left <Callsign> make a tree-sixty to the right <Callsign> tree-sixty to the right <Callsign> make a right tree-sixty <Callsign> circle to the right
Contact Arrival	<Callsign> contact (Frankfurt) arrival (on) 120.8 (1 2 0 decimal 8) <Callsign> call (Frankfurt) arrival (on) 120.8 (1 2 0 decimal 8) <Callsign> change (Frankfurt) arrival (on) 120.8 (1 2 0 decimal 8)
Contact Radar	<Callsign> contact (Frankfurt) radar on 129.67 (1 2 niner decimal 6 7) <Callsign> call (Frankfurt) radar on 129.67 (1 2 niner decimal 6 7) <Callsign> change (Frankfurt) radar on 129.67 (1 2 niner decimal 6 7)
Holding	<Callsign> enter the <FIX> holding <Callsign> join <FIX> holding <Callsign> one pattern over <FIX> <Callsign> one holding over <FIX> <Callsign> one holding pattern over <FIX> <Callsign> hold over <FIX> <Callsign> hold overhead <FIX> <Callsign> enter the holding at <FIX>

Appendix C: Class Structure

The following section gives an overview of the major classes specified by the Cognitive Controller Model:

- Aircraft — Aircraft class definition with properties and associated functions which are required to describe the behavior of aircraft
- AirCont — Aircraft container class which is used to manage the different sets of aircraft, such as aircraft in sector WR1, arrival traffic, overflight traffic, etc.
- Clearance — Definition of the clearance object
- ClearCont — Clearance container class which is used to manage the different sets of clearances, such as possible clearances and probable clearances
- Position — Defines a geometric position, i.e. it's coordinates; the reference point of the coordinate system is waypoint Rüdesheim (RUD); the x-axis points east while the y-axis points north; the flight level is above mean sea level; coordinates are given in Nautical Miles (NM) for x and y and in flight levels for z
- Waypoint — Defines an aviation waypoint, usually a navigation aid, such as NDB or VOR
- Flightplan — Defines an aircraft flight plan, i.e. the route

C.1 Aircraft

Class	**Aircraft**
Parent Classes	Position Flightplan

Properties

```
callsign            // callsign
type                // aircraft type, JET or PROP
rocd                // rate of climb / descent
gs                  // groundspeed
ias                 // indicated airspeed
tas                 // true airspeed
heading             // heading
last_gs             // last ground speed (required for incrementation)
last_heading        // last heading (required for incrementation)
cl_level            // cleared flight level, 0 if none
cl_rocd             // cleared rate of climb / descent, 0 if none
cl_ias              // cleared indicated airspeed, 0 if none
cl_heading          // cleared heading, 0 if none
cl_fix              // cleared fix, type: Waypoint
status              // status (ARR, DEP, or OVFL)
sector              // sector in which aircraft is flying, usually WR1
WR1_control         // WR1 control status (INIT, CONTROL or HANDOVER)
lat_state           // lateral state (TOFIX, HEADING, CIRCLE, HOLD)
holdfix             // holding fix
d_gs[6]             // array of ground speeds, required for incrementation
clear[450]          // array of all clearances, type: Clearance
Clears              // clearance container of all clearances, type: ClearCont
PossClears          // container of possible clearances, type: ClearCont
ProbClears          // container of probable clearances, type: ClearCont
```

Functions:

```
Aircraft()                    // Default-Constructor
Aircraft(a)                   // Constructor with Callsign
read_radar(a, b, c, d, e, f)  // Read radar entry in lis file
set_pos(a, b, c)              // set position
set_callsign(a)               // set callsign
set_type(a)                   // set type
```

```
set_holdfix(a)              // set holding fix
set_status(a)               // set aircraft status as ARR DEP or OVFL
set_WR1_control(a)          // set WR1 control status as INIT, CONTROL
                            // or HANDOVER
set_cl_fix(a)               // set cleared fix (parameter type: Waypoint)
set_cl_level(a)             // set cleared flight level
set_cl_rocd(a)              // set cleared rate of climb / descent
set_cl_heading(a)           // set cleared heading
set_cl_ias(a)               // set cleared indicated airspeed
set_lat_state(a)            // set lateral status as TOFIX, HEADING,
                            // CIRCLE, or HOLD
get_callsign()              // get callsign
get_type()                  // get aircraft type
get_rocd()                  // get rate of climb / descent
get_holdfix()               // get holding fix
get_ias()                   // get indicated airspeed
get_tas()                   // get true airspeed
get_heading()               // get heading
get_pos()                   // get current position, type: Position
get_status()                // get aircraft status
get_sector()                // get sector
get_WR1_control()           // get WR1 control status
get_lat_state()             // get lateral status
get_cl_fix()                // get cleared fix, type: Waypoint
get_cl_level()              // get cleared flight level
get_cl_ias()                // get cleared indicated airspeed
get_cl_heading()            // get cleared heading
get_cl_rocd()               // get cleared rate of climb /descent
distance_to(P)              // get distance to Waypoint P
bearing_to(P)               // get bearing to Waypoint P
print_all()                 // print all aircraft parameters to standard output
protocol_all(prot)          // print all aircraft parameters to protocol file stream prot
get_future_level(t, step)   // estimate flight level at time simtime + t
                            // calculation resolution is step seconds
get_future_gs (t, step)     // estimate ground speed at time simtime + t
get_future_pos (t, step)    // estimate position at time simtime + t, type: Position
get_prec_ac_num()           // get the number of aircraft ahead of this aircraft
```

C.2 AirCont

Class	**AirCont**
Parent Classes	-

Properties

elem	// elements, type: references to objects of type Aircraft
size	// size of the container, should be greater than number of aircraft in // the container, otherwise it must be resized
num	// number of aircraft in the container

Functions:

AirCont()	// default-constructor
AirCont(i)	// constructor for size i
resize(i)	// resize the container to new size i
add(A)	// add aircraft A to the container, type: Aircraft reference
remove(a)	// remove aircraft with callsign a from the container
print()	// print the elements of the container to standard output
find(a)	// search for the element with the callsign a
get_num()	// get the number of elements in the container
get(i)	// get element number i of the container // type: Aircraft reference
update(a)	// updating the container in sector a
update(a, b)	// updating the container in sector a with aircraft of status b

C.3 Clearance

Class	**Clearance**
Parent Classes	-

Properties

type	// clearance type
parameter	// clearance parameter
probability	// clearance probability as estimated by CCM (0,1, or 2)

Functions:

Clearance()	// default-constructor
Clearance(a, b, c)	// default-constructor with type, parameter, and probability
set_type(a)	// set clearance type
set_parameter(a)	// set parameter
set_ probability(a)	// set probability
set(a, b, c)	// set type, parameter, and probability
get_type(a)	// get clearance type
get_parameter(a)	// get parameter
get_ probability(a)	// get probability
print()	// print clearance to standard output
protocol_all(prot)	// print clearance to protocol file stream prot

C.4 ClearCont

Class **ClearCont**

Parent Classes -

Properties

```
elem                // elements, type: references to objects of type Clearance
size                // size of the container, should be greater than number of
                    // clearances in the container, otherwise it must be resized
num                 // number of clearances in the container
```

Functions:

```
ClearCont()                 // default-constructor
ClearCont(i)                // constructor for size i
resize(i)                   // resize the container to new size i
shrink(i)                   // shrinks the container to newsize, possibly smaller than
                            // old size; objects may be removed
add(C)                      // add clearance C to the container, type: Clearance reference
empty()                     // empty the container
remove(i)                   // remove clearance number i from the container
lookup_propability(C)       // get the probability of a clearance when in the container
                            // else return -1, type: Clearance reference
initialize()                // initialize the container
reset()                     // reset all probabilities to zero
print()                     // print the elements of the container to standard output
protocol(prot)              // print elements of the container to protocol file stream prot
find(a, b)                  // find the clearance which corresponds to type a and
                            // parameter b, type: Clearance reference
                            // and return it's number
get_num()                   // get the number of elements in the container
get(i)                      // get element number i of the container
update(a)                   // updating the container with clearances of a probability
                            // greater or equal a
```

C.5 Position

Class **Position**

Parent Classes -

Properties

```
x_pos               // coordinate in x-axis
y_pos               // coordinate in y-axis
level               // flight level
last_x_pos          // last coordinate in x-axis
last_y_pos          // last coordinate in y-axis
```

Functions:

```
Position()                  // default-constructor
Position(a, b, c)           // default-constructor with x- and y-position and flight level
set_x_pos(A, B)             // set x-position calculated from Latitude A and Longitude B
set_y_pos(A)                // set y-position calculated from Latitude A
```

set_x_pos(a)	// set x-position to a
set_y_pos(a)	// set y-position to a
set_ level(a)	// set flight level
get_x_pos()	// get x-position
get_y_pos()	// get y-position
get_ level()	// get flight level
get_distance_to(a, b)	// get (lateral) distance to point with coordinates x and y
get_ bearing _to(a, b)	// get bearing to point with coordinates x and y
print()	// print current position to standard output
protocol_pos(prot)	// print current position to protocol file stream prot

C.6 Waypoint

Class	**Waypoint**
Parent Classes	Position

Properties

name	// waypoint designator in 3-letter code

Functions:

Waypoint()	// default-constructor
Waypoint(a, b, c)	// default-constructor with name and x- and y-position
read(A, B, C)	// assign name A and position calculated from Latitude B // and Longitude C to waypoint
get_name()	// get waypoint designator
print()	// print waypoint designator and position to standard output

C.7 Flightplan

Class	**Flightplan**
Parent Classes	-

Properties

fplan_fix[11]	// array of fixes that describe the route, type: Waypoint

Functions:

Flightplan ()	// default-constructor
set_fplan_fix (i, A)	// assign waypoint A to fplan_fix[i]
get_fplan_fix (i)	// get fplan_fix[i], type: Waypoint
print()	// print flight plan to standard output
prot_flplan (prot)	// print flight plan to protocol file stream prot

Appendix D: Production Rules

APPENDIX D.1: PRODUCTION RULES - POSSIBLE CLEARANCES

D.1.1 TURN TO HEADING, LEFT / RIGHT TURN TO HEADING

In steps of 10 degrees
next left heading: next heading to the left in steps of 10 degrees
reverse left heading: next heading to the left in steps of 10 degrees minus 170 degrees
a case distinction is required whether north is in this range or not

IF	type of clearance equals "LEFT TURN TO HEADING"
	AND next left heading is less than reverse left heading
	AND ((parameter of clearance is greater than zero
	AND parameter of clearance is less or equal next left heading)
	OR parameter of clearance is greater or equal reverse left heading)
THEN	set weight of clearance to 1

IF	type of clearance equals "LEFT TURN TO HEADING"
	AND next left heading is greater than reverse left heading
	AND parameter of clearance is greater or equal reverse left heading
	AND parameter of clearance is less or equal next left heading
THEN	set weight of clearance to 1

In steps of 10 degrees
next right heading: next heading to the right in steps of 10 degrees
reverse right heading: next heading to the right in steps of 10 degrees plus 170 degrees
a case distinction is required whether north is in this range or not

IF	type of clearance equals "RIGHT TURN TO HEADING"
	AND next right heading is greater than reverse right heading
	AND ((parameter of clearance is greater than zero
	AND parameter of clearance is less or equal reverse right heading)
	OR parameter of clearance is greater or equal next right heading)
THEN	set weight of clearance to 1

IF	type of clearance equals "RIGHT TURN TO HEADING"
	AND next right heading is less than reverse right heading
	AND parameter of clearance is greater or equal next right heading
	AND parameter of clearance is less or equal reverse right heading
THEN	set weight of clearance to 1

In steps of 10 degrees for a heading between 0 and 360 degrees

IF	type of clearance equals " TURN TO HEADING"
	AND parameter of clearance is greater than zero
	AND parameter of clearance is less or equal 360
THEN	set weight of clearance to 1

D.1.2 TURN LEFT /RIGHT BY DEGREES

In steps of 10 degrees for a heading increment between 10 and 90 degrees

IF	type of clearance equals " TURN LEFT BY DEGREES" AND parameter of clearance is greater than zero AND parameter of clearance is less or equal 90
THEN	set weight of clearance to 1

In steps of 10 degrees for a heading increment between 10 and 90 degrees

IF	type of clearance equals " TURN RIGHT BY DEGREES" AND parameter of clearance is greater than zero AND parameter of clearance is less or equal 90
THEN	set weight of clearance to 1

D.1.3 PROCEED DIRECT TO

Possible for any waypoint in the airspace

IF	type of clearance equals "PROCEED DIRECT TO" AND parameter of clearance is waypoint in the airspace
THEN	set weight of clearance to 1

D.1.4 CLEARED SPEED, REDUCE / INCREASE SPEED

In steps of 10 degrees
advised speed must be greater or equal to the minimum airspeed of the aircraft type and less than the present speed

IF	type of clearance equals "REDUCE IAS" AND parameter of clearance is less than airspeed of aircraft AND parameter of clearance is greater or equal minimum airspeed of aircraft type of aircraft
THEN	set weight of clearance to 1

In steps of 10 degrees
advised speed must be greater than the present speed and less or equal to the maximum speed of the aircraft type

IF	type of clearance equals "INCREASE IAS" AND parameter of clearance is less or equal maximum airspeed of aircraft type of aircraft AND parameter of clearance is greater than airspeed of aircraft
THEN	set weight of clearance to 1

In steps of 10 degrees
advised speed must be at least the minimum airspeed of the aircraft type and less or equal to the maximum speed of the aircraft type

IF	type of clearance equals "CLEARED IAS" AND parameter of clearance is greater or equal minimum airspeed of aircraft type of aircraft AND parameter of clearance is less or equal maximum airspeed of aircraft type of aircraft
THEN	set weight of clearance to 1

D.1.5 CLEARED FLIGHT LEVEL, CLIMB / DESCEND TO FLIGHT LEVEL, STOP CLIMB / DESCEND AT FLIGHT LEVEL

In steps of 10 degrees
maximum descent level: next flight level below the present flight level in steps of 10

IF	type of clearance equals "DESCEND FL" AND parameter of clearance is less or equal maximum descent level
THEN	set weight of clearance to 1

A descent to a cleared flight level must have been issued in the past and the clearance parameter must be greater than the cleared flight level and less or equal to the present flight level

IF	type of clearance equals "STOP DESCENT FL" AND cleared flight level has been advised AND parameter of clearance is less or equal present flight level AND parameter of clearance is greater than cleared flight level
THEN	set weight of clearance to 1

minimum climb level: next flight level above the present flight level in steps of 10

IF	type of clearance equals "CLIMB FL" AND parameter of clearance is greater or equal minimum climb level
THEN	set weight of clearance to 1

presupposition: a climb to a cleared flight level has been issued in the past
parameter must be greater or equal to the present flight level and less than the cleared flight level

IF	type of clearance equals "STOP DESCENT FL" AND cleared flight level has been advised AND parameter of clearance is greater or equal present flight level AND parameter of clearance is less than cleared flight level
THEN	set weight of clearance to 1

maximum descent level: next flight level below the present flight level that can be divided by 10
minimum climb level: next flight level above the present flight level that can be divided by 10

IF	type of clearance equals "CLEARED FL" AND (parameter of clearance is less or equal maximum descent level OR parameter of clearance is greater or equal minimum climb level)
THEN	set weight of clearance to 1

D.1.6 RATE OF CLIMB /DESCENT

In steps of 500 feet per minute; a rate of climb may be advised if a climb has been advised, i.e. the cleared flight level is above the present flight level; it may also be advised if the aircraft is in a climb for whichever reasons

IF	type of clearance equals "RATE OF CLIMB" AND ((cleared flight level has been advised AND present flight level is less than cleared flight level) OR present rate of climb/descent is greater than zero)
THEN	set weight of clearance to 1

A rate of descent may be advised if a descent has been advised, i.e. the cleared flight level is below the present flight level; it may also be advised if the aircraft is in a descent for whichever reasons

IF	type of clearance equals "RATE OF DESCENT" AND ((cleared flight level has been advised AND present flight level is greater than cleared flight level) OR present rate of climb/descent is less than zero)
THEN	set weight of clearance to 1

D.1.7 MAINTAIN

A clearance to maintain the present heading, indicated airspeed, or flight level can be advised at any time; a clearance to maintain the rate of climb/descent can be advised if the aircraft is in a climb/descent

IF	type of clearance equals "MAINTAIN HEADING"
THEN	set weight of clearance to 1
IF	type of clearance equals "MAINTAIN IAS"
THEN	set weight of clearance to 1

IF	type of clearance equals "MAINTAIN FL"
THEN	set weight of clearance to 1

IF	type of clearance equals " MAINTAIN RATE OF CLIMB " AND present rate of climb/descent is greater than zero
THEN	set weight of clearance to 1

IF	type of clearance equals " MAINTAIN RATE OF DESCENT " AND present rate of climb/descent is less than zero
THEN	set weight of clearance to 1

D.1.8 HANDOVER

Arrival traffic may be instructed to contact the arrival sector when less than 25 miles west of handover position (waypoint RUD)

IF	type of clearance equals "CONTACT ARRIVAL" AND status of aircraft is ”ARRIVAL” AND x position of aircraft minus x position of waypoint RUD is less or equal minus 25 NM
THEN	set weight of clearance to 1

Overflight traffic may be instructed to contact the adjacent radar sector at any point

IF	type of clearance equals "CONTACT RADAR" AND status of aircraft is ”OVERFLIGHT”
THEN	set weight of clearance to 1

D.1.9 RESPONSE TO INIT CALL

Aircraft may be welcome in the sector provided their WR1 control status is ”INIT”, i.e. the aircraft has issued an init call but has not yet been assumed by the ATCO

IF	type of clearance equals "INIT CALL" AND WR1 control status of aircraft is ”INIT”
THEN	set weight of clearance to 1

D.1.10 DISREGARD

A clearance to disregard an earlier clearance may be issued at any time, provided the aircraft’s WR1 control status is ”CONTROL”, i.e. the aircraft has been assumed and is controlled by by the ATCO

IF	type of clearance equals "DISREGARD" AND WR1 control status of aircraft is ”CONTROL”
THEN	set weight of clearance to 1

D.1.11 CIRCLE

A clearance to circle at the present position may be issued at any time; the aircraft may be advised to circle to the left (360L) or to the right (360R)

IF	type of clearance equals "360L"
THEN	set weight of clearance to 1

IF	type of clearance equals "360R"
THEN	set weight of clearance to 1

D.1.12 HOLD

A clearance to enter a holding pattern at the waypoint Rüdesheim (RUD) may be advised if the aircraft is west of RUD; holdings patterns in WR1 are only published for waypoint RUD

IF	type of clearance equals "HOLD" AND name of holding fix is ”RUD” AND x position of aircraft is less than x position of waypoint RUD
THEN	set weight of clearance to 1

D.1.13 REPORT STATE

A clearance to report the present heading, indicated airspeed, or flight level can be advised at any time; a clearance to report the present rate of climb/descent can be advised if the aircraft is in a climb/descent

IF	type of clearance equals "REPORT HEADING"
THEN	set weight of clearance to 1

IF	type of clearance equals " REPORT IAS"
THEN	set weight of clearance to 1

IF	type of clearance equals " REPORT FL"
THEN	set weight of clearance to 1

IF	type of clearance equals " REPORT RATE OF CLIMB " AND present rate of climb/descent is greater than zero
THEN	set weight of clearance to 1

IF	type of clearance equals " REPORT RATE OF DESCENT " AND present rate of climb/descent is less than zero
THEN	set weight of clearance to 1

APPENDIX D.2: PRODUCTION RULES - PROBABLE CLEARANCES

ARRIVAL TRAFFIC

D.2.1 TURN TO HEADING, LEFT / RIGHT TURN TO HEADING

In steps of 10 degrees
If Aircraft flies inbound Nattenheim (NTM) it may be turned left to a heading between 090 and 130

IF	(type of clearance equals "LEFT TURN TO HEADING"
	OR type of clearance equals "TURN TO HEADING")
	AND status of aircraft equals "ARRIVAL"
	AND lateral status of aircraft equals "TOFIX"
	AND next waypoint of flightplan of aircraft equals "NTM"
	AND parameter of clearance is greater or equal 090
	AND parameter of clearance is less or equal 130
THEN	set weight of clearance to 2

If Aircraft flies inbound Nattenheim (NTM) and is maximum 15 miles from NTM, it wouldn't enter the military area TRA ED R 204 when cleared to turn left to a heading between 70 and 90

IF	(type of clearance equals "LEFT TURN TO HEADING"
	OR type of clearance equals "TURN TO HEADING")
	AND lateral status of aircraft equals "TOFIX"
	AND status of aircraft equals "ARRIVAL"
	AND next waypoint of flightplan of aircraft equals "NTM"
	AND distance to next waypoint of flightplan of aircraft is less or equal 15 NM
	AND parameter of clearance is greater or equal 070
	AND parameter of clearance is less or equal 090
THEN	set weight of clearance to 2

If Aircraft flies somewhere inbound NTM although it is not cleared to NTM which means that it's x-position is less than -50[30] and it's heading between 85 and 185 it may be cleared to turn left to a heading between 70 and 90

IF	(type of clearance equals "LEFT TURN TO HEADING"
	OR type of clearance equals "TURN TO HEADING")
	AND status of aircraft equals "ARRIVAL"
	AND x_position of aircraft is less or equal minus 50 NM
	AND heading of aircraft is greater or equal 085
	AND heading of aircraft is less or equal 185
	AND parameter of clearance is greater or equal 070
	AND parameter of clearance is less or equal 090
THEN	set weight of clearance to 2

If Aircraft flies inbound Rüdesheim (RUD) or Frankfurt (FFM) and is maximum 40 miles from RUD it may be turned in a linear holding left to headings 40, 50, 60, or 70

IF	(type of clearance equals "LEFT TURN TO HEADING"
	OR type of clearance equals "TURN TO HEADING")
	AND status of aircraft equals "ARRIVAL"
	AND lateral status of aircraft equals "TOFIX"
	AND (next waypoint of flightplan of aircraft equals "RUD"
	OR next waypoint of flightplan of aircraft equals "FFM")
	AND x_position of aircraft is greater or equal minus 40 NM
	AND parameter of clearance is greater of equal 040
	AND parameter of clearance is less or equal 070
THEN	set weight of clearance to 2

[30] The coordinate system originates in waypoint Rüdesheim (RUD).

If the aircraft flies inbound Rüdesheim (RUD) or Frankfurt (FFM) and is maximum 40 miles from RUD it may be turned in a linear holding right to headings 110, 120, 130, or 140

IF	(type of clearance equals "RIGHT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "ARRIVAL" AND lateral status of aircraft equals "TOFIX" AND (next waypoint of flightplan of aircraft equals "RUD" OR next waypoint of flightplan of aircraft equals "FFM") AND x_position of aircraft is greater or equal minus 40 NM AND parameter of clearance is greater or equal 110 AND parameter of clearance is less or equal 140
THEN	set weight of clearance to 2

If the aircraft flies in lateral state ”HEADING” and the cleared heading is 90...140 i.e. the aircraft is in a linear holding, it may be turned back to heading 30, 40, 50, 60, 70 or 90

IF	(type of clearance equals "LEFT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "ARRIVAL" AND lateral status of aircraft equals "HEADING" AND cleared heading of aircraft is greater or equal 090 AND cleared heading of aircraft is less or equal 140 AND x_position of aircraft is greater or equal minus 60 NM AND ((parameter of clearance is greater or equal 030 AND parameter of clearance is less or equal 070) OR parameter of clearance is equal 090)
THEN	set weight of clearance to 2

If the aircraft flies in lateral state ”HEADING” and the cleared heading is 40...90 i.e. the aircraft is in a linear holding, it may be turned back to heading 110, 120, 130, or 140 or 90

IF	(type of clearance equals "RIGHT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "ARRIVAL" AND lateral status of aircraft equals "HEADING" AND cleared heading of aircraft is greater or equal 090 AND cleared heading of aircraft is less or equal 140 AND x_position of aircraft is greater or equal minus 60 NM AND ((parameter of clearance is greater or equal 110 AND parameter of clearance is less or equal 140) OR parameter of clearance is equal 090)
THEN	set weight of clearance to 2

If the aircraft is less than 10 miles from Rüdesheim (RUD) it may be cleared to heading 90; if the aircraft’s present heading is greater or equal 90 this would be a left turn

IF	(type of clearance equals "LEFT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "ARRIVAL" AND cleared heading of aircraft is greater or equal 090 AND x_position of aircraft is greater or equal minus 10 NM AND parameter of clearance is equal 090
THEN	set weight of clearance to 2

If the aircraft is less than 10 miles from Rüdesheim (RUD) it may be cleared to heading 90; if the aircraft's present heading is less or equal 90 this would be a right turn

IF	(type of clearance equals "RIGHT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "ARRIVAL" AND cleared heading of aircraft is less or equal 090 AND x_position of aircraft is greater or equal minus 10 NM AND parameter of clearance is equal 090
THEN	set weight of clearance to 2

If the aircraft is west of Rüdesheim (RUD) it may be cleared to a heading matching the bearing to RUD roughly; if the actual heading is greater than the bearing to RUD this would be a left turn

IF	(type of clearance equals "LEFT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is less than x_position of waypoint RUD AND heading of aircraft is greater than bearing of aircraft to waypoint RUD AND absolute value of (parameter of clearance minus bearing of aircraft to waypoint RUD) is less or equal 10
THEN	set weight of clearance to 2

If the aircraft is west of Rüdesheim (RUD) it may be cleared to a heading matching the bearing to RUD roughly; if the actual heading is less than the bearing to RUD this would be a right turn

IF	(type of clearance equals "RIGHT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is less than x_position of waypoint RUD AND heading of aircraft is less than bearing of aircraft to waypoint RUD AND absolute value of (parameter of clearance minus bearing of aircraft to waypoint RUD) is less or equal 10
THEN	set weight of clearance to 2

D.2.2 TURN LEFT / RIGHT BY DEGREES

In steps of 10 degrees; west of Nattenheim (NTM) the aircraft may be cleared to turn left by 10 to 40 degrees

IF	type of clearance equals "TURN LEFT BY DEGREES" AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is less than x_position of waypoint NTM AND parameter of clearance is less or equal 40
THEN	set weight of clearance to 2

In steps of 10 degrees; west of Nattenheim (NTM) the aircraft may be cleared to turn right by 10 to 20 degrees

IF	type of clearance equals "TURN RIGHT BY DEGREES" AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is less than x_position of waypoint NTM AND parameter of clearance is less or equal 20
THEN	set weight of clearance to 2

In steps of 10 degrees; east of Nattenheim (NTM) the aircraft may be cleared to turn left by 10 to 50 degrees

IF	type of clearance equals "TURN LEFT BY DEGREES" AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is greater or equal x_position of waypoint NTM AND parameter of clearance is less or equal 50
THEN	set weight of clearance to 2

In steps of 10 degrees; east of Nattenheim (NTM) the aircraft may be cleared to turn right by 10 to 50 degrees

IF	type of clearance equals "TURN RIGHT BY DEGREES" AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is greater or equal x_position of waypoint NTM AND parameter of clearance is less or equal 50
THEN	set weight of clearance to 2

D.2.3 PROCEED DIRECT TO

If the aircraft flies inbound Nattenheim (NTM) in lateral status ”TOFIX” it may be cleared to proceed direct to Rüdesheim (RUD); attention must be paid to the fact that the aircraft must not enter into the military area TRA ED R 204; the clearance may therefore only be applied when the aircraft is 15 NM from NTM or less

IF	type of clearance equals "DIRECT TO" AND status of aircraft equals "ARRIVAL" AND x position of aircraft is less or equal to x position of waypoint "NTM" AND distance of aircraft to waypoint "NTM" is less or equal 15 NM AND lateral status of aircraft equals "TOFIX" AND next but one waypoint of flightplan of aircraft equals "RUD" AND parameter of clearance equals "RUD"
THEN	set weight of clearance to 2

If the aircraft flies west of Rüdesheim (RUD) in lateral status ”HEADING” it may be cleared to proceed direct to RUD

IF	type of clearance equals "DIRECT TO" AND status of aircraft equals "ARRIVAL" AND lateral status of aircraft equals "HEADING" AND parameter of clearance equals "RUD"
THEN	set weight of clearance to 2

If the aircraft flies direct to Rüdesheim (RUD) or Frankfurt (FFM) in lateral status ”TOFIX” it may be cleared to proceed direct to RUD again

IF	type of clearance equals "DIRECT TO" AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is less or equal 3 NM AND lateral status of aircraft equals "TOFIX" AND (cleared fix of aircraft equals "RUD" OR cleared fix of aircraft equals "FFM") AND parameter of clearance equals "RUD"
THEN	set weight of clearance to 2

If the aircraft flies west of Rüdesheim (RUD) in lateral status ”CIRCLE” it may be cleared to proceed direct to RUD again

IF	type of clearance equals "DIRECT TO" AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is less or equal 0 NM AND lateral status of aircraft equals "CIRCLE" AND parameter of clearance equals "RUD"
THEN	set weight of clearance to 2

If the aircraft flies in lateral status ”TOFIX” or in lateral status ”HEADING” it may be cleared to proceed direct to Frankfurt (FFM)

IF	type of clearance equals "DIRECT TO"
	AND status of aircraft equals "ARRIVAL"
	AND (lateral status of aircraft equals "TOFIX"
	OR lateral status of aircraft equals "HEADING")
	AND parameter of clearance equals "FFM"
THEN	set weight of clearance to 2

If the aircraft flies west of Rüdesheim (RUD) in lateral status ”CIRCLE” or in lateral status ”HOLDING” it may be cleared to proceed direct to Frankfurt (FFM)

IF	type of clearance equals "DIRECT TO"
	AND status of aircraft equals "ARRIVAL"
	AND x-position of aircraft is less or equal 5 NM
	AND (lateral status of aircraft equals "CIRCLE"
	OR lateral status of aircraft equals "HOLDING")
	AND parameter of clearance equals "FFM"
THEN	set weight of clearance to 2

D.2.4 CLEARED SPEED, REDUCE / INCREASE SPEED

Arrival traffic is slowed down when approaching; the most frequent clearances are 210, 220, 250, 270 knots indicated airspeed (IAS); the clearance parameter must be less than the present speed and the cleared speed; tolerance is 10 knots and the cleared speed mustn't be more than 70 knots below the current speed; if the Aircraft is west of NTM, speed reductions may range from 300 to 220

IF	(type of clearance equals "REDUCE IAS"
	OR type of clearance equals "CLEARED IAS")
	AND status of aircraft equals "ARRIVAL"
	AND parameter of clearance is less than airspeed of aircraft plus 10 knots
	AND airspeed of aircraft minus parameter of clearance is less or equal 70 knots
	AND x_position of aircraft is less or equal minus 55 NM
	AND parameter of clearance is less or equal 300 knots
	AND parameter of clearance is greater or equal 220 knots
THEN	set weight of clearance to 2

If the Aircraft is east of NTM, but at least 25 miles west of RUD, speed reductions may range from 300 to 210

IF	(type of clearance equals "REDUCE IAS"
	OR type of clearance equals "CLEARED IAS")
	AND status of aircraft equals "ARRIVAL"
	AND parameter of clearance is less than airspeed of aircraft plus 10 knots
	AND airspeed of aircraft minus parameter of clearance is less or equal 70 knots
	AND x_position of aircraft is greater or equal minus 55 NM
	AND x_position of aircraft is less or equal minus 25 NM
	AND parameter of clearance is less or equal 300 knots
	AND parameter of clearance is greater or equal 210 knots
THEN	set weight of clearance to 2

If the aircraft is less than 25 miles west of RUD, speed reductions may range from 300 to 200

```
IF      (type of clearance equals "REDUCE IAS"
            OR type of clearance equals "CLEARED IAS")
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is less than airspeed of aircraft plus 10 knots
        AND airspeed of aircraft minus parameter of clearance is less or equal 70 knots
        AND x_position of aircraft is greater or equal minus 25 NM
        AND parameter of clearance is less or equal 300 knots
        AND parameter of clearance is greater or equal 200 knots
THEN    set weight of clearance to 2
```

Arrival traffic may also be cleared to increase the indicated airspeed; the parameter must be greater than the present speed and the cleared speed; speed tolerance is 10 knots; increase speed clearances are only feasible if the present speed is less than 300 knots; maximum cleared speed mustn't be more than 50 knots greater than the current speed and it must be greater than 200

```
IF      (type of clearance equals " INCREASE IAS "
            OR type of clearance equals "CLEARED IAS")
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is greater than airspeed of aircraft minus 10 knots
        AND ((aircraft has received speed clearance
            AND parameter of clearance is greater than cleared speed of aircraft)
            OR aircraft has not received speed clearance)
        AND airspeed of aircraft is less or equal 300 knots
        AND parameter of clearance is less or equal maximum airspeed of aircraft type of aircraft
        AND parameter of clearance is greater or equal 200 knots
        AND parameter of clearance minus airspeed of aircraft is less or equal 50 knots
THEN    set weight of clearance to 2
```

D.2.5 CLEARED FLIGHT LEVEL, CLIMB / DESCEND TO FLIGHT LEVEL, STOP CLIMB / DESCENT AT FLIGHT LEVEL

If the flag ALLOW_DESCEND_ALL_FL is set to TRUE, a descend to all flight levels below FL_MAX_DESC (as defined in ccm.h, presently 160) is considered probable; the purpose of this is to overcome the long compilation time of the newly generated syntax

```
IF      (type of clearance equals "DESCEND FL"
            OR type of clearance equals "CLEARED FL")
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is less than flight level of aircraft
        AND ((aircraft has received flight level clearance
            AND parameter of clearance is less or equal cleared flight level of aircraft)
            OR aircraft has not received flight level clearance)
        AND parameter of clearance is less or equal maximum descent level
THEN    set weight of clearance to 2
```

If the flag ALLOW_DESCEND_ALL_FL is set to TRUE, a clearance to stop the descent at any flight level between the cleared flight level and either the present level or FL_MAX_DESC is considered probable

```
IF      type of clearance equals "STOP DESCENT FL"
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is less or equal flight level of aircraft plus 5
        AND parameter of clearance is less or equal maximum descent level
        AND ((aircraft has received flight level clearance
            AND parameter of clearance is greater than cleared flight level of aircraft)
            OR aircraft has not received flight level clearance)
THEN    set weight of clearance to 2
```

If the aircraft is less than 40 NM from RUD it may be advised to descend to flight level 70 or 80 provided no other aircraft has been cleared to the respective flight level

```
IF      (type of clearance equals "DESCEND FL"
            OR type of clearance equals "CLEARED FL")
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is less than flight level of aircraft
        AND ((aircraft has received flight level clearance
            AND parameter of clearance is less or equal cleared flight level of aircraft)
            OR aircraft has not received flight level clearance)
        AND x_position of aircraft is greater or equal minus 40 NM
        AND ((parameter of clearance is equal 70
            AND no other aircraft has been cleared to flight level 70)
            OR (parameter of clearance is equal 80
            AND no other aircraft has been cleared to flight level 80))
THEN    set weight of clearance to 2
```

If no other aircraft has been cleared to flight level 90 it is likely that the arrival aircraft will be cleared to 90

```
IF      (type of clearance equals "DESCEND FL"
            OR type of clearance equals "CLEARED FL")
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is less than flight level of aircraft
        AND ((aircraft has received flight level clearance
            AND parameter of clearance is less or equal cleared flight level of aircraft)
            OR aircraft has not received flight level clearance)
        AND parameter of clearance is equal 90
        AND no other aircraft has been cleared to flight level 90
THEN    set weight of clearance to 2
```

The aircraft may be cleared to flight level 100 even if no other aircraft has been cleared to flight level 90 in order to avoid VFR traffic below flight level 100

```
IF      (type of clearance equals "DESCEND FL"
            OR type of clearance equals "CLEARED FL")
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is less than flight level of aircraft
        AND ((aircraft has received flight level clearance
            AND parameter of clearance is less or equal cleared flight level of aircraft)
            OR aircraft has not received flight level clearance)
        AND parameter of clearance is equal 100
        AND no other aircraft has been cleared to flight level 100
THEN    set weight of clearance to 2
```

If one level is occupied by other traffic, the descending aircraft will most likely be cleared to the lowest free level

```
FOR(INT i=100; i<240; i+10)
  IF    (type of clearance equals "DESCEND FL"
            OR type of clearance equals "CLEARED FL")
        AND status of aircraft equals "ARRIVAL"
        AND parameter of clearance is less than flight level of aircraft
        AND ((aircraft has received flight level clearance
            AND parameter of clearance is less or equal cleared flight level of aircraft)
            OR aircraft has not received flight level clearance)
        AND parameter of clearance is equal i plus 10
        AND another aircraft has been cleared to flight level i
        AND no other aircraft has been cleared to flight level i plus 10
  THEN  Set weight of clearance to 2; CONTINUE
```

However, if the preceding aircraft is less than 10 NM ahead and flies in a level within a 2500 feet range of the level under consideration a descent clearance may be given in order to avoid that the trailing aircraft gets too close to the leading aircraft

```
IF        (type of clearance equals "DESCEND FL"
                OR type of clearance equals "CLEARED FL")
          AND status of aircraft equals "ARRIVAL"
          AND parameter of clearance is less than flight level of aircraft
          AND ((aircraft has received flight level clearance
                AND parameter of clearance is less or equal cleared flight level of aircraft)
                OR aircraft has not received flight level clearance)
          AND distance of aircraft to trailing aircraft is less or equal 10 NM
          AND parameter of clearance minus flight level of next aircraft ahead of aircraft is less or
          equal 25
THEN      set weight of clearance to 2
```

The aircraft may be cleared to descend to a flight level between 70 and 240 even if another aircraft has been cleared to the same level, provided that the required separations are met
LATSEP: required lateral separation, currently 6 NM
ALTSEP: required vertical separation, currently 10 flight levels

```
FOR(INT i=100; i<240; i+10)
  IF      (type of clearance equals "DESCEND FL"
                OR type of clearance equals "CLEARED FL")
          AND status of aircraft equals "ARRIVAL"
          AND parameter of clearance is less than flight level of aircraft
          AND ((aircraft has received flight level clearance
                AND parameter of clearance is less or equal cleared flight level of aircraft)
                OR aircraft has not received flight level clearance)
          AND parameter of clearance is equal i
          AND another aircraft x has been cleared to flight level i
          AND aircraft x is in sector WR1
          AND (lateral distance of aircraft to aircraft x is greater than LATSEP
                OR vertical distance aircraft to aircraft x is greater than ALTSEP)
  THEN    set weight of clearance to 2
CONTINUE
```

A clearance to stop the descent is probable if a conflict to the preceding aircraft may arise (say the distance is less than 20 miles and the preceding aircraft is cleared to or flies in a level equal or above the cleared level of the aircraft); the level to stop the descent should be in the range of +- 10 flight levels of the present flight level of the preceding aircraft or it's cleared flight level plus 10

IF	(type of clearance equals "STOP DESCEND FL " OR type of clearance equals "CLEARED FL") AND status of aircraft equals "ARRIVAL" AND parameter of clearance is less than flight level of aircraft AND aircraft has received flight level clearance AND parameter of clearance is greater than cleared flight level of aircraft AND there is a trailing aircraft AND trailing aircraft has been cleared to a flight level AND distance of aircraft to trailing aircraft is less than 20 NM AND cleared flight level of aircraft is less than flight level of trailing aircraft AND parameter of clearance is less or equal flight level of trailing aircraft plus 20 AND (present flight level of aircraft is greater than cleared flight level of trailing aircraft OR present flight level of aircraft is greater than present flight level of trailing aircraft) AND ((parameter of clearance is greater or equal cleared flight level of trailing aircraft AND parameter of clearance is less or equal cleared flight level of trailing aircraft plus 20) OR (parameter of clearance is less or equal flight level of trailing aircraft plus 20 AND parameter of clearance is greater or equal flight level of trailing aircraft minus 20))
THEN	set weight of clearance to 2

D.2.6 RATE OF CLIMB / DESCENT

In steps of 500 feet per minute; if a descent has been advised, i.e. a cleared flight level exists which is below the present flight level, a descent rate between 1000 and 4000 feet per minute may be advised

IF	type of clearance equals "RATE OF DESCENT " AND status of aircraft equals "ARRIVAL" AND cleared flight level has been advised AND cleared flight level is less than present flight level AND parameter of clearance is greater or equal 1000 AND parameter of clearance is less or equal 4000
THEN	set weight of clearance to 2

D.2.7 MAINTAIN

A clearance to maintain the present heading may be advised if the aircraft is in lateral state "TOFIX" or in lateral state "HEADING"

IF	type of clearance equals "MAINTAIN HEADING" AND status of aircraft equals "ARRIVAL" AND (lateral status of aircraft equals "TOFIX" OR lateral status of aircraft equals "HEADING")
THEN	set weight of clearance to 2

A clearance to maintain the present airspeed is always possible

IF	type of clearance equals "MAINTAIN IAS" AND status of aircraft equals "ARRIVAL"
THEN	set weight of clearance to 2

A clearance to maintain the present flight level is always possible

IF	type of clearance equals "MAINTAIN FL" AND status of aircraft equals "ARRIVAL"
THEN	set weight of clearance to 2

A clearance to maintain the present rate of climb is possible if the aircraft is climbing

IF	type of clearance equals "MAINTAIN RATE OF CLIMB" AND status of aircraft equals "ARRIVAL" AND present rate of climb/descent is greater than zero
THEN	set weight of clearance to 2

A clearance to maintain the present rate of descent is possible if the aircraft is descending

IF	type of clearance equals "MAINTAIN RATE OF DESCENT" AND status of aircraft equals "ARRIVAL" AND present rate of climb/descent is less than zero
THEN	set weight of clearance to 2

D.2.8 HANDOVER

Arrival traffic may be instructed to contact the arrival sector when cleared to a flight level equal or below 110 and flying direct to RUD, FWF or FFM; it mustn't be more than 20 miles west of RUD

IF	type of clearance equals "CONTACT ARRIVAL" AND status of aircraft equals "ARRIVAL" AND cleared flight level of aircraft is less or equal 110 AND lateral status of aircraft equals "TOFIX" AND next waypoint in flightplan of aircraft is ”RUD” or ”FFM” or ”FWF” AND x position of aircraft minus x position of waypoint RUD is less or equal minus 20 NM
THEN	set weight of clearance to 2

Arrival traffic may be instructed to contact the arrival sector when cleared to a flight level equal or below 110 and in lateral status ”HEADING”, provided the heading is between 40 and 140; the aircraft mustn't be more than 20 miles west of RUD

IF	type of clearance equals "CONTACT ARRIVAL" AND status of aircraft equals "ARRIVAL" AND cleared flight level of aircraft is less or equal 110 AND lateral status of aircraft equals "HEADING" AND heading of aircraft is greater or equal 40 AND heading of aircraft is less or equal 140 AND x position of aircraft minus x position of waypoint RUD is less or equal minus 20 NM
THEN	set weight of clearance to 2

If the aircraft is already east of RUD, it may be advised to contact arrival in any case

IF	type of clearance equals "CONTACT ARRIVAL " AND status of aircraft equals "ARRIVAL" AND x_position of aircraft is greater or equal minus 5 NM
THEN	set weight of clearance to 2

D.2.9 RESPONSE TO INIT CALL

Aircraft may be welcome in the sector provided their WR1 control status is ”INIT”, i.e. the aircraft has issued an init call but has not yet been assumed by the ATCO

IF	type of clearance equals "INIT CALL"
	AND status of aircraft equals "ARRIVAL"
	AND WR1 control status of aircraft equals ”INIT”
THEN	set weight of clearance to 2

D.2.10 DISREGARD

A clearance to disregard an earlier clearance may be issued at any time, provided the aircraft’s WR1 control status is ”CONTROL”, i.e. the aircraft has been assumed and is controlled by the ATCO

IF	type of clearance equals "DISREGARD"
	AND status of aircraft equals "ARRIVAL"
	AND WR1 control status of aircraft equals "CONTROL"
THEN	set weight of clearance to 2

D.2.11 CIRCLE

A clearance to circle at the present position may be issued if the aircraft flies direct to cleared fix RUD maximum 55 miles inbound; the aircraft may be advised to circle to the left (360L) or to the right (360R)

IF	(type of clearance equals "360L"
	OR type of clearance equals "360R")
	AND status of aircraft equals "ARRIVAL"
	AND lateral status of aircraft equals "TOFIX"
	AND next waypoint in flightplan of aircraft is "RUD"
	AND x_position of aircraft is greater or equal minus 55 NM
	AND x_position of aircraft is less or equal 0
THEN	set weight of clearance to 2

A clearance to circle at the present position may as well be issued if the aircraft flies heading east maximum 55 miles inbound RUD; the aircraft may be advised to circle to the left (360L) or to the right (360R)

IF	(type of clearance equals "360L"
	OR type of clearance equals "360R")
	AND status of aircraft equals "ARRIVAL"
	AND lateral status of aircraft equals "HEADING"
	AND heading of aircraft is greater or equal 80
	AND heading of aircraft is less or equal 100
	AND x_position of aircraft is greater or equal minus 55 NM
	AND x_position of aircraft is less or equal 0
THEN	set weight of clearance to 2

D.2.12 HOLD

A clearance to circle at the present position may be issued if the aircraft flies direct to cleared fix RUD maximum 55 miles inbound; a holding can only be advised if the aircraft is cleared to proceed to this waypoint

IF	type of clearance equals "HOLD"
	AND status of aircraft equals "ARRIVAL"
	AND lateral status of aircraft equals "TOFIX"
	AND next waypoint in flightplan of aircraft is "RUD"
	AND x_position of aircraft is greater or equal minus 55 NM
	AND x_position of aircraft is less or equal 0
THEN	set weight of clearance to 2

D.2.13 REPORT STATE

A clearance to report the present heading or indicated airspeed can be advised at any time; a clearance to report the present rate of climb/descent can be advised if the aircraft is in a climb/descent; a clearance to report the present flight level is not probable because the ATCO sees the flight level on the radar screen

IF	type of clearance equals "REPORT HEADING" AND status of aircraft equals "ARRIVAL"
THEN	set weight of clearance to 2

IF	type of clearance equals " REPORT IAS" AND status of aircraft equals "ARRIVAL"
THEN	set weight of clearance to 2

IF	type of clearance equals "REPORT RATE OF CLIMB" AND status of aircraft equals "ARRIVAL" AND present rate of climb/descent is greater than zero
THEN	set weight of clearance to 2

IF	type of clearance equals "REPORT RATE OF DESCENT" AND status of aircraft equals "ARRIVAL" AND present rate of climb/descent is less than zero
THEN	set weight of clearance to 2

OVERFLIGHT TRAFFIC

D.2.14 TURN TO HEADING, LEFT / RIGHT TURN TO HEADING

In steps of 10 degrees; a turn to a heading roughly equal to the bearing to one of the next three fixes in the flight plan may be advised; if this heading would be greater than the present heading it would be a right turn; allow for 20 degrees difference between heading and bearing; a case distinction must be made whether the turn would be a left turn or a right turn

bearing1: bearing to next waypoint of flightplan of aircraft
bearing2: bearing to next but one waypoint of flightplan of aircraft
bearing3: bearing to next but two waypoint of flightplan of aircraft

IF	(type of clearance equals "RIGHT TURN TO HEADING" OR type of clearance equals "TURN TO HEADING") AND status of aircraft equals "OVERFLIGHT" AND ((bearing1 is greater or equal heading of aircraft AND absolute value of (parameter of clearance minus bearing1) is less or equal 20) OR (bearing2 is greater or equal heading of aircraft AND absolute value of (parameter of clearance minus bearing2) is less or equal 20) OR (bearing3 is greater or equal heading of aircraft AND absolute value of (parameter of clearance minus bearing3) is less or equal 20))
THEN	set weight of clearance to 2

IF	(type of clearance equals "LEFT TURN TO HEADING"
	OR type of clearance equals "TURN TO HEADING")
	AND status of aircraft equals "OVERFLIGHT"
	AND ((bearing1 is less or equal heading of aircraft
	AND absolute value of (parameter of clearance minus bearing1) is less or equal 20)
	OR (bearing2 is less or equal heading of aircraft
	AND absolute value of (parameter of clearance minus bearing2) is less or equal 20)
	OR (bearing3 is less or equal heading of aircraft
	AND absolute value of (parameter of clearance minus bearing3) is less or equal 20))
THEN	set weight of clearance to 2

D.2.15 TURN LEFT / RIGHT BY DEGREES

In steps of 10 degrees; the aircraft may be cleared to turn left by 10 to 40 degrees

IF	type of clearance equals "TURN LEFT BY DEGREES"
	AND status of aircraft equals “OVERFLIGHT”
	AND parameter of clearance is less or equal 40
THEN	set weight of clearance to 2

IF	type of clearance equals "TURN RIGHT BY DEGREES"
	AND status of aircraft equals “OVERFLIGHT”
	AND parameter of clearance is less or equal 40
THEN	set weight of clearance to 2

D.2.16 PROCEED DIRECT TO

If the aircraft flies in lateral status ”HEADING” it may be cleared to proceed direct to one of the next two fixes in the flightplan; in lateral status ”TOFIX” the aircraft may be cleared to proceed direct to one of the next three fixes in the flightplan

IF	type of clearance equals "DIRECT TO"
	AND status of aircraft equals “OVERFLIGHT”
	AND lateral status of aircraft equals "HEADING"
	AND (parameter of clearance equals next waypoint of flightplan of aircraft
	OR parameter of clearance equals next but one waypoint of flightplan of aircraft)
THEN	set weight of clearance to 2

IF	type of clearance equals "DIRECT TO"
	AND status of aircraft equals “OVERFLIGHT”
	AND lateral status of aircraft equals "TOFIX"
	AND (parameter of clearance equals next waypoint of flightplan of aircraft
	OR parameter of clearance equals next but one waypoint of flightplan of aircraft
	OR parameter of clearance equals next but two waypoint of flightplan of aircraft)
THEN	set weight of clearance to 2

D.2.17 CLEARED SPEED, REDUCE / INCREASE SPEED

Speeds of 250 - 270 knots are advised frequently; this may either be a speed reduction or a speed increase, depending on the aircraft's present speed

IF	(type of clearance equals "REDUCE IAS" OR type of clearance equals "CLEARED IAS") AND status of aircraft equals "OVERFLIGHT" AND parameter of clearance is less than airspeed of aircraft plus 5 knots AND parameter of clearance is greater or equal 250 knots AND parameter of clearance is less or equal 270 knots AND airspeed of aircraft minus parameter of clearance is less or equal 70 knots
THEN	set weight of clearance to 2

IF	(type of clearance equals "INCREASE IAS" OR type of clearance equals "CLEARED IAS") AND status of aircraft equals "OVERFLIGHT" AND parameter of clearance is greater than airspeed of aircraft minus 5 knots AND parameter of clearance is greater or equal 250 knots AND parameter of clearance is less or equal 270 knots AND parameter of clearance minus airspeed of aircraft is less or equal 50 knots
THEN	set weight of clearance to 2

D.2.18 CLEARED FLIGHT LEVEL, CLIMB / DESCEND TO FLIGHT LEVEL, STOP CLIMB / DESCENT AT FLIGHT LEVEL

A descent may be advised to any flight level between the present flight level and 200, provided it is smaller than the cleared flight level (if there is one)

IF	(type of clearance equals "DESCEND FL" OR type of clearance equals "CLEARED FL") AND status of aircraft equals "OVERFLIGHT" AND parameter of clearance is less than flight level of aircraft AND parameter of clearance is greater or equal 200 AND ((aircraft has received flight level clearance AND parameter of clearance is less or equal cleared flight level of aircraft) OR aircraft has not received flight level clearance)
THEN	set weight of clearance to 2

A climb may be advised to any flight level between the present flight level and 200, provided it is greater than the cleared flight level (if there is one)

IF	(type of clearance equals "CLIMB FL" OR type of clearance equals "CLEARED FL") AND status of aircraft equals "OVERFLIGHT" AND parameter of clearance is greater than flight level of aircraft AND parameter of clearance is less or equal 270 AND ((aircraft has received flight level clearance AND parameter of clearance is greater or equal cleared flight level of aircraft) OR aircraft has not received flight level clearance)
THEN	set weight of clearance to 2

D.2.19 RATE OF CLIMB / DESCENT

In steps of 500 feet per minute; if a descent has been advised, i.e. a cleared flight level exists which is below the present flight level, a descent rate between 2000 and 4000 feet per minute may be advised

IF	type of clearance equals "RATE OF DESCENT " AND status of aircraft equals “OVERFLIGHT” AND cleared flight level has been advised AND cleared flight level is less than present flight level AND parameter of clearance is greater or equal 2000 AND parameter of clearance is less or equal 4000
THEN	set weight of clearance to 2

If a climb has been advised, i.e. a cleared flight level exists which is above the present flight level, a climb rate between 1500 and 3500 feet per minute may be advised

IF	type of clearance equals "RATE OF CLIMB " AND status of aircraft equals “OVERFLIGHT” AND cleared flight level has been advised AND cleared flight level is greater than present flight level AND parameter of clearance is greater or equal 1500 AND parameter of clearance is less or equal 3500
THEN	set weight of clearance to 2

D.2.20 MAINTAIN

A clearance to maintain the present heading may be advised if the aircraft is in lateral state ”TOFIX” or in lateral state ”HEADING”

IF	type of clearance equals "MAINTAIN HEADING" AND status of aircraft equals “OVERFLIGHT” AND (lateral status of aircraft equals "TOFIX" OR lateral status of aircraft equals ”HEADING”)
THEN	set weight of clearance to 2

A clearance to maintain the present flight level is always possible

IF	type of clearance equals "MAINTAIN FL" AND status of aircraft equals “OVERFLIGHT”
THEN	set weight of clearance to 2

A clearance to maintain the present rate of climb is possible if the aircraft is climbing

IF	type of clearance equals "MAINTAIN RATE OF CLIMB" AND status of aircraft equals “OVERFLIGHT” AND present rate of climb/descent is greater than zero
THEN	set weight of clearance to 2

A clearance to maintain the present rate of descent is possible if the aircraft is descending

IF	type of clearance equals "MAINTAIN RATE OF DESCENT" AND status of aircraft equals “OVERFLIGHT” AND present rate of climb/descent is less than zero
THEN	set weight of clearance to 2

D.2.21 HANDOVER

Overflight traffic may be instructed to contact the radar sector at any point

IF	type of clearance equals "CONTACT ARRIVAL" AND status of aircraft equals "OVERFLIGHT"
THEN	set weight of clearance to 2

D.2.22 RESPONSE TO INIT CALL

Aircraft may be welcome in the sector provided their WR1 control status is ”INIT”, i.e. the aircraft has issued an init call but has not yet been assumed by the ATCO

IF	type of clearance equals "INIT CALL" AND status of aircraft equals "OVERFLIGHT" AND WR1 control status of aircraft equals ”INIT”
THEN	set weight of clearance to 2

D.2.23 DISREGARD

A clearance to disregard an earlier clearance may be issued at any time, provided the aircraft’s WR1 control status is ”CONTROL”, i.e. the aircraft has been assumed and is controlled by the ATCO

IF	type of clearance equals "DISREGARD" AND status of aircraft equals "OVERFLIGHT" AND WR1 control status of aircraft equals "CONTROL"
THEN	set weight of clearance to 2

D.2.24 REPORT STATE

A clearance to report the present heading or indicated airspeed can be advised at any time; a clearance to report the present rate of climb/descent can be advised if the aircraft is in a climb/descent; a clearance to report the present flight level is not probable because the ATCO sees the flight level on the radar screen

IF	type of clearance equals "REPORT HEADING" AND status of aircraft equals "OVERFLIGHT"
THEN	set weight of clearance to 2

IF	type of clearance equals " REPORT IAS" AND status of aircraft equals "OVERFLIGHT"
THEN	set weight of clearance to 2

IF	type of clearance equals "REPORT RATE OF CLIMB" AND status of aircraft equals "OVERFLIGHT" AND present rate of climb/descent is greater than zero
THEN	set weight of clearance to 2

IF	type of clearance equals "REPORT RATE OF DESCENT" AND status of aircraft equals "OVERFLIGHT" AND present rate of climb/descent is less than zero
THEN	set weight of clearance to 2

Appendix E: Excerpt from a Decode Log File

Test Subject: 6
Syntax: dynamic
Phraseology: ICAO standard
Traffic: 4
Starttime: Thu Jan 15 199810:42:39
...
Decode No.: 23
Simulation Time: 37365
Response Time: 9106
Recognition Confidence: 725
Decode Category: Correct
Instruction Category: Init/HO
Error Category: -
Spoken Utterance: loofthunsa 1 niner 0 5 contact frankfurt arrival 1 2 0 decimal 8
Decoded Utterance: loofthunsa 1 niner 0 5 contact frankfurt arrival 1 2 0 decimal 8

Decode No.: 24
Simulation Time: 37409
Response Time: 16155
Recognition Confidence: 605
Decode Category: Error
Instruction Category: IAS
Error Category: CE (Callsign Error)
Spoken Utterance: air fraunce 7 4 6 reduce speed to 2 5 0 knots indicated
Decoded Utterance: loofthunsa 2 0 niner reduce speed to 2 5 0 knots indicated

Decode No.: 25
Simulation Time: 37428
Response Time: 10091
Recognition Confidence: 739
Decode Category: Repeat
Instruction Category: IAS

Error Category: -

Spoken Utterance: `air fraunce 7 4 6 reduce speed to 2 5 0 knots indicated`

Decoded Utterance: `air fraunce 7 4 6 reduce speed to 2 5 0 knots indicated`

Decode No.: `26`

Simulation Time: `37446`

Response Time: `7292`

Recognition Confidence: `714`

Decode Category: `Correct`

Instruction Category: `FL`

Error Category: -

Spoken Utterance: `air fraunce 7 4 6 descend flight level niner 0`

Decoded Utterance: `air fraunce 7 4 6 descend flight level niner 0`

...

Appendix F: Questionnaire

Fragebogen zu den Versuchen an der Flugsicherungsakademie der DFS Deutschen Flugsicherung GmbH

(Questionnaire for the experiments at the air traffic control academy of the German Air Navigation Services)

Wie beurteilen Sie die Erkennungsrate des Spracherkenners ohne Unterstützung durch das Lotsenmodell?
(How do you judge the recognition rate of the ASR during simulations without the Cognitive Controller Model?)

sehr gut (very good) — sehr schlecht (very bad)

Wie beurteilen Sie die Erkennungsrate des Spracherkenners mit Unterstützung durch das Lotsenmodell?
(How do you judge the recognition rate of the ASR during simulations with the Cognitive Controller Model?)

sehr gut (very good) — sehr schlecht (very bad)

Wie beurteilen Sie die Antwortzeiten der simulierten Piloten?
(How do you judge the response times of the simulated pilots?)

sehr schnell (very quick) — sehr langsam (very slow)

Wie beurteilen Sie die Qualität der Sprachsynthese?
(How do you judge the quality of the speech synthesis?)

sehr gut (very good) — sehr schlecht (very bad)

Wie bequem lassen sich Ihrer Meinung nach Fehlerkennungen des Spracherkenners korrigieren?
(How easy is it, in your opinion, to correct misrecognitions of the speech recognizer?)

sehr gut (very good) — sehr schlecht (very bad)

Wie beurteilen Sie die Handhabung von Headset und Push-To-Talk-Button?
(How do you judge the handling of headset and push-to-talk button?)

sehr bequem (very comfortable) — sehr unbequem (very uncomfortable)

Als wie realistisch empfanden Sie Radardarstellung?
(How realistic do you judge the radar display ?)

sehr realistisch (very realistic) — sehr unrealistisch (very unrealistic)

Als wie hoch empfanden Sie die Verkehrsdichte in den Simulationen?
(How do you judge the traffic density during the simulations?)

sehr niedrig (very low) — sehr hoch (very high)

Als wie realistisch beurteilen Sie die Verkehrsszenarien (Verkehrsmix, Flugpläne, etc.?
(How do you judge the fidelity of the traffic scenarios (aircraft mix, flight plans, etc.)?)

sehr realistisch (very realistic) — sehr unrealistisch (very unrealistic)

Wie beurteilen Sie die Simulationsumgebung ohne Paper Flight Strips?
(How convenient do you judge the simulation without paper flight strips?)

sehr angenehm (very convenient) — sehr unangenehm (very inconvenient)