



Athermalization of space instruments with mechanical metamaterials: structural instrument architectures and conceptual design of an in-orbit demonstration experiment

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Abstract

Space instruments are nowadays inevitable for astronomy and Earth observation. Designing and building them remain a costly and challenging engineering task as they are exposed to harsh environmental conditions in space and during transfer to orbit. In particular, the induced thermal deformations into the instrument structure must be mitigated in order to ensure optimal instrument performance which is called athermalization. Current research addresses this challenge primarily through the application of advanced shape control systems as well as sophisticated materials and manufacturing methods. With the advent of metallic multi-material additive manufacturing, the production of advanced materials such as thermoelastic metamaterials becomes feasible for space applications. These materials are lattice structures with tunable coefficient of thermal expansion (CTE), including both negative and zero CTE, and high stiffness. Furthermore, the controlled heating of these metamaterials allows for the design of thermoelastic structures with advanced shape control. They are therefore well-suited for thermostable space instrument structures which is addressed only rarely in research. This work presents the derivation of principle space instrument architectures with athermalization through the utilization of thermoelastic metamaterials. In this course, architectures with and without shape control are considered. The required steps for implementing this technology are presented according to a Technology Readiness Level (TRL) classification. Finally, a suitable in-orbit demonstration experiment is presented, namely the Modern Structures Experiment of the SeRANIS mission.

Keywords Metamaterial · Space instrument · Thermoelasticity · Athermalization · Shape control

1 Introduction

Space instruments primarily serve two purposes: remote sensing of the Earth and astronomy. Observing the Earth from space has contributed greatly to a more holistic understanding of the atmosphere, oceans and Earth's surface from a global perspective, and is becoming increasingly important for monitoring human-made environmental change [1, 2]. For astronomy, space-based telescopes offer certain unique observation capabilities compared to ground-based telescopes because of the lack of Earth's disturbing atmosphere and other influences, and have enabled new eras of science about exoplanets and the universe [3]. In contrast to their outstanding observational capabilities, space instruments are very costly and technically challenging. This is due to the hostile space environment, remote operation with little opportunity for maintenance and repair, and limitations in mass, power and size, as well as the high mechanical stresses during launch [4]. It is of particular importance to ensure

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that the deformation of the instrument's structure resulting from the orbital thermal loads is maintained within specified limits in order to guarantee optimal instrument performance. The current research of this process called athermalization can be organized according to two foci [5–8]:

- Application of advanced materials and manufacturing methods such as additive manufacturing
- Equipping space instruments with advanced shape control systems

Both approaches are considered in this work. Additive manufacturing enables advanced optomechanical structures with, for example, enhanced thermal performance and reduced weights due to the high design freedom [9–11] and even printing functional optical components itself [12, 13]. In particular, through the recent advances in metallic multi-material additive manufacturing, thermoelastic metamaterials suitable for space environment became available. Those are in fact stiff lattice structures with tunable coefficient of thermal expansion (CTE), including negative and zero CTE, and have therefore a high potential for athermalization of instruments. To date, various metamaterial geometries have been investigated, with a particular focus on their CTE and stiffness properties [14–17]. For example, those metamaterial configurations can be used for the compensation of thermal mismatch in lens barrels [18, 19] and in satellite structures [20–22]. More recently, a primary mirror mounting structure for a telescope [23] and a space lattice structure with each near-zero thermal expansion [24] was investigated. However, a systematic consideration of instrument architectures of instruments athermalized by thermoelastic metamaterials and the design of a related in-orbit demonstration experiment is generally not addressed in research. Thermoelastic metamaterial mechanism can also be used to build thermally driven actuators [25–27]. Also this concept would be beneficial for advanced shape control of instruments, it is only discussed in limited work [28]. The concept of shape control for high-precision instruments has been employed in a number of applications, including vibration mitigation, shape readjustment in orbit and thermoelastic control [29]. The capacity to regulate shape is particularly advantageous for the latest generation of telescopes and deployable instruments [8, 30, 31]. More recently, model-based control approaches for high-precision instruments are investigated in order to reach higher dimensional stability [32–37]. While the usage of smart materials in shape control like piezoelectric materials and shape memory materials is well-established [38–40], thermoelastic metamaterials are considered only rarely here. However, thermoelastic metamaterials would be beneficial due to their wide range of tunable properties, such as the CTE and the potential to design custom actuators through the high design freedom offered by additive manufacturing.

Moreover, shape control approaches featuring thermoelastic metamaterials are especially useful for thermally induced errors as both are in the thermal domain with comparable timescales.

This work presents the derivation of space instrument architectures with athermalization through the utilization of thermoelastic metamaterials. Initially, the requirements and the constraints of space instruments are presented to provide a foundation for the subsequent study. Thereafter, thermoelastic metamaterials are introduced and applied to the athermalization of instruments. Five levels of instrument architectures, covering both passive and active forms of athermalization, are developed, with particular reference to space instruments. Then, the technology of athermalization with thermoelastic metamaterials is classified in accordance with the Technology Readiness Levels in order to facilitate the implementation. Ultimately, an appropriate in-orbit experiment is developed.

2 Structural design of space instruments

In order to develop the new type of structural design and to derive a suitable in orbit demonstration experiment, it is necessary to clearly state the problem of designing space instruments. Therefore, the fundamental requirements and constraints as well as the basic design principles for space instruments are presented in the following.

2.1 Requirements and constraints of space instruments

The space instrument design process starts with the question "What is to be measured?" [4]. This question is defined by the mission goals and leads to the technical performance requirements of the instrument. For instance, in the case of Earth observation, this would include the minimum resolution and a certain field of view. Throughout the interlinked process of the satellite system design and the instrument implementation, the constraints on the instrument design are identified. These constraints can be broadly classified into two categories:

- Budgetary constraints, which originate from the mission concept and primarily concern mass, size, and power.
- Environmental constraints, which pertain to the conditions experienced by the satellite during ascent and its operation in orbit. This primarily concerns the acceleration, acoustic, and shock loads during launch and the harsh thermal environment in orbit.

Importantly, there are major changes in conditions when entering the orbit, e.g., disappearing gravity forces in

orbit, vacuum, radiation, and the change from a constant to an alternating thermal environment.

2.2 Structural architecture of space instruments

Within the development of the space instrument, a layout of the functional elements is defined. Subsequently, a mechanical structure is developed for keeping the relative position and orientation of those elements. For illustration, the principal architecture of an exemplary lens barrel is depicted in in Fig. 1.

The lens system serves to focus the image onto the focal plane, where the sensor is located. The functional elements are held in position by a mechanical structure with functional element mounts. In some cases, a (re-)adjustment mechanism is foreseen. Generally, there is a thermal expansion mismatch between satellite and mechanical structure which is compensated by an isostatic mounting. There are many configurations, e.g., active and passive sensing or reflecting and refracting configurations can distinguished. However, it should be noted that in order to achieve the required technical instrument performance, there are only low tolerance limits for changing the relative position and orientation of the functional elements. Therefore, the mechanical structure must be dimensionally stable, primarily with respect to the mechanical launch loads and orbital thermal loads [42]. First, in order to avoid permanent deformation, a minimum stiffness and in order to avoid resonances a minimum natural frequency is required. Second, the harsh thermal environment and heat from the internal environment of the satellite would cause thermally induced deformations and variations of optical materials which requires the athermalization of the instrument [43]. At the same time, the design of the mechanical structure has to enable accurate and simple assembly and alignment of the instrument.

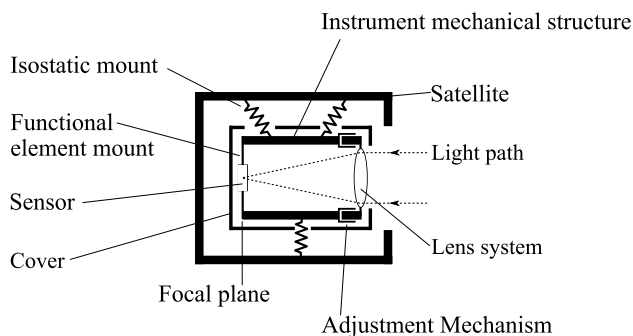


Fig. 1 Principal structural architecture of a lens barrel instrument (cf. [41])

2.3 Athermalization

Athermalization denominates the process of making the instrument insensitive with respect to temperature variances [44]. First, this can be reached by holding the temperature of the instrument as constant as possible (e.g., by insulation and a high thermal conductivity) which is not always sufficient or beneficial. Second, the thermally induced changes can be compensated. In general, two principal techniques can be distinguished:

- Passive Athermalization
- Active Athermalization

Both are described in the following:

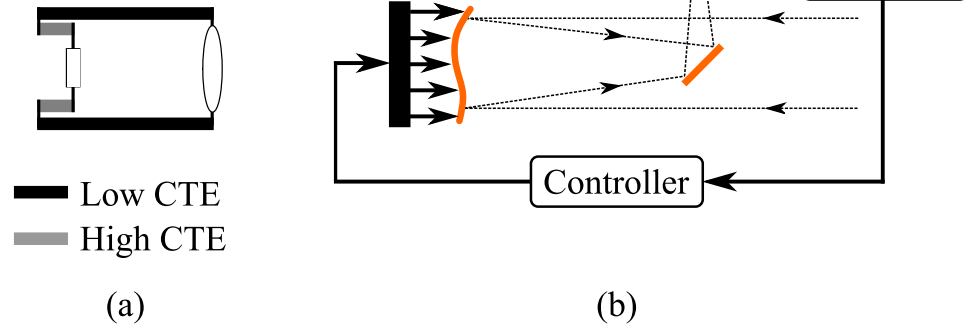
2.3.1 Passive athermalization

Passive athermalization means that materials and designs chosen for the mechanical structure compensate for the deformations in such a way, that the relative position and orientation of functional elements is maintained. This can be done applying materials with low CTE like certain CFRP configurations or Invar [45]. Second, dimensional stability can be reached by combining materials with different CTEs in a compensating geometric arrangement. An exemplary re-entrant arrangement based on the Gridiron Pendulum principle by Harrison is illustrated in Fig. 2a [46].

2.3.2 Active athermalization

Active athermalization denotes the compensation of induced deformations by actuators in controlled manner. This technique allows the compensation of thermal gradients and a higher allowable thermal operating range. Furthermore, the design of structures and materials is more flexible when complete passive athermalisation is not a requirement. However, this technique adds complexity and needs power [49]. In fact, the technique is a thermoelastic shape control and has been implemented in various forms. First, precise thermal control can be used [32]. Instead of using dedicated actuators, heating elements are directly attached on the instrument structure. Second, structural control with dedicated actuators like stepper motors can be applied. For reflecting space telescopes, the main challenge is the deformation of the primary mirror due to high apertures. Therefore, there the compensation is achieved through the use of an actuated deformable mirror and which is referred to active optics (see Fig. 2b) [48].

Fig. 2 Schematic diagrams of athermalization forms. **a** Bi-material re-entrant compensation (cf. [47]). **b** Principle of active optics at a Newtonian telescope (cf. [48])



3 Thermoelastic metamaterials

Mechanical metamaterials are a class of multiphase materials with exceptional macroscopic properties, such as a negative Poisson's ratio, resulting from a rationally designed multiphase material structure (consisting of elementary phases, e.g., an aluminum phase and a void phase) at a smaller length scale than that of the macroscopic properties (cf. [50, 51]). A particular category of metamaterials are those that have unusual coefficients of thermal expansion, and are therefore referred to as thermoelastic metamaterials. Those materials are in fact lattice structures with dedicated arrangement of at least two material phases with different CTE. In particular, structures with zero or even negative CTEs are feasible. With the emergence of metallic multi-material additive manufacturing, they are becoming available for space applications. The tunable CTE of the material is a consequence of the thermal expansion mechanism of the general constituting building block depicted in Fig. 3.

In addition to the CTE, other properties that are important for instrument structures, such as thermal conductivity and stiffness, can be designed. However, it has to be noted, that those properties are highly coupled and can not be designed independently.

Notably, the responsive behavior to external stimuli such as joule heating can be designed leading to active mechanical metamaterials [51]. For instance, thermoelastic actuators that can be activated with heating patches can be printed, as depicted in in Fig. 3. Summing up, unprecedented high-performance space instrument structures with position-dependent, anisotropic and multi-functional properties are theoretically conceivable. However, the design and the implementation of such structures are part of current research [52].

4 Athermalization with thermoelastic metamaterials

The designable thermal expansion behavior of thermoelastic metamaterials is initially advantageous for passive athermalization of space instruments. These materials enable the fabrication of instrument structures with zero CTE as well as of instrument structures with compensated thermal expansion. Second, active thermoelastic metamaterials (see Fig. 3b) with adjustable properties such as thermal conductivity are beneficial for active athermalization approaches.

There are numerous additional potential benefits that can be realized, particularly due to the unique capabilities of additive manufacturing methods. On the one hand, the high design freedom enables to tune a wide range of further material properties, such as stiffness, damping, and thermal capacity, and therefore enables improvements in multiple instrument characteristics. Moreover, they can be enhanced with further functionalities such as thermally triggered release mechanisms applicable in deployable systems. On the other hand, the ability to rapidly redesign and remanufacture parts during the project life cycle, thereby enhancing speed and flexibility in instrument design.

In this course, both fully metamaterial structures and hybrid structures, i.e., structures with metamaterial components, are suitable for athermalizing instruments. The main advantage of hybrid structures is that they allow the right material to be used in the right place, for example optical glass for lenses, metamaterial for thermoelastic compensation, and economical aluminum for structural parts of the instrument. They also overcome the size limitations of printable parts.

However, the metamaterial itself is barely usable directly in engineering applications. Metamaterial configurations and elements must be adapted to fulfill engineering requirements and constraints, such as stiffness and mechanical interfaces to other parts of the engineering structure. Additionally,

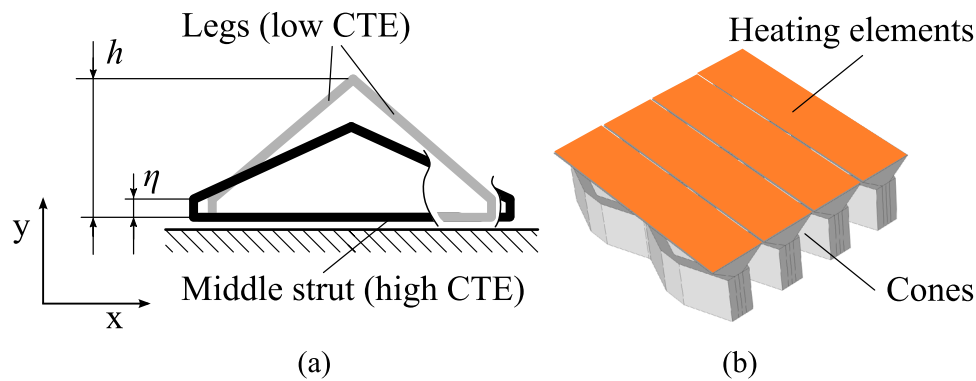


Fig. 3 **a** Building block of a thermoelastic metamaterial with negative CTE. The thermal expansion of the middle strut is higher than those of the legs. This results in a reduction of the height h of the triangle when heated. The offset η avoids overlaps in the junctions with

non-negligible wall thicknesses. **b** Active thermoelastic metamaterial actuator for unidirectional expansion with conical structural protrusions to accommodate heating elements (orange) (cf. [26])

manufacturing constraints of currently available manufacturing methods, in particular part size limitation, required support structures and the available material combinations must be considered. Therefore, dedicated structural architectures for specific engineering applications need to be engineered, which is subject of ongoing research. In the following, structural instrument architectures for space instruments athermalized by thermoelastic metamaterials are developed through systematization, i.e., through establishing different classification criteria for the structural concepts and then systematically investigating the resulting variants. The definition of different classification criteria is useful due to the following main reasons:

- Exploring the solution space.
- Facilitating the development of dedicated structural elements and structural concepts including their characteristics as well as systematic design methods.
- Identifying development directions and research needs.

In this work, two classification criteria for instrument architectures are applied.

(1) Classification based on the metamaterial working directions. This approach particularly fosters the development of unit cells with tailored kinematics, taking into account manufacturing constraints. Moreover, it enables the creation of universally applicable compensators, thereby broadening the scope of potential applications.

(2) Classification based on integration level. Especially, by categorizing architectures based on their integration level, the development of multifunctional metamaterial modules for specific engineering applications is promoted. For example modules that are specifically suited for use in space instruments (see also Sect. 4.4).

Further criteria (e.g., specific weight, applicable temperature range) should be investigated in future work.

In the following, both categories are developed with a focus on passive athermalization at a lens barrel and are then extended to the active approach. Then, the use of both categories in the design of structural metamaterial components for a Cassegrain-type space telescope is discussed briefly.

4.1 Classification of instrument architectures based on metamaterial working directions

Thermoelastic metamaterials use the inherent thermal expansion of materials through rationally geometries in order to produce desired deformations between particular interfaces. These desired deformations can be classified according their working direction into the following categories (see Fig. 4):

- No deformation
- Translational deformation along 1, 2, or 3 axes
- Rotational deformation about 1, 2, or 3 axes
- Other types of deformation such as coupled deformation or shear

For example, the triangle presented in Fig. 3 is designed to reach a certain uniaxial translational deformation between the base and the top. Notably, the triangle also expands in lateral direction at the same time which is not used for this building block. This expansion has to be considered in engineering applications, particularly at a zero CTE in working direction that involves a non-zero CTE in lateral direction. The three translational and rotational categories are particularly useful for the compensation of certain undesired thermally triggered movements of functional elements with specific position shifting and orientation stability requirements.

(1) Initially, the entire instrument structure could be made out of metamaterial with zero CTE, as shown in Fig. 4a. Compared to traditional instrument structures, this would

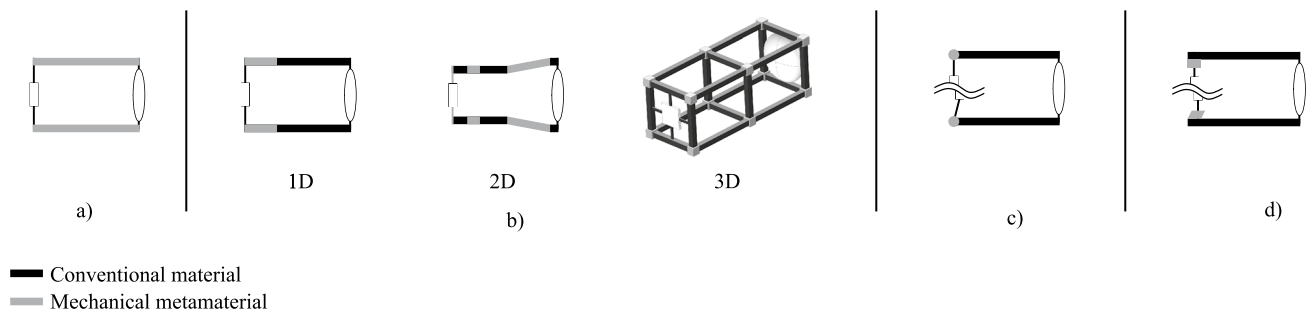


Fig. 4 Illustration of principle instruments architectures athermalized with thermoelastic metamaterials classified based on the metamaterial working direction. **a** Zero-CTE instrument structure. **b** Translationally compensating metamaterial units. (1D) Unit with negative CTE in series with the rest of the instrument structure (cf. [47, 53]). (2D) Lens barrel with two metamaterial units compensating in axial

(left) and axial and radial (right) direction. (3D) Frame construction with triaxially compensating nodes. **c** The sensor's compensating translational movement is achieved by two attached levers that are rotated with two metamaterial units at the left lens barrel end. **d** Compensating elements using a shear mechanism

simplify the design and manufacturing, and improve stiffness and toughness. However, this type of design has two principal disadvantages: first, to achieve zero CTE certain lattice structures must be used. These are generally unfavorable in terms of other instrument requirements, such as stiffness and weight. In particular, it is hardly possible to design load introduction and functional element mounts with zero CTE due to the accommodation of joints. In addition, if the instrument structure is larger than the build volume of the 3D printer, it must be manufactured and assembled in parts which also requires joints. Second, functional elements typically do not have a zero CTE. Therefore, compensation elements with non-zero CTE are required for athermalization.

(2) Second, thermoelastic metamaterials can be utilized to build compensating units with a translational working direction as depicted in Fig. 4b. For example, they can be used to uniaxially compensate for the lens barrel structure when applied in series with the instrument structure, as shown in Fig. 4 (b, 1D) (cf. [53]). 2D/3D compensators can be used for more complex design and are beneficial regarding athermalization performance and stiffness properties. For illustration, a lens barrel with two units compensating in axial and radial direction (Fig. 4 (b, 2D)) and a frame construction with triaxially compensating nodes (Fig. 4 (b, 3D)) is shown. Notably, anisotropic compensators with different CTEs in the three directions can be built. However, uniaxial compensators have a simple design and are easier to print than 2D/3D compensators with 3D unit cells, which generally require support structure during printing.

(3) Third, metamaterials with rotational working directions around 1, 2 and 3 axes can be built. They can be used to compensate for certain rotational movements or – in combination with a lever – to generate translational movement. In Fig. 4c, the sensor's compensating translational movement is achieved by two attached levers that are rotated with two metamaterial units at the left lens barrel end.

(4) Fourth, the described rotational and translational deformations can be coupled (cf. [54]) in order to meet specific compensation requirements or geometric constraints of the instrument structure. Moreover, other kinematic mechanisms such as shear (Fig. 4d) or bending can be applied.

4.2 Classification of instrument architectures based on integration level

Thermoelastic metamaterials can be beneficial on all levels of integration. Therefore, 5 levels of compensating architectures are developed starting from component level (compensator) to system level (satellite) in the following (see Fig. 5).

(1) First, thermoelastic metamaterial elements can be utilized as simple compensator. In this course, functional material properties of the metamaterial (thermal expansion) dominate structural properties (load bearing) clearly. In Fig. 5 (1), a lens barrel with compensating elements using a negative CTE (above) and a high positive CTE in combination with a re-entrant mechanism (below) is depicted. The structural loads are carried by translational joints.

(2) Second, metamaterial compensating units can be structurally integrated to carry load besides their compensating function. Due to the variable CTE, the size and shape of the compensation element is highly customizable, enabling designs with good flux of forces. For illustration, a ring-shaped compensating unit for lens barrels is depicted in Fig. 5 (2). In many cases, the metamaterial shall meet different requirements in different working direction which should be considered for enhanced application-specific properties. For instance, the illustrated ring-shaped compensating unit should only compensate for axial movement and be stiff in all other directions. For challenging requirements, complex integral instrument structures with multiple metamaterial compensation units can be built with any anisotropic CTE, but this involves a complex design.

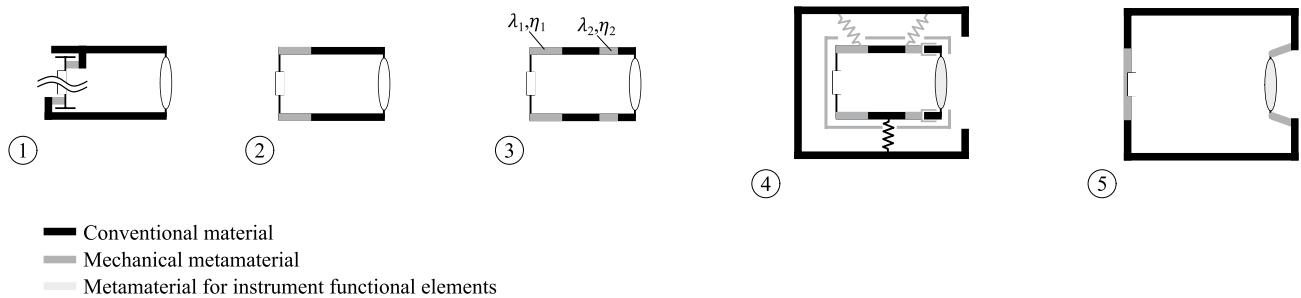


Fig. 5 Illustration of principle instruments architectures athermalized with thermoelastic metamaterials classified based on the integration level. (1) Lens barrel with simple thermoelastic metamaterial compensator with only subordinate structural function and negative CTE (above) and positive CTE (below). (2) Structurally integrated unidirectionally compensating metamaterial unit with negative CTE in

(3) Third, further properties besides thermoelasticity and stiffness such as the thermal conductivity λ or damping properties η of the compensating element can be designed (see Fig. 5 (3)). This allows the instrument structure to be specifically adapted to the instrument's environment, such as high radiant thermal loads. Particularly, this is advantageous for instruments manufactured in space where the installation of systems for vibration damping or thermal control would be both expensive and impractical [55, 56]. However, the design and manufacturing of such structures is complex.

(4) Fourth, multifunctional metamaterial compensating blocks can be designed as depicted in Fig. 5 (4). This allows for the integration of further functions required by the instrument, such as heat exchangers, vibration dampers [57] or isostatic mounts [58–60].

(5) Fifth, instead of building a dedicated instrument structure, the functional elements can be integrated into higher level structures such as the satellite structure (see Fig. 5 (5)). These fully integrated structures could potentially have various functions enabled by metamaterials such as thermal control [61–63]. On the one hand, very specific instrument structures can be created for very specific applications. On the other hand, structures can be built that are unparalleled in their ability to withstand a wide range of environmental loads. Ultimately, functionally graded structures can be considered.

However, the passive approach has disadvantages: first, the compensated structure still exhibits thermal expansion when exposed to temperature gradients. This phenomenon also occurs in metamaterials itself, which are composites of at least two materials. This can be explained using the building block depicted in Fig. 3. The desired expansion in y-direction is only reached by exact relative thermal expansions of the middle strut and the legs. A temperature gradient between the legs and the middle strut will lead to an undesired relative thermal expansion resulting in a different

series with the rest of the instrument structure (cf. [47, 53]). (3) Metamaterial units featuring additional custom properties such as thermal conductivities λ or damping properties η . (4) Instrument structure with several functional metamaterial components, such as isostatic mounting, functional optical elements, and self-adapting cover. (5) Highly integrated multi-functional satellite structure

expansion in y-direction. This effect is strengthened by the different thermal conductivity of the different materials constituting the lattice. Second, the compensation readily is only effective for narrow temperature ranges where the CTEs can be approximated as non-temperature-variant. For larger temperature ranges, the differently changing CTEs of the individual constituents lead to not-compensated length differences that can be addressed with active systems. As a consequence, active athermalization with thermoelastic metamaterials is considered in the following.

4.3 Active athermalization with thermoelastic metamaterials

Active athermalization with thermal actuators makes use of controlled thermal stimulation of the inherent thermal expansion of materials. As a result, any structural element with a non-zero coefficient of thermal expansion (CTE) can serve as an actuator. However, active thermoelastic metamaterials are particularly advantageous due to the tunable temperature–displacement relationship and adjustable further properties, such as thermal conductivity and heat capacity. Hence, active thermoelastic metamaterials covering all the working directions (see Fig. 5) with parametrized thermal properties should be developed. They can be applied on all levels of integration (see Fig. 6). In the following, specific characteristics and challenges are discussed by applying the integration level-based classification to the case of a lens barrel with active athermalization using thermoelastic metamaterials.

(1) At first, simple compensating elements can be equipped with heating elements as depicted in Fig. 6 (1). It is important to note that negative displacement action through heating can be achieved with metamaterials that have negative CTEs, which was previously only possible by cooling.

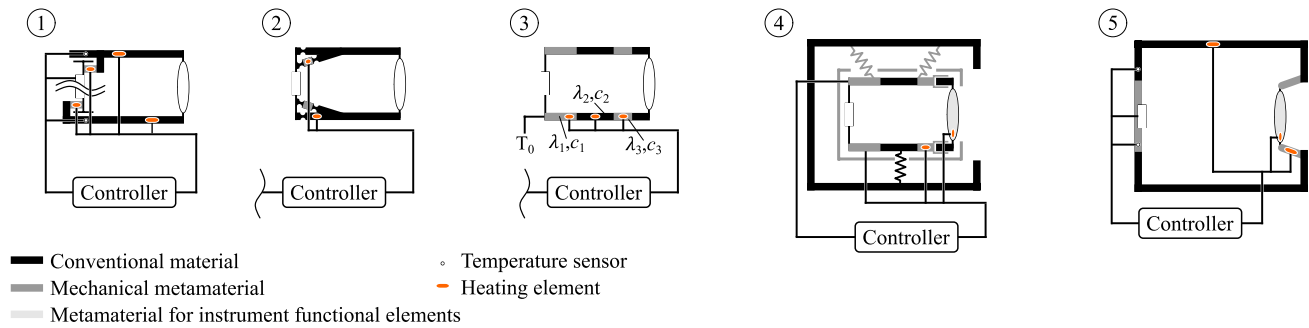


Fig. 6 Illustration of principle instruments architectures actively athermalized with thermoelastic metamaterials classified based on the integration level. (1) Lens barrel with simple thermoelastic metamaterial actuator capable of negative displacement action through heating due to negative CTEs (above). (2) Metamaterial units and instrument structure are combined to form a compound kinematic mechanism that facilitates compensation. (3) Metamaterial units and instrument structure featuring additional custom properties such

Temperature sensors or wavefront sensors can be used as inputs to the control system.

(2) Second, the thermoelastic metamaterial actuators can be structurally integrated which refers to level 2 (see Fig. 6 (2)). This is important for load-bearing purposes, as well as kinematic considerations. The instrument structure and metamaterial units can be combined to form a higher-level kinematic mechanism that benefits from compliant hinges for instance.

(3) Third, the dynamic thermal behavior of the whole instrument can be considered as the heat fluxes to and from the actuators affect both the magnitude and decay of displacement responses. Therefore, material properties such as thermal conductivity λ or heat capacity c of the compensating element as well as of the surrounding instrument structure should be designed (see Fig. 5 (3)). In this course, all the mechanisms of heat transfer and thermal boundaries (e.g temperature boundary T_0) have to be considered. For space applications, heat transfer is dominated by radiation and conduction.

(4) Fourth, the functionality of the instrument structure can be extended by integrating advanced metamaterial configurations, e.g., pantographic metamaterials for deployable structures, metamaterials with adaptive thermal conductivity or optical properties (see Fig. 5 (4)) [64, 65]. Particularly, deformable mirrors could be equipped with thermoelastic metamaterials which is explained in Sect. 4.4. For re-adjustment, thermoelastic metamaterials with residual displacement could be developed using stability effects in metamaterial mechanisms [66]. Moreover, advanced metamaterial units with integrated Joule heating and sensing functionalities could be incorporated.

(5) Fifth, numerous thermally triggered functionalities can be used in higher level structures such as the satellite

as thermal conductivities λ or specific heat capacities c taking thermal boundaries such as temperature T_0 into account. (4) Instrument structure with several functional metamaterial components, such as re-adjustment mechanisms, deformable mirrors, and elements with adaptive optical properties and integrated sensing and Joule heating activation. (5) Highly integrated multi-functional active satellite structure

structure or lead to new structural satellite concepts (see Fig. 5 (5)).

4.4 Thermoelastic metamaterials for the athermalization of cassegrain-type space telescopes

Many space missions employ similar structural design concepts for optical instruments, such as Cassegrain-type reflectors. Consequently, metamaterial structural elements of such concepts can be systematically developed for wide application. It should be noted that this also applies to elements of high level of integration, such as deformable mirrors. In the following, the athermalization of a Cassegrain-type space telescope with thermoelastic metamaterials is briefly discussed, as depicted in Fig. 7. The classification system introduced earlier is applied to the relevant sub-elements, namely the support rods and the deformable mirror.

For the rods supporting the secondary mirror, passive athermalization is a suitable solution. In this course, metamaterial units with no deformation or translational working directions (see Sect. 4.1) would be applicable straightforwardly: The rods can be made of zero CTE metamaterial (a), with uniaxially compensating units (b) or bi/tri-axially compensating joints. For the rotational mechanisms as well as for the advanced mechanisms, a structural revision of the design would be necessary.

For the deformable mirror, active athermalization is suitable as it also enables active optics. The deformable mirror can be build with simple metamaterial actuators with positive (+) and negative (-) CTE, with structurally integrated metamaterial configuration (levels 2 and 3, e), with additionally added metamaterial-based deployment

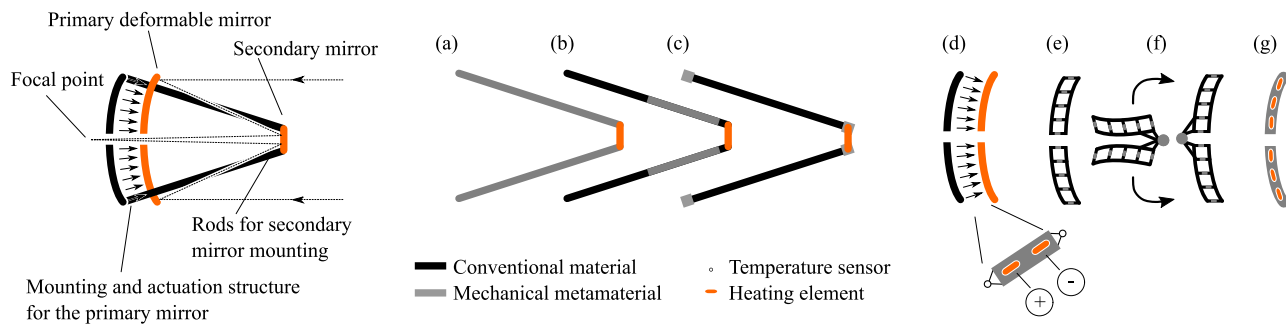


Fig. 7 Illustration of the use of thermoelastic metamaterials for the athermalization of Cassegrain-type space telescopes. The rods for holding the secondary mirror can be made of zero CTE metamaterial (a), with uniaxially compensating units (b) or bi/tri-axially compensating joints (c). The deformable mirror can be built with simple

metamaterial actuators with positive (+) and negative (-) CTE (level 1, d), with structurally integrated metamaterial configuration (levels 2 and 3, e), with additionally added metamaterial-based deployment systems (level 4, f) or as fully integrated metamaterial mirror (g)

systems (level 4, f) or as fully integrated metamaterial mirror (g).

5 Technology roadmap

Although the technology of athermalization with thermoelastic metamaterials has the potential to enable unprecedentedly accurate and robust instrument structures, it is still in its infancy and not yet ready for application. The knowledge gaps can be broadly classified as follows:

- Development of suitable metamaterial geometries and structural instrument design concepts, as well as the creation of suitable design methods.
- Mature the metallic multi-material additive manufacturing process and characterization of the multi-material joints.
- Advance the system designs, system design methods and testing. This also includes the development of a prototype for in-orbit demonstration.

In order to provide a roadmap for taking this technology into application, the essential steps are presented according to the Technology Readiness Levels, as illustrated in Table 1. Within the research in the context of the Modern Structures Experiment of the SeRANIS mission it is aimed at to advance the technology to TRL 6/7.

6 The modern structures experiment: in-orbit demonstration of athermalization with thermoelastic metamaterials

In order to pave the way for the application of athermalization with thermoelastic metamaterials, the proof of the technology in an in-orbit demonstration experiment is necessary. The Modern Structures Experiment as part of the SeRANIS Mission presented in the following aims at giving that proof [68, 69]. The sun-synchronous low Earth orbit of the mission presents significant thermal challenges for the in-orbit demonstration of the technology and offers a high degree of practical relevance. In the following, the experiment objectives, system design and mechanical design are explained.

6.1 Experiment objectives

The Modern Structures Experiment will develop an exemplary structure to demonstrate and explore passive and active athermalization with thermoelastic metamaterials. Furthermore, the development process itself of instruments with this technology within a real space mission life cycle is investigated as part of the SeRANIS mission.

6.2 Conceptual and system design

The experiment comprises two installation spaces: Outside the satellite for the experimental structure called the Distortion Structure Assembly, and inside the satellite for the controller, logger, and laser interferometer measurement system (see Fig. 8).

As a result, the Distortion Structure is subjected to significant temperature fluctuations, which are essential for the in-orbit demonstration. In contrast, the systems for

Table 1 Technology readiness levels for the technology athermalization of space instruments with thermoelastic metamaterials (cf. [67])

TRL	Milestone	Meaning for the Athermalization of Space Instruments with Thermoelastic Metamaterials
1	Basic principles observed	• Literature review of works on mechanical metamaterials in thermoelastic and thermal regime • Analytical and numerical investigation of (active) thermoelastic metamaterials
2	Technology concept and application formulated	• Description of the principle of active and passive athermalization with thermoelastic metamaterials • Consideration of space instruments as application
3	Analytical and experimental proof-of-concept	• Studies of potential metamaterial designs and space instrument architectures considering space instrument requirements and constraints • Development, manufacturing and laboratory tests of basic (active) thermoelastic metamaterial elements (e.g., unit cells)
4	Component functional verification in laboratory environment	• Design of instrument architectures and related control techniques • Development, manufacturing and laboratory tests of applicable (active) thermoelastic metamaterial elements (e.g., multi-cell actuators) • Development and laboratory tests of critical elements (e.g., suitable mechanical joints, heating element application) of the instrument architecture
5	Component function verification in a relevant environment	• Experimental vibration and thermal vacuum tests of components ((active) thermoelastic metamaterial actuators, controller, structure) • Numerical investigation of the thermoelastic behavior of the system (structure and controller) in orbit
6	Model demonstrating the critical functions of the element in a relevant environment	• Development, manufacturing of a functional prototype (structure and controller) • Experimental vibration and thermal vacuum tests of the functional prototype
7	Model demonstrating the element performance for the operational environment	• Development, manufacturing of a suitable technology demonstrator of in-orbit operation. • Evaluating performance of in-orbit technology demonstrator
8	Actual system completed and accepted for flight ("flight qualified")	• Development, manufacturing of a space instrument athermalized with thermoelastic metamaterials. • Qualification and rigorous testing of the instrument
9	Actual system "flight proven" through successful mission operations	• Usage of space instrument athermalized with thermoelastic metamaterials, e.g., in a Earth observation or astronomy mission • Investigate space instrument performance to confirm reliability and effectiveness of this technology

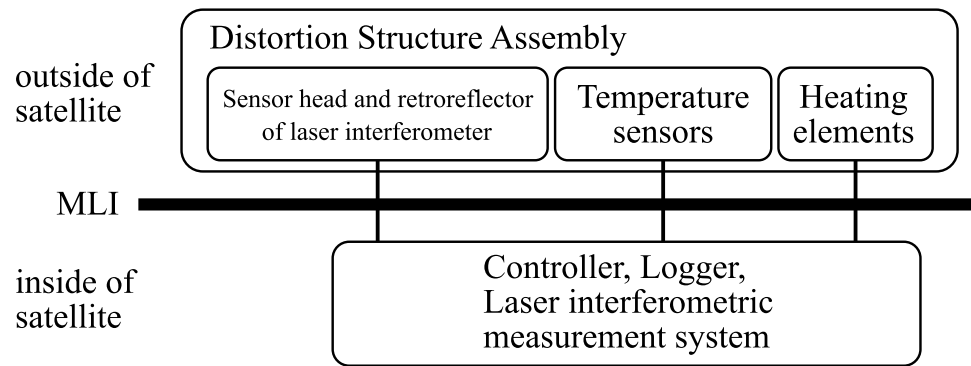
measurement and control are inside of the satellite in a thermally more stable environment. The Distortion Structure is equipped with a laser interferometric measurement system and temperature sensors to measure the current thermoelastic state. Moreover, it is outfitted with heating elements to purposefully influence its thermoelastic shape. The experiment has in principal three operational modes:

- Monitoring the displacement and temperatures
- Heating one or several heating elements according to a predefined schedule while monitoring the displacement and temperatures

- Heating one or several heating elements in a feedback loop with temperatures and or displacement as input while monitoring the displacement and temperatures

In order to apply model-based control approaches, the controller is capable of transient heating, which differs from the conventional on/off functionality [36, 37]. In order to facilitate the investigation of a number of schedules and control algorithms, the software installed on the controller is capable of being updated in orbit. The monitored data are recorded by a logger and downlinked for analysis.

Fig. 8 System level block diagram of the main components



6.3 Mechanical design of the distortion structure assembly

The Distortion Structure is, in essence, a unidirectional expansion structure comprising an aluminum U-profile and a thermoelastic metamaterial actuator with negative thermal expansion arranged in series (see Fig. 9).

This refers to the uniaxial working direction and integration level 2 (see Figs. 4, 5, and 6). Due to this simple design, a reliable investigation of the athermalization techniques is possible while keeping the applicability for future instruments. In order to facilitate the investigation of this structure, supportive structures were incorporated into the design, resulting in the Distortion Structure Assembly. The assembly consists of six main components grouped in three modules that are described in Tables 2, 3.

The design of the thermoelastic metamaterial actuator is based on the work of Buchmann et al. [26] (see Fig. 10 and Table 4).

Placing the cone-shaped activation structures along the hypotenuses is advantageous as it does not impede the rotation of the legs. Additionally, it enhances negative displacement upon heating due to both the slightly higher stiffness of the hypotenuses and the localized heat input, which causes the hypotenuses to expand more than the legs. It serves for two purposes: on the one hand, it partially compensates the expansion of the U-profile in order to investigate the passive compensation mechanism. On the other hand, it can be activated with heating elements to create negative thermal expansion in y-direction. Together with the heating elements placed on the aluminum with positive CTE, the investigation of active athermalization mechanisms is enabled.

6.4 Principal thermoelastic behavior

The principal thermoelastic behavior of the Distortion Structure Assembly was investigated in passive and active regimes using finite element method. Mechanically, the

Fig. 9 Illustration of the Distortion Structure Assembly. For the description of the components refer to Table 2

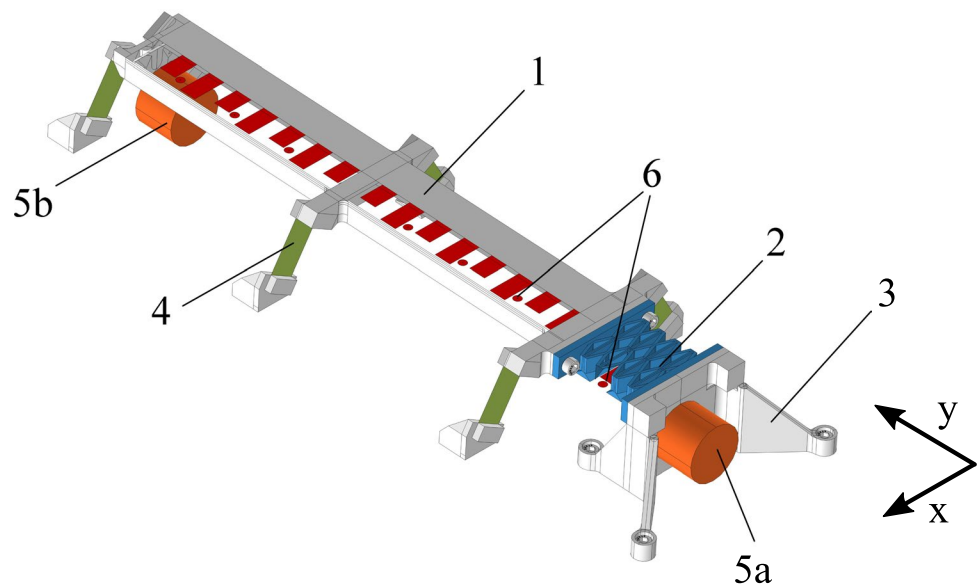
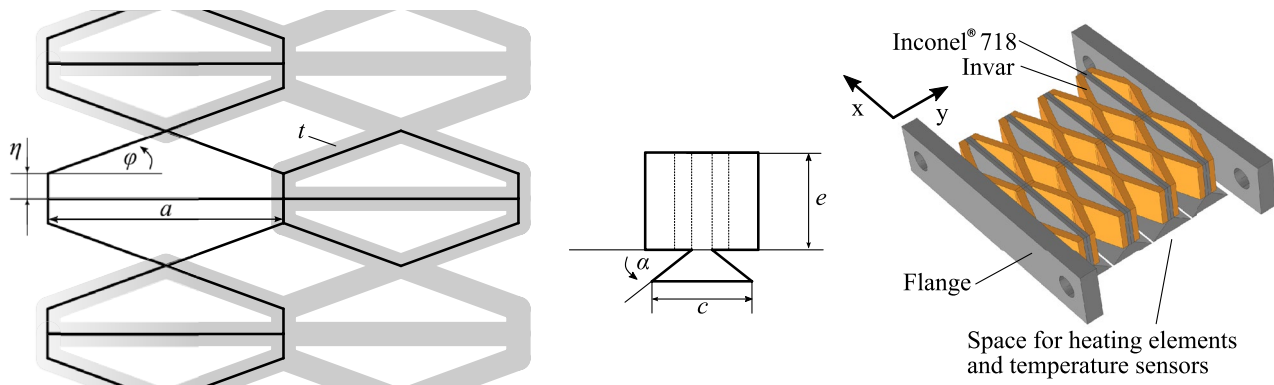


Table 2 Main components and modules of the Distortion Structure Assembly and their functional purpose. For the material properties, refer to Table 3

No.	Component	Purpose	Module
1	U-Profile	Aluminum structure with positive CTE. Accommodates heaters, temperature sensors and retroreflector of the laser interferometer	Distortion Structure
2	Metamaterial actuator	Multimaterial (Invar and Inconel [®] 718) compensating element with negative CTE. Accommodates heaters and temperature sensors	
3	Sensorbracket	Aluminum structure providing the fixpoint for the thermal expansion of the Distortion Structure. Accommodates the sensor head of the laser interferometer	Structural isostatic mount of the Distortion Structure
4	Flexure mounts with foots	Isostatic mounts with titanium flexures enabling the deformation in y-direction of the Distortion Structure	
5	Laser interferometric displacement measurement system	Measuring the thermal expansion of the Distortion Structure with sensorhead (5a) and retroreflector (5b)	Measurement and Actuation System
6	Heating elements and temperature sensors	For measuring the temperature field on the Distortion Structure and for purposefully triggering thermal expansion through joule heating	

Table 3 Material properties of the Distortion Structure Assembly

Property	Aluminum	Titanium	Invar	Inconel [®] 718
Young's modulus (GPa)	69	113.8	140	200
Poisson's ratio	0.33	0.33	0.3	0.3
Density (kg/m ³)	2730	4430	8100	8200
Thermal conductivity (W/m·K)	155	6.7	13.5	12
Specific heat capacity (J/kg·K)	893	526	515	450

**Fig. 10** Geometry of the metamaterial actuator with negative CTE in y-direction. For the dimensions refer to Table 4**Table 4** Main dimensions of the mechanical metamaterial actuator

Property	Value
a	25 mm
η	2 mm
φ	20°
t	2 mm
α	35°
c	12.5 mm
e	11 mm

structure was constrained at the six support feet and at the four bolted interfaces of the sensor bracket. Thermally, heat exchange was limited exclusively to the defined heating elements; no additional thermal interactions with the environment were considered here.

In the passive regime, athermalization was assessed using two uniform temperature load cases: a hot case with $\Delta T = +100^\circ\text{C}$ and a cold case with $\Delta T = -100^\circ\text{C}$. The resulting displacements of the actuator (d_{Act}) and of the

Fig. 11 Experimental structure with characteristic lengths of $d_{Act} = 62$ mm for the actuator and $d_{Exp} = 434$ mm for the overall assembly (above). The functionality of the flexures is illustrated in the deformed plots showing scaled y-displacements for the hot case ($\Delta T = +100^\circ\text{C}$) and the cold case ($\Delta T = -100^\circ\text{C}$) (below)

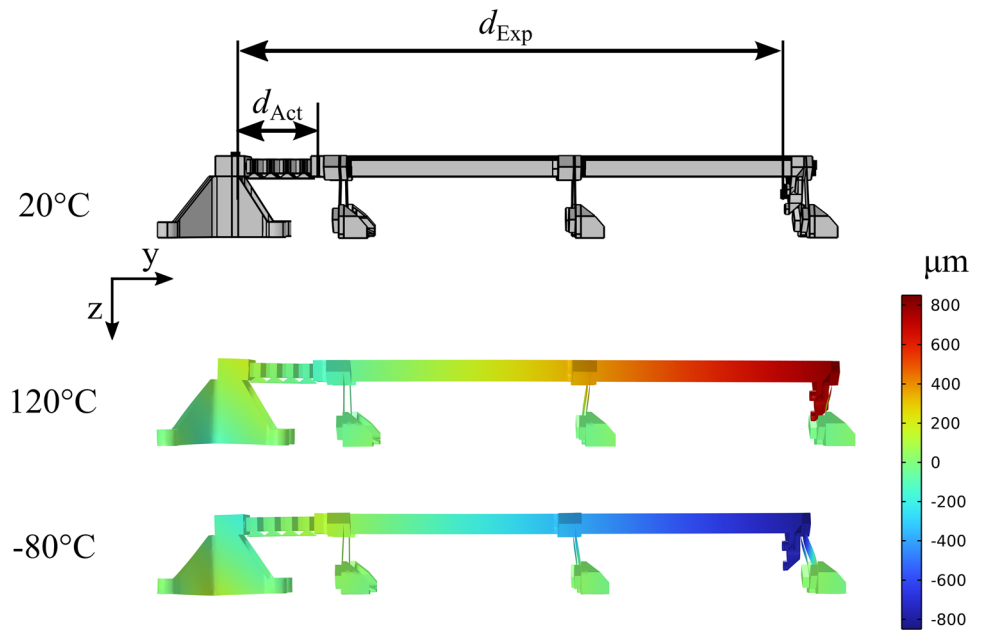


Table 5 Comparison of displacements of an aluminum and multi-material actuator triggered by hot case and cold case

Actuator Material	Hot case ($\Delta T = +100^\circ\text{C}$)		Cold case ($\Delta T = -100^\circ\text{C}$)		$\Delta d_{total} (\mu\text{m})$
	$\Delta d_{Act} (\mu\text{m})$	$\Delta d_{Exp} (\mu\text{m})$	$\Delta d_{Act} (\mu\text{m})$	$\Delta d_{Exp} (\mu\text{m})$	
Inv./Inc	-201	734	201	-734	1468
Aluminum	121	1032	-121	-1032	2064

experimental structure (d_{Exp}) were compared for two material configurations: the metamaterial design and a reference design made entirely of aluminum (see Fig. 11). The actuator has a characteristic length of $d_{Act} = 62$ mm, while the overall experimental structure spans $d_{Exp} = 434$ mm.

It was observed that the metamaterial actuator contracts in the hot case ($\Delta d_{Act} < 0$) and expands in the cold case ($\Delta d_{Act} > 0$) whereas the aluminum actuator exhibits the opposite behavior as shown in Table 5. As a result, the total displacement difference between the hot and cold cases was reduced from $\Delta d_{total} = 2064 \mu\text{m}$ in the aluminum reference design to $\Delta d_{total} = 1468 \mu\text{m}$ in the metamaterial configuration. This behavior enables passive athermalization to be validated under in-orbit conditions while still providing sufficient displacement range for testing active compensation strategies. Additionally, the functionality of the flexures is illustrated in Fig. 11, where the deformed shapes are shown with scaled y-displacements for both temperature extremes.

In the active regime, the displacement response of the structure to thermal excitation was investigated. A heat pulse of 4 W was applied for 30 s, once using the four heating elements attached to the metamaterial, and once using sixteen heating elements on the aluminum structure. Heating

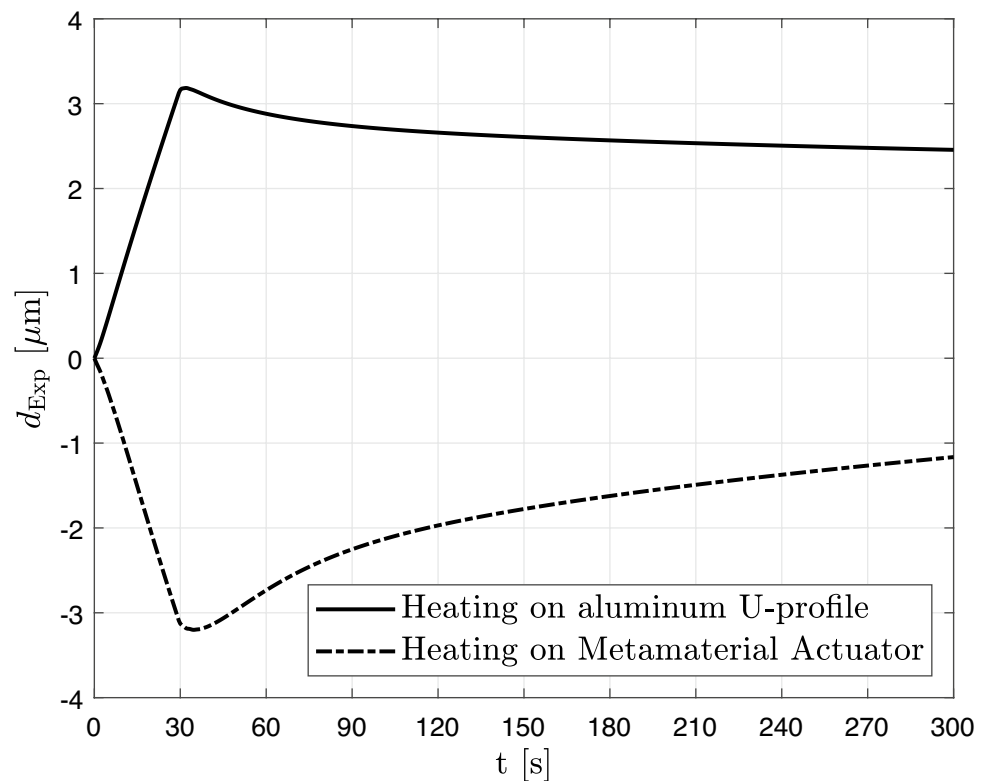
the metamaterial actuator resulted in a negative displacement of approximately $3 \mu\text{m}$ while heating the aluminum U-Profile produced a positive displacement of about $3 \mu\text{m}$ (see Fig. 12).

The response time and the displacement amplitude were similar in both cases, while the decay of the displacement of the pulse on the metamaterial is faster. These results demonstrate the feasibility of precise displacement control through thermal actuation. Future work will focus on the development and implementation of dedicated control algorithms.

7 Conclusion

In this paper, architectures for space instruments athermalized with thermoelastic metamaterials are systematically derived. Principally, five levels of integrating metamaterial elements reaching from zero-CTE instrument structures to fully integrated multifunctional satellite structures are distinguished. Due to the highly tunable material properties of metamaterials, functionally and structurally efficient metamaterial elements for both passive and active athermalization approaches can be designed. At the same

Fig. 12 Thermoelastic displacement response to a 4 W, 30-second heat pulse: comparison of actuation via heating elements on the U-profile (above) and the metamaterial actuator (below)



time, knowledge gaps hindering its application are identified. In order to facilitate the implementation of the technology, the essential steps are presented according to the Technology Readiness Levels (TRL). Then, the conceptual system and the mechanical design of the Modern Structures Experiment as a suitable in-orbit demonstration experiment of this technology are presented. Subsequent research should entail a detailed mechanical design of the Distortion Structure Assembly, followed by an implementation and empirical investigation. Moreover, space missions aiming at the application of the technology to enhanced space instrument architectures such as reflective telescopes with deformable mirrors can be done.

Author Contributions E.B.: Writing – original draft, Investigation, Methodology, Validation, Visualization, Project administration, Formal analysis, Conceptualization. I.B.P.: Writing – review & editing, Validation, Formal analysis. E.A.J.: Writing – review & editing, Validation, Formal analysis, Resources, Funding acquisition, Conceptual design of the research project. P.H.: Writing – review & editing, Validation, Formal analysis, Resources, Methodology, Supervision, Funding acquisition, Conceptual design of the research project.

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Data Availability Not applicable

Declarations

Conflict of interest The authors declare that they have no competing interests.

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Consent to participate Not applicable.

Consent for publication Not applicable.

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