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Telepresence in Industrial Applications: Implementation Issues for Assembly Tasks

Abstract

In contrast to automated production, human intelligence is deemed necessary for successful execution of assembly tasks that are difficult or expensive to automate in small and medium lots. However, human ability is hindered in some cases by physical barriers such as miniaturization or in contrast, very heavy components. Telepresence technology can be considered a solution for performing a wide variety of assembly tasks where human intelligence and haptic sense are needed. This work highlights several issues involved in deploying industrial telepresence systems to manipulate and assemble microparts as well as heavy objects. Two sets of experiments are conducted to investigate telepresence related aspects in an industrial setting. The first experiment evaluates the usefulness of haptic feedback for a human operator in a standard pick-and-place task. Three operation modes were considered: visual feedback, force feedback, and force assistance (realized as vibration). In the second experiment, two different guidance strategies for the teleoperator were tested. The comparison between a position and a velocity scheme in terms of task completion time and subjective preferences is presented.

1 Introduction

The human haptic sense is an important aspect for numerous assembly processes, especially in manual assembly where (1) human intelligence is necessary for successful execution of given assembly tasks and (2) automation is costly (Reinhart, Radi, & Zaidan, 2008). In manual assembly, the laborer uses the haptic sense to identify the position and orientation of components with respect to each other, while trying to reduce the contact forces. Such an act minimizes the risk of unintended collisions or deformation of parts and thus guarantees a successful completion of the assembly process.

Although the assembly of small/medium lots is normally carried out manually by a laborer, the help of robots in manual assembly is mandatory in some cases where the ability of the human is hindered or reaches its physical barrier. The assembly of microparts or heavy parts represent the two extremes that are considered here. In this regard, telepresence facilitates the combination of robotic manipulation and human flexibility in one system. In such an industrial telepresence system, the human operator steers the teleoperator and reacts to the measured forces that arise during the assembly process.

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Deploying telepresence in production incurs additional costs through the substitution of a standard manual workplace by a telepresent workplace. Equipment for the operator workplace can vary from off-the-shelf components and devices such as TFT monitors and gaming joysticks that are usually cost-effective, to custom-built or research-oriented components such as head mounted displays and high fidelity haptic devices. A guideline for the design of workplaces is given in ISO9241-920 (2009). Apart from costs, a robust performance and disturbance rejection capability has to be ensured. In industrial environments, the system has to be fully functional through the whole working day, which is governed by industrial reliability and quality guidelines (ISO26303, 2008; ISO9000, 2005), which places enormous stress on production equipment.

2 Microscopic and Macroscopic Assembly

In contrast to automated production, manual assembly calls for applying human precision and sensory skills to assemble components in a predefined fashion. In this regard, different physical properties of the workpiece play a significant role. For instance, weight and size are crucial factors in determining the requirements associated with the assembly process. The two extreme cases that arise here are on the one hand manipulating very small or microparts and on the other hand handling very heavy and/or large parts. In both cases the range of human motor skills is rendered insufficient to perform the task adequately. Furthermore, the workpiece material itself plays a significant role. Some materials have adverse health effects on humans (e.g., radioactive materials), but also operators can contaminate highly sensitive parts, for example, in the case of clean surfaces or microproducts. Figure 1 gives an overview of the important requirements of assembly.

2.1 Challenges in Microassembly

Miniaturization of products is an ongoing trend (Nexus-Association, 2005) driven mainly by the microelectronics revolution. Contemporary examples are the increased functionality offered by mobile phones, the miniaturization of acoustic hearing aids, and the invention of microfluidic pumps for medical use. This was only made possible by the capability of the manufacturing process to scale down many components and subsequently integrate them in a limited space. Not only does microtechnology confine itself to the mass production realm, but it also covers customized or special products (e.g., microsensors) that are produced in small volumes. This group of products is usually assembled manually due to the high cost of automation and/or the requirement of human decision making capability which renders the process impossible to automate.

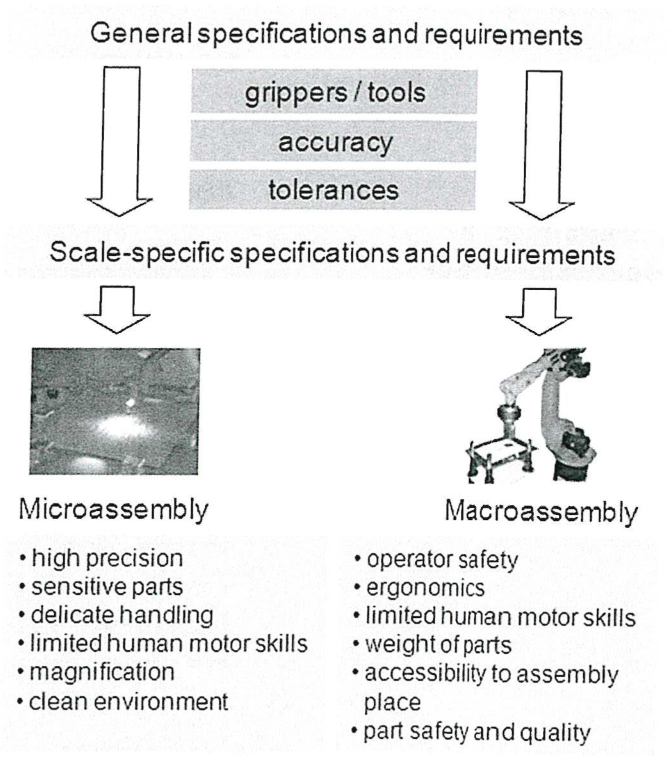


Figure 1. *Requirements of microscopic and macroscopic manual assembly.*

In microtechnology, microparts are often manipulated in clean room environments, because even dust particles might destroy their functional structures, often in the range of only a few micrometers. To guarantee a reduced particle presence, the air intake is filtered before being pumped in the room. In addition, all the equipment used is tested for low particle emission. Reasonably enough, humans are considered one of the main particle sources in such a protected environment. Therefore, entry is only allowed after workers put on special garments including shoes, head covers, and gloves. This is a time-consuming procedure; furthermore, the room itself with the required special equipment is cost-intensive in terms of acquisition and maintenance (ISO14644, 1999; FED-STD-209E, 1992).

Apart from the production environment, the tools required for microassembly differ from their macroscopic assembly counterparts. Detection of miniature features could strain the human eye or be missed altogether. Visualization techniques ranging from magnifying glasses to electronic microscopes could be successfully applied to offset this drawback. In addition, the parts must be handled with tweezers, because the human fingers cannot grip microparts in a specific way, for example, at a designated gripping area. This could easily lead to the destruction of functional structures on the part. Using tweezers might help to handle the problem of a defined grip process, but the grip forces still cannot be controlled. Grip forces from humans can easily exceed the maximum force that microparts can withstand (Vudathu, Duganapalli, Laur, Kubalinska, & Bunse-Gerstner, 2007). Consequently, the risk of damaging fragile microparts during the gripping process is very high. Furthermore, adhesive forces make microparts stick to the gripper, and special techniques have to be used to pull the part off again (Zhou, Aurelian, Chang, del Corral, & Koivo, 2004).

In addition, human fine motor skills for precise movements and accurate placement are not adequate for the demands of microassembly. Parts with dimensions smaller than 1 mm also require highly accurate assembly, where common tolerances of 0.1 mm are insufficient. Human workers need a lot of training to fulfill these requests (Gross & Dirks, 2004).

2.2 Challenges in Macroassembly

Up to now, industrial robots and human workers have mostly been separated during assembly. In manual assembly work-cells, the human worker uses superior sensory capability and intelligence to accomplish the task and thus adds tremendous flexibility to the system. However, manual assembly workstations suffer low production rates and higher running costs in comparison to automated systems. In addition, it is perilous for workers to carry heavy loads or even medium-weight parts frequently. It was statistically determined that more than 30% of European manufacturing workers suffer from lower back pain, which incurs enormous social and economic costs (Krüger, Lien, & Verl, 2009). Accordingly, the help of lifting machines in such situations is deemed mandatory. These machines, including among others industrial robots, free workers from the drudgery and tedium often associated with handling and assembly applications.

In contrast, an automated assembly work-cell exhibits higher production rates, more accuracy, and also steady quality, but the initial costs are comparably higher. Although the robots in such a work-cell have a greater load-bearing capacity in comparison to the worker, they have yet to match human flexibility.

In the case of small lot sizes, a high number of variants, and short lifetime of products, there is a need for a flexible and changeable system. Combining the strengths of both manual and automated work-cells enables new concepts of flexible systems and opens up new application scopes. One way to realize such a combination is by using a telepresence system. With such an arrangement, the safety aspect of the process would be greatly reinforced. The concern that the operator is present in a dangerous or harmful environment would be totally eliminated due to the separation between the worker and the assembly place.

However, the use of an industrial articulated robot as a teleoperator in macroassembly is still challenging due to several reasons. Industrial robots generally boast a sophisticated position controller which is designed to ensure high position accuracy for noncontact tasks such as unconstrained motion in a free space without any influence of the environment on the robot. A compliance control loop needs to be closed around the position control loop to allow the robot to come in contact with the environment during assembly. Increasingly, industrial manufacturers provide limited access to the robot controller to allow for alteration in the position commands in real time. However, building a feedback loop based on robots entails closing the force control over an existing position control, consequently leading to a decrease in the available bandwidth. Taking into account the reliable performance of the position controller, a sufficiently accurate and robust compliance control built around such interfaces could be achieved (Vukobratović, 2009).

Stability of the transient motion, representing all transition phases between the free space and compliant motion, is also a challenging issue. Since industrial robots have high apparent inertia and stiffness due to the high accurate position controller (e.g., position control gains usually have inertia on the order 10^6 N.m, Vukobratović, 2009), the existing stabilizing methods based on the passivity concept appear to be conservative in some applications where the interaction between the robot and a stiff environment should be controlled.

Another issue is the scaling between the robot and the human workspace. Since the robot in macroassembly carries a high payload, a downscaling of the interaction dynamics between the robot and the environment is needed. To provide a transparent interaction to the human operator, the force will be fed back to the human operator in accordance with the impedance of the environment, that is, if there is an upscaling of the position sent to the robot, the forces fed back to the human operator will be downscaled in a manner that the user feels the same environment as without scaling. This can be achieved by setting the same scaling factor for both position and force (Preusche & Hirzinger, 2000), or by using the impedance shaping concept (Colgate, 1993).

3 Related Work

This section presents relevant research done in microassembly and macroassembly to cope with the challenges mentioned in Section 2. Although telepresence technologies represent viable solutions for aforementioned problems, they have yet to be widely deployed in the industry.

3.1 Microassembly

In the microdomain, several research projects aim to overcome the described barriers in microassembly (see Section 2.1). In some cases, this is realized by designing automated assembly systems that are more flexible than standard automation work cells. Gaugel, Bengel, and Malthan (2004), Bengel (2005), Schmidt and Kegeler (2005), Clevy, Hubert, and Chaillet (2008), and Brecher, Freundt, and Wenzel (2009) described systems with flexible transportation modules that automatically move from one station to the next. Several methods to increase the precision in microassembly were proposed, including the design and implementation of new sensor concepts (Slatter & Burisch, 2005) as well as new robots for microassembly (Hesselbach & Heuer, 2005).

These systems suffice for an automated process that is flexible and can easily be adapted to new requirements. Nevertheless, every change requires reprogramming the system to incorporate all additional parameters associated with the process. The variety of tasks that can be assembled automatically depends on the different sensor concepts or even image processing abilities of the specific assembly system. Okazaki, Mishima, and Ashida (2002) proposed a small transportable microfactory that is manually guided by a joystick, where the human operator receives visual feedback from the environment but no force feedback.

In Fahlbusch, Shirinov, and Fatikow (2000), Fahlbusch and Fatikow (2001), and Kortschack, Shirinov, Trueper, and Fatikow (2005), a haptic joystick is used to execute nanomanipulations in an atomic force microscope. Research was also done to automate manipulation tasks within a microscope's vacuum chamber (Krohs et al., 2008; Nakazato et al., 2009). Kim, Kang, Kim, and Park (2006) investigated a hybrid microassembly system with telepresent and automated functions. They also studied the effects of scaling factors in a teleoperated microassembly system with force feedback. They asserted that the scaling factor from human movements to the teleoperator micromovements has an enormous benefit with respect to the system's overall accuracy.

Unger, Klatzky, and Hollis (2004) presented a self-developed high accuracy input/output device, the magnetic levitation device, and used it for micromanipulation and microassembly. This 6 degree of freedom (DOF) device has multiple possibilities for manipulation tasks and haptic feedback in virtual or telepresent environments. But to this point it has not been distributed commercially and therefore it is inadequate for cost-effective industrial use.

Shen, Xi, Song, Li, and Pomeroy (2006) as well as Zäh, Ehrenstrasser, and Schilp (2003) presented telepresent environments for microassembly that deal with cooperative assembly processes. Both systems aim to join together operators separated over great distances in the same teleoperator environment. The problem considered in those distributed environments is time delay, which reduces system transparency and consequently affects the operator's ability to execute the task.

3.2 Macroassembly

Several research projects have successfully addressed automated assembly (Chin, Ratnam, & Rajeswari, 2003) and automated assembly in motion tasks (Reinhart & Werner, 2007). In spite of significant advances in the field of artificial intelligence and industrial automation (Brooks et al., 2004), human intelligence is far superior in terms of factors such as reasoning, language comprehension, vision, and ingenuity (Nichol et al., 2005). Some tasks require both the acute reasoning and perceptive abilities of a human, and the strength and cooperation of an industrial robot. Therefore, manual assembly continues to be an important feature of many industrial processes. Cobots introduced by Colgate, Wannasuphoprasit, and Peshkin (1996) provide guidance through the use of servomotors, while the human operator provides motion commands. As passive mechanical devices they were primarily used for the assembly of car doors. The virtual surfaces are used to constrain and guide the workers' motion. Schraft, Meyer, Parlitz, and Helms (2005) introduced the PowerMate as a robot assistant. Krüger, Bernhardt, and Surdilovic (2006) introduced a novel intelligent power assist device (IPAD) that integrates sophisticated force-feedback and programming functions, but requires direct interaction with the manipulator.

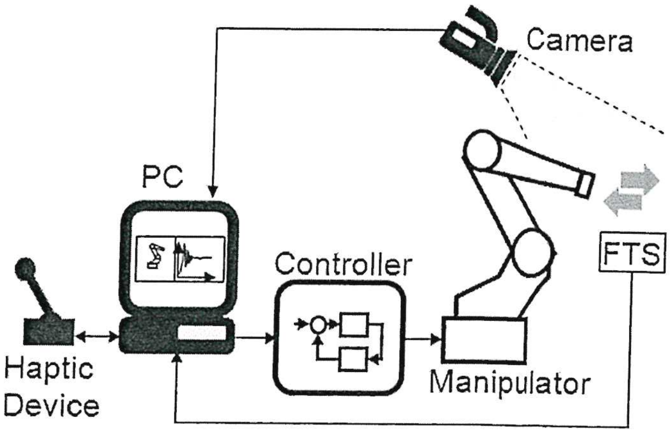
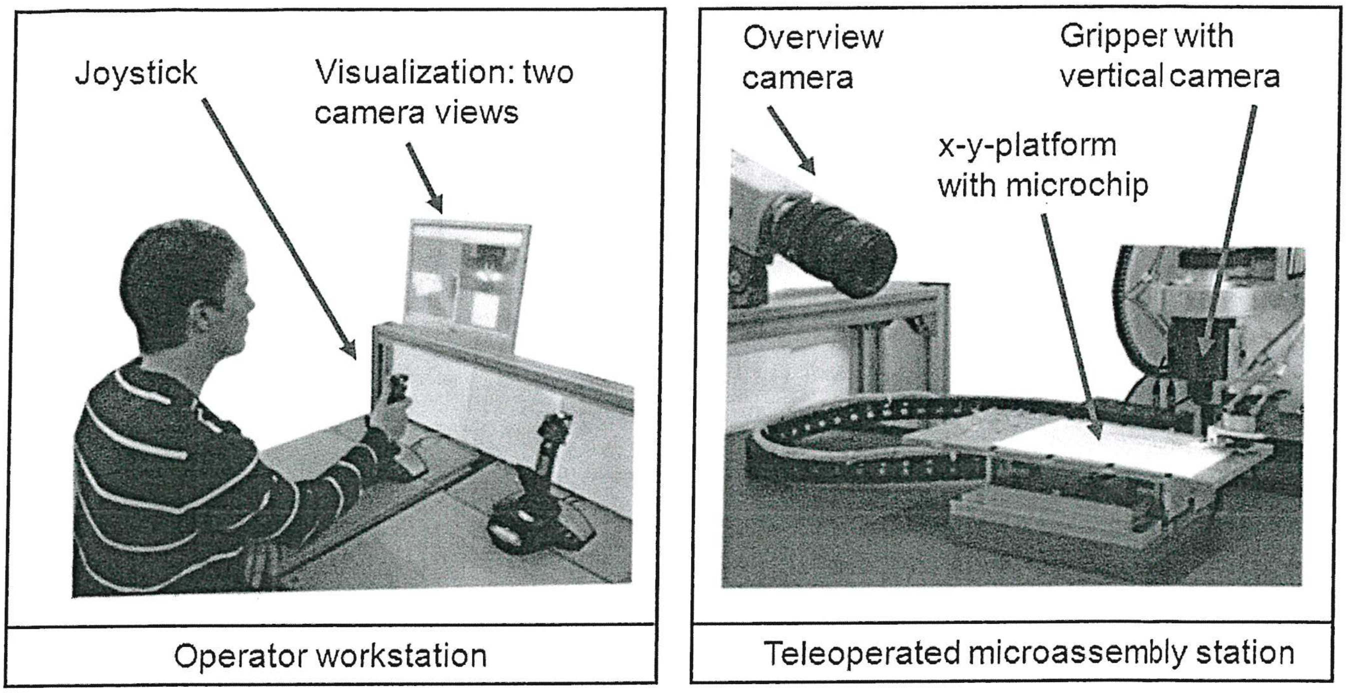


Figure 2. *Overview of a generic industrial telepresence system.*

Generally, during assembly tasks that entail contact with the environment, the robot performs three kinds of motions: gross motion in free space, compliant motion in contact with the environment, and transient motion between the gross and compliant motions. The position controller of industrial robots ensures a high position accuracy for gross motion in free space. For the compliant motions, impedance control is one of the most important control strategies to be used. It can be defined as designing a controller so that the interaction forces compensate for the error between desired and actual position of the end effector of the robot. One of the first approaches to impedance control was proposed by Whitney (1977). In this approach, a force control loop is closed around the velocity control loop in a way that the interaction forces are converted into a velocity modification command of the desired velocity. Salisbury (1980) proposed to modify the desired position rather than the velocity of the end-effector in accordance with the interaction force. The most general impedance control was introduced in Hogan (1985).

Regarding the transient motion between noncontact and contact motions, the existing stabilizing methods based on the passivity concept appear to be conservative in some applications, especially when an interaction between the robot and a very stiff environment is controlled. Surdilovic (2007) proposed a new interaction stability paradigm based on robust control theory. It ensures contact stability during all phases of interaction and allows a considerable reduction of the high apparent industrial robot inertia and stiffness.



Operator workstation

Teleoperated microassembly station

Figure 3. *Microassembly telepresence system: operator workplace (left) and teleoperator station (right).*

4 System Architecture

In this section, two experimental rigs of telepresence systems developed at the authors' institute are described. The first system is used for the assembly of microproducts and the other is for macroscopic assembly (large scale/heavy work pieces). A general overview of a generic telepresence system is depicted in Figure 2. Both systems discussed in the next sections are variants of this architecture. The dominant characteristic is the reliance on readily available commercial components (e.g., personal computers and cameras) and standard industry equipment (e.g., force/torque sensors, FTS, and industrial manipulators). In its generic form, the controller is either embedded in the manipulator's controller or an external one that communicates with the manipulators.

4.1 Microassembly

4.1.1 Operator Workplace. The operator workplace consists of a haptic input/output device and a monitor for visual feedback (Figure 3, left). The haptic device is a standard force-feedback joystick from Saitek with 2 DOF, which is a very cost-effective input/output device. The joystick's x and y directions control the teleoperator's xy plane. To match the 2 DOF device to the 3 DOF teleoperator kinematic system, the z axis moves up or down when an additional button is pressed and the joystick is moved forward or backward in the y direction. A standard TFT monitor is used for visualization, which displays two different camera views. The operator and the teleoperator motor controller boards communicate via UDP (User Datagram Protocol). Sensors are connected directly to a data acquisition device on the operator side.

4.1.2 Teleoperator. On the teleoperator side a high precision planar table (x and y axis) and a linear drive (z axis) with an accuracy of $1.0\ \mu m$ are located in a clean room environment, whereas the operator workplace is outside (Figure 3, right). Therefore, costs are drastically reduced due to the size and maintenance of the clean room and furthermore the quality is increased due to the absence of workers.

A vacuum gripper and a magnifying camera are mounted onto the linear axis moving in the vertical direction. A one degree of freedom force sensor, positioned on the planar table, is used to measure forces

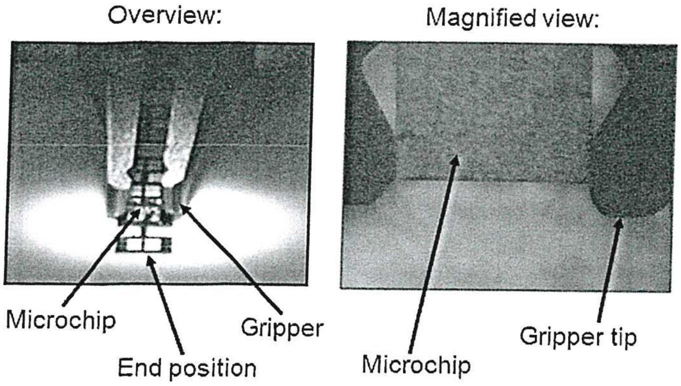


Figure 4. *Camera views in microassembly setup: overview camera (left) and telecentric camera (right).*

in the *z* direction and thus to detect contact between the gripper and the table. Two cameras give a complete overview of the teleoperator via a live video stream. One camera presents an overview of the whole scene, whereas a special telecentric scaling camera, integrated into the tooling system, gives a closeup picture of the microparts (Figure 4). The telecentric lens system provides pictures without distortion, which gives a clear picture of the micropart's features. A pneumatic two-finger gripper is used in Experiment 1 to handle a microchip with 1 × 1 × 0.5 mm size. Adhesive forces that make the chip stick to the gripper did not hinder the pick-and-place process. For the second experiment, presented in Section 5, which is a transportation task under two different guidance strategies, a laser sensor with a small focus of 1 mm is used to display the actual position of the tooling system.

4.2 Macroassembly

4.2.1 Operator Workplace. At the human operator side, there is a haptic device that displays the forces/torques sensed at the tool centerpoint of the robot to the human operator. The device receives the motion commands from the human operator and sends them to the robot side via a communication link. In order to make it easier for the human operator to understand the device's movement (Deml, 2007), it is preferred to have a simple input device, by which task-relevant degrees of freedom are enabled. Therefore, a 2 DOF force-feedback joystick is used in this setup as an input device. This joystick can display forces up to 8.9 N in both directions. In addition, a monitor is used for the visual feedback. The total setup of the operator workplace is shown in Figure 5.

A central bilateral controller running on a real time operating system QNX is located between the operator and teleoperator. The force-feedback joystick is connected to the central bilateral controller through a UDP connection. Avoiding the overhead of checking whether every packet actually arrived makes UDP faster and more efficient than, for example, TCP (transmission control protocol). Since the system is time sensitive, it was decided to use UDP, because dropped packets are preferable to delayed packets which introduce a destabilizing effect in the control loop. A low pass filter was used to overcome the round trip time delay observed in the system (about 20 msec).

4.2.2 Teleoperator. A KUKA KR6 industrial robot is used in our setup as a teleoperator. It is a 6 DOF articulated industrial robot with a nominal payload of 6 kg (Figure 5). The robot has a controller with a real-time communication interface, KUKA Ethernet remote sensor interface (RSI). The RSI is used to connect the teleoperator (KUKA robot) with the central controller. The exchanged data are transmitted via the Ethernet TCP/IP protocol in XML (extensible markup language) format. The cyclical data transmission from the robot controller to the central controller is executed in the interpolation cycle each 12 msec. For the pick-and-place task, a pneumatic gripper is mounted at the tool centerpoint of the robot. A pan-tilt camera is used to give the human operator the visual feedback needed to accomplish the task. A flat metal block is to be picked and placed on a compliant fixture with a stiffness of 75 N/mm.

5 Experimental Settings and Results

Any assembly process is composed of three distinct phases that in turn are divided into further smaller subphases. The main phases could be described as follows.

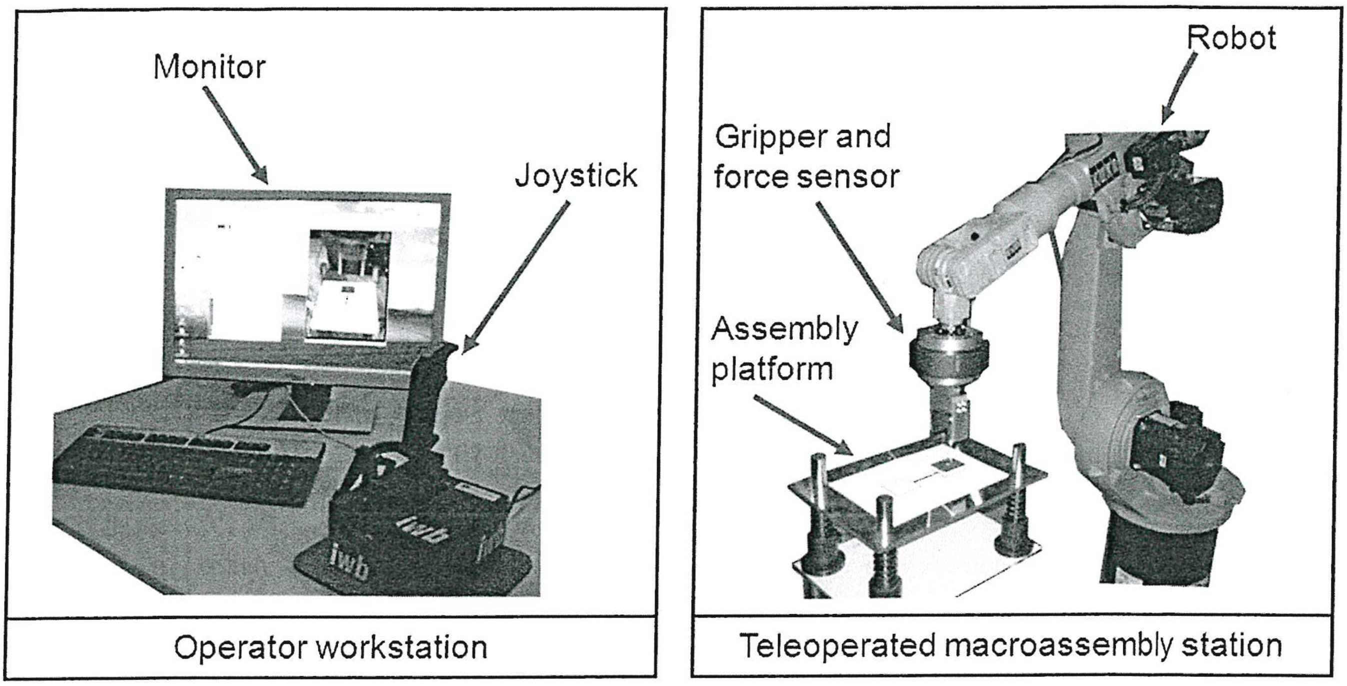


Figure 5. *Macroassembly telepresence system: operator workplace (left) and teleoperator station (right).*

1. Gripping or picking up an object from a given position on a fixture or a jig.
2. Manipulating or transporting; that is, changing the position and orientation of an object with respect to a fixed coordinate system.
3. Mounting or placing the object in a predefined position/orientation on a surface or joining it with another object.

Accordingly, to study issues concerning implementation of telepresence in assembly, two experiments using a pick-and-place task, which is representative of a wide range of assembly processes, are realized (Figure 6). The first experiment tackles the issues occurring during the first and the last phases of an assembly process by studying the effect of force feedback on task quality. The second experiment studies the effect of the chosen guidance strategy (position or velocity) during transportation, and thus considers the manipulation phase of an assembly task. Ten participants (mean age: 27.1 yr, *SD*: 2.6 yr) took part in this study, all of whom were naive to the purpose of the experiment and inexperienced in the use of force-feedback joysticks.

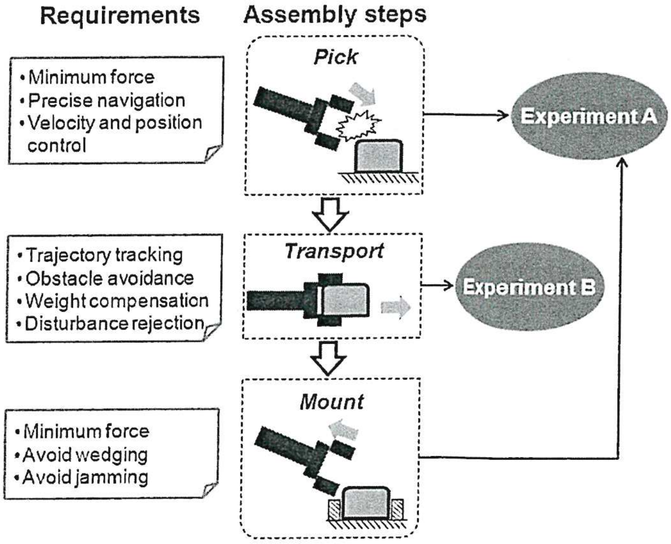


Figure 6. *Concept of the experiments based on the definition of assembly.*

5.1 Experiment A: Effect of Force Feedback in Pick-and-Place Tasks

5.1.1 Experimental Design. In order to test which, if any, form of haptic feedback improved

Table 1. *Survey Results (10 Participants)*

	Micro-assembly	Macro-assembly
Notification of haptic feedback	9	10
Without haptic feedback is easier	1	2
Force feedback facilitates the task	5	4
Force assistance facilitates the task	5	6
Allocation of feedback to contact event		
Immediately	6	4
After 2–4 trials	3	4

task performance in a pick-and-place task, a factorial repeated-measures experimental design was used, whereby haptic feedback was manipulated on three levels: no force feedback (NF), with force feedback (FF), and with force assistance in the form of vibration (FA). Measured was the vertically applied pressure on the table (N in the vertical direction) during the pick-and-place processes, as well as overall task completion time for each trial (in units of seconds). In addition, with the aim to assess the subjective experience of haptic feedback during a typical assembly task, a questionnaire was developed and administered to participants.

5.1.2 Procedure. Prior to the experiment, participants were given the opportunity to practice control of the experimental apparatus until they felt comfortable with it. Participants were instructed to pick up a target object (a rectangular metal plate for macroassembly, a microchip for microassembly) from a prespecified position and place it as accurately and quickly as possible on a target position. The respective target objects were thin in order to ensure a contact between the gripper and the table during the pick and place processes. This procedure was repeated four times with each of the three manipulations of haptic feedback (NF, FF, FA). To avoid practice and order effects, the order in which the three types of haptic feedback were presented was randomized. Participants followed the same procedure for both the microassembly and the macroassembly setups. Half of all participants started with microassembly, and the other half started with macroassembly. After completion of all experimental trials, the questionnaire was administered.

5.1.3 Results. The survey results are summarized in Table 1. All force data were inspected for outliers, as well as for the normality of variance. Histograms and Shapiro-Wilk test statistics indicated a non-normal distribution for all measurements. Accordingly, statistics for nonparametric data were applied in Table 1, unless specifically stated otherwise.

For both setups, Friedman analyses of variance (ANOVAs) for nonparametric, repeated-measures data showed that neither mean pressure forces nor task completion times varied systematically over the four repetitions of each trial within each haptic feedback condition, indicating that participants did not apply significantly less pressure or complete their task significantly faster as they became more practiced. Thus, for each of the three haptic feedback conditions, force measurements of each of the four trials conducted were combined into overall mean force scores for picking and placing, respectively.

In the next step, nonparametric ANOVAs were conducted with data gathered in the microassembly and macroassembly setups which tested whether applied pressure forces varied significantly depending on the type of haptic feedback employed and/or the task process (picking/placing). Accepted significance levels for ANOVA test statistics were set at $p < .05$.

5.1.3.1 Microassembly. The mean pressure forces and standard deviations are displayed in Figure 7. For trials with the microassembly setup, Friedman's ANOVA showed that mean forces varied significantly between the three haptic feedback conditions for the picking process, $\chi^2(2) = 8.60, p < .05, r = 0.40$. Follow-up comparisons of the three conditions were performed according to a statistical procedure described by Siegel and Castellan (1988). For this method, the differences between the mean ranks of the different conditions are compared

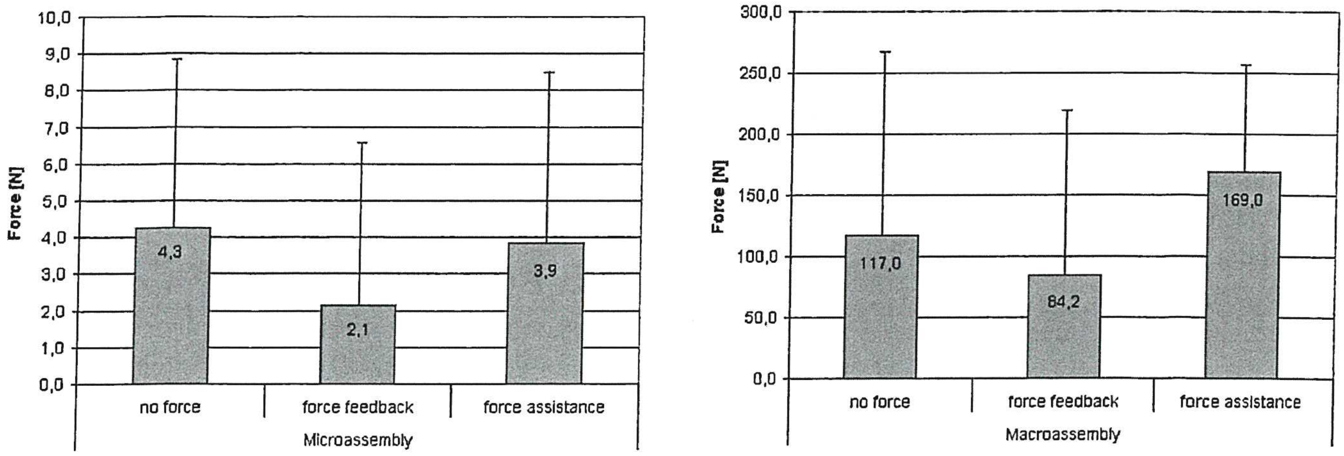


Figure 7. *Results of Experiment A: pressure forces in microassembly (left) and in macroassembly (right).*

to a value based on the respective standardized score (z; corrected for the number of comparisons being done) and a constant which is based on the total sample size ($n = 10$) and the number of conditions ($k = 3$).

With a critical mean rank difference (mrd) of 1.07 and an adjusted significance acceptance level of $p < .0167$, the analyses found that participants applied significantly less pressure when they experienced force feedback ($FF_{median} = 2.15$ N) compared to when they received no haptic feedback ($NF_{median} = 4.24$ N; $NF - FF_{mrd} = 1.30$). On the other hand, the differences in applied pressure between trials with force feedback (FF) and those with force assistance ($FA_{median} = 3.80$ N) just failed to reach significance ($FA - FF_{mrd} = 0.80$). There was no significant difference between trials with force assistance and those without any form of haptic feedback (mrd = 0.50).

In contrast, Friedman's ANOVA found that mean applied forces did not significantly vary between the three haptic feedback conditions when the object was placed on the target position, $\chi^2(2) = 5.60, p = .06$.

5.1.3.2 Task Completion Time. For each trial, the time that participants took to pick and place the target object was measured. Again, there was no significant practice effect over the four different trials; therefore, the measured task completion times for each task repetition were combined into one overall mean task completion score for each haptic feedback condition. Friedman's ANOVA showed no significant effects of haptic feedback on task completion times for microassembly trials, $\chi^2(2) = 3.68, p = .83$, indicating that the type of haptic feedback received did not significantly influence participants' speed in completing the pick-and-place task.

5.1.3.3 Macroassembly. For trials with the macroassembly setup, the ANOVA did not reveal a significant effect of haptic feedback type on mean pressures applied during picking, $\chi^2(2) = 5.40, p = .06$. Contrary to findings of the microassembly setup, however, the ANOVA did indicate significant differences in applied pressure during placing, depending on the haptic feedback used, $\chi^2(2) = 8.60, p < .05, r = 0.40$. Follow-up comparisons revealed that participants applied significantly less pressure when they received force feedback ($FF_{median} = 56.98$ N) compared to when they had no haptic feedback ($NF_{median} = 205.83$; mrd = 1.30). On the other hand, the differences in applied pressure between trials with force feedback (FF) and those with force assistance ($FA_{median} = 106.75$ N) just failed to reach significance ($FA - FF_{mrd} = 0.80$). In keeping with previous findings, there were no significant differences in mean applied pressure between trials with force assistance and those without haptic feedback (mrd = 0.50).

5.1.3.4 Task Completion Time. As with the microassembly setup, the type of haptic feedback received was not found to have a significant influence on the time it took participants to complete a pick-and-place task, $\chi^2(2) = 2.60, p = .27$.

5.1.4 Discussion. In summary, while a survey showed that approximately half of all participants thought force assistance in the form of vibratory signals facilitated the task, the present study did not find it to be effective in reducing applied forces nor did it lead to faster task performance. On the contrary, while it also did not lead to time gains, force feedback turned out to significantly reduce the amount of pressure that operators of teleoperated systems applied in the event of surface contact. This was true for both microassembly and macroassembly setups. An interesting finding is that the degree to which force feedback is effective in reducing pressure is process-dependent. That is, the results indicated that in microassembly, force feedback is more likely to reduce surface pressure in picking up an object, whereas in macroassembly, it is more effective in this regard when placing an object. It is conceivable that during microassembly, participants were less afraid to drop a lightweight microchip from a short distance onto the target position than they were to drop a relatively heavy metal object. On the other hand, people seemed to take greater care in picking up the microchip from the table, possibly for fear of losing it if they missed it, than they were to pick up a larger object. This may indicate that the expectation of object weight and/or size, rather than the actual representation of these dimensions, influences operating behavior. Since the present experiment was not designed to investigate such claims, future research into process-dependency of haptic feedback features in telepresence systems seems warranted.

5.2 Experiment B: Effect of Guidance Control Strategy

Two different control strategies were designed to guide the teleoperator during the part transportation process, position and velocity control. By the position control paradigm, the deflection of the joystick within its workspace dictates displacement of the teleoperator.

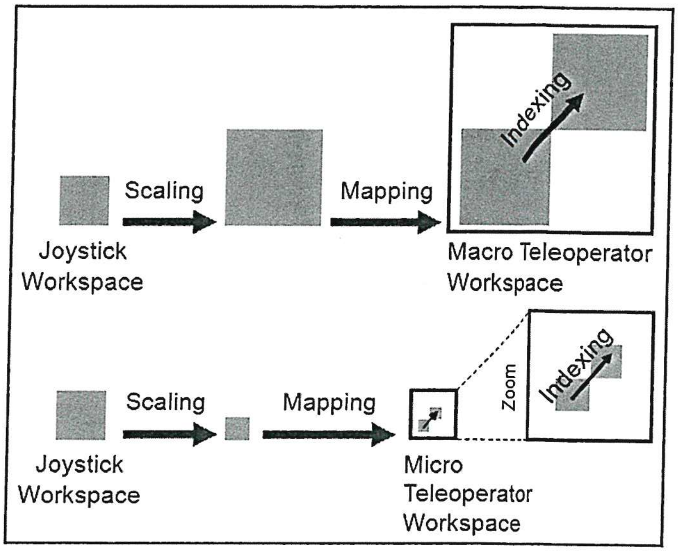


Figure 8. *Workspace indexing.*

The mapping between the movement of the joystick and the teleoperator has a scale factor, in order to scale down in the microassembly case and up in the macroassembly. Although scaling is used, the scaled workspace of the joystick cannot cover the whole workspace of the teleoperator because of the required accuracy. Therefore, an indexing method (Preusche & Hirzinger, 2000) is used to relocate the scaled workspace of the joystick within the workspace of the teleoperator. Figure 8 shows the indexing method for microassembly and macroassembly.

The second strategy is the velocity control, in which the deflection of the joystick dictates a velocity of the teleoperator (Grange, Conti, Helmer, Rouiller, & Baur, 2001). The further the joystick is deflected (P_{joy}) from the initial position (P_{joy_i}), the greater the velocity of the teleoperator. Scaling is also applied in order to scale the velocity commands up and down. Equation 1 describes this control strategy. K is the scaling factor and $\Delta x(t)$ is the displacement of the teleoperator during a period of time Δt.

$$\Delta x(t) = K \times (P_{\text{joy}} - P_{\text{joy}_i}) \tag{1}$$

Using the velocity control paradigm does not need any indexing, since the human operator can control and reach any point within the whole workspace of the teleoperator.

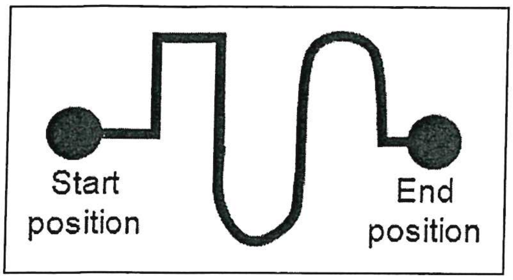


Figure 9. *Transportation path (Experiment B).*

5.2.1 Experimental Design. In order to assess each control strategy in terms of efficiency, a 4 (repetition 1–4) × 2 (position/velocity control) within-subjects experiment was conducted, in which participants were asked to follow a prespecified path as quickly and as accurately as possible. This path included both straight as well as curvy elements (Figure 9). Task completion times (in units of seconds) were measured. In addition, another survey was conducted, aiming to assess the users' subjective impressions. The participants ($n = 10$) who participated in this study also took part in the experiment described above.

5.2.2 Procedure. Prior to the experiment, the participants were given the opportunity to familiarize themselves with the different control strategies. They were then asked to trace a given path from a prespecified starting point to a given end point. This task was repeated eight times, with alternating position and velocity control for each trial. Half of all participants started with position control, the other half with velocity control. Afterward, participants were asked which control strategy they preferred. As before, participants conducted this experiment with the microassembly as well as with the macroassembly setup; half started with microassembly, and the rest started with macroassembly tasks.

5.2.3 Results. The survey showed that the majority of participants preferred velocity control to position control. This preference was stated by 90% of participants in the microassembly setup and by 60% of participants in the macroassembly setup (Figure 10).

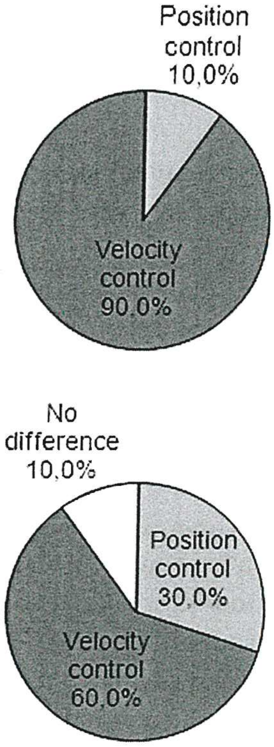


Figure 10. *Results of Experiment B: Survey about the control strategy preference of the subjects in microassembly (upper) and macroassembly (lower).*

5.2.3.1 Microassembly. The measured task completion times were inspected for outliers and normality of variance. An inspection of histograms and Shapiro-Wilk test statistics indicated that assumptions of parametric data were not violated. The mean task completion times and standard deviations are displayed in Figure 11. For microassembly, a factorial ANOVA for parametric data with repetition number (1–4) and control type (position/velocity control) found a significant, albeit weak practice effect, $F(3,27) = 3.30, p < .05$, partial $\eta^2 = .27$. Bonferroni-adjusted post hoc comparisons of the mean times of each trial with the first trial revealed only a significant difference in task completion time between the first trial and the fourth repetition, $F(1,9) = 8.70, p < .05$, partial $\eta^2 = .49$. That is, participants became significantly faster with practice, regardless of the type of control employed. However, the ANOVA also found a significant, strong control type main effect, $F(1,9) = 144.51, p < .001$, partial $\eta^2 = .94$. The estimated marginal mean times for

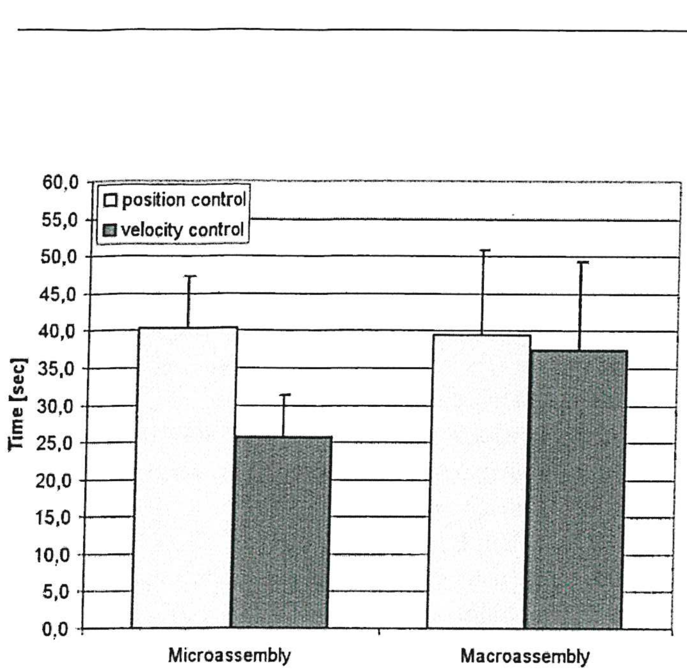


Figure 11. *Results of Experiment B: task completion time.*

each condition show that participants performed their task significantly quicker when using velocity control ($M = 25.67$ s, $SD = 7.00$ s) compared to the use of position control ($M = 40.25$ s, $SD = 5.64$ s), regardless of the amount of practice.

5.2.3.2 Macroassembly. For tasks completed with the macroassembly setup, the ANOVA also found a significant practice effect, $F(3, 27) = 6.66, p < .05$, partial $\eta^2 = .43$. Again, corrected post hoc comparisons and estimated marginal means found participants to perform significantly faster in their fourth trials ($M = 49.87$ s, $SD = 10.44$ s) than in their first trials ($M = 42.01$ s, $SD = 9.38$ s). On the other hand, contrary to microassembly control times, the ANOVA did not find a significant effect of control type on task completion times in the macroassembly setup, $F(1, 9) = 0.77, p = .40$.

Finally, inspections of the paths that were taken by participants indicated that, for both setups, participants seemed to follow the specified path more accurately using velocity control rather than position control.

5.2.4 Discussion. In summary, although velocity control was preferred to position control in both setups, that is, in microassembly as well as macroassembly, when the amount of practice with each control type is taken into consideration, it was only found to be significantly more time-effective in the case of microassembly. Again, these findings may imply a process-dependency of control type. Future studies are recommended to investigate more closely which elements of telepresence control are, perhaps uniquely, suited for microassembly and macroassembly.

6 Conclusion and Outlook

Although extensive research work has been conducted in telepresence, wide scale deployment in the industrial and commercial realm has yet to materialize. This could be attributed to the cost-effectiveness and design guidelines of such novel types of systems. In this work, a promising application domain for telepresence technology was investigated, namely manual assembly. This is a very common task in industrial engineering which is usually limited by two extreme cases; assembly of either very large or very small components. Working in these areas could lead to either destruction of components and/or unsafe operation for the operator. In this regard, telepresence offers a convenient solution for such a problem. This paper presented two telepresent test rigs for execution of assembly tasks on the microscale and macroscale. General requirements and specifications for manual assembly systems covering scale-specific aspects were also discussed. To evaluate the feasibility of both test rigs, two experiments were designed and conducted. The experiments exhibit a reduction in pressure forces when force feedback is applied, but not when force assistance (vibration) is used.

The results show a difference between grip forces in microassembly and macroassembly. Participants pick up micro-objects with care, but tend to let them fall instead of placing them carefully. The opposite case occurred for macroassembly. Force measurements showed that the heavy macro-object was placed significantly more carefully than it was gripped.

In addition, the guidance strategy mode for the transportation component of the task was evaluated. Not only did velocity control demonstrate a faster transportation capability for microassembly than the position control, but was also overwhelmingly favored by the participants. Along with the specifications and requirements, the results outline successful practices and implementation issues that should be considered during the design and deployment of telepresent assembly systems.

Acknowledgments

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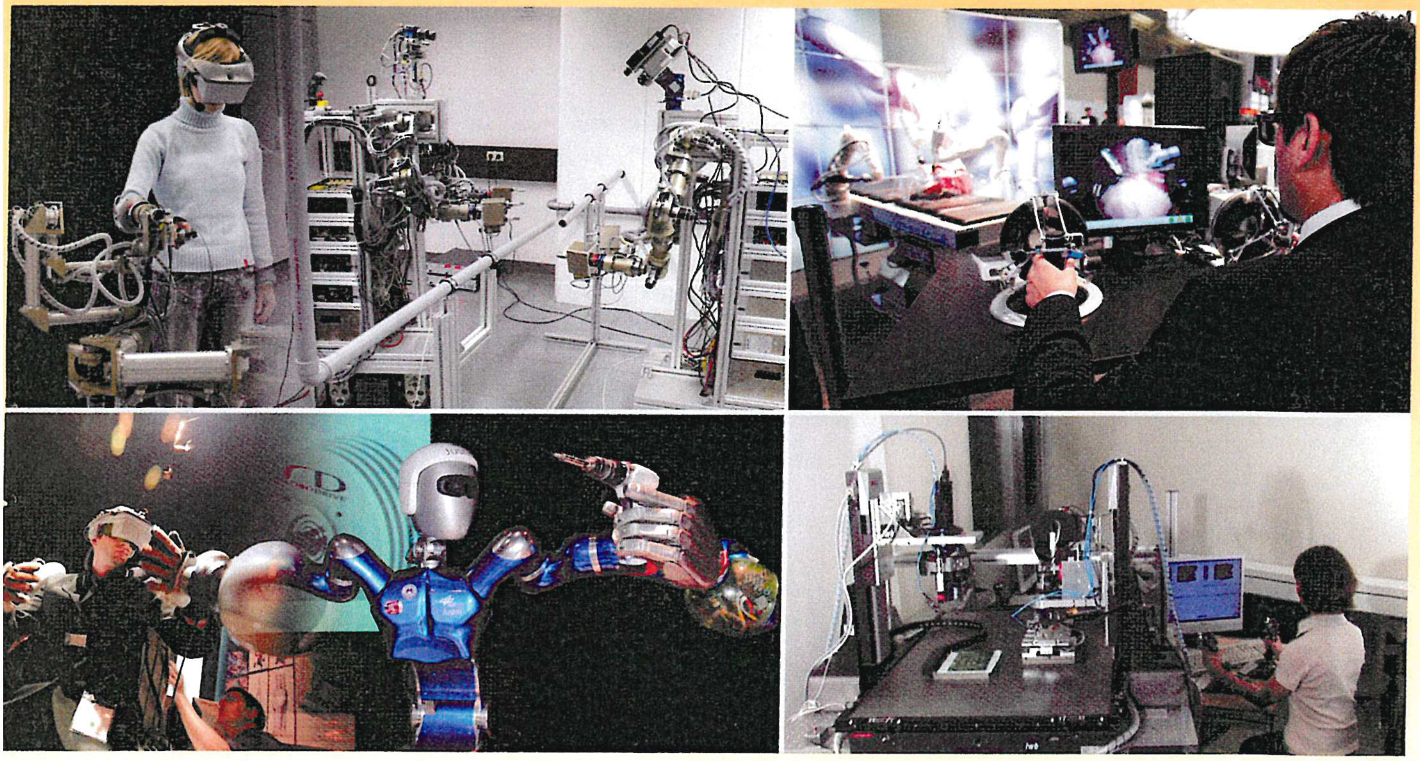
TELEOPERATORS AND VIRTUAL ENVIRONMENTS



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