Advancing Architecture Through Shape Memory Alloy Actuators: A Knowledge Framework

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ABSTRACT

This thesis explores the integration of Shape Memory Alloy (SMA) actuators into architectural design, proposing a comprehensive knowledge framework that bridges material science, responsive technologies, and architectural theory. Motivated by the ontological and experiential implications of kinetic architecture, the research underscores the potential of SMAs to infuse the built environment with vitality, adaptability, and emotional resonance. Through a qualitative and praxis-informed methodology, this study investigates the epistemological and technical dimensions of SMA actuation, identifying current limitations in cost, control, scalability, and design integration. The thesis synthesizes multidisciplinary knowledge across empirical, theoretical, and procedural domains, aiming to support architects in the material selection, system programming, and spatial integration of SMA-based components. By fabricating and analyzing functional prototypes and case studies, the research contributes actionable design guidelines and predictive strategies for SMA application in dynamic and user-centered environments. The proposed framework not only facilitates the creative and systematic adoption of SMA technologies but also positions architecture as a forward-thinking discipline capable of responding sensitively to human presence and environmental stimuli. This work serves as a foundational resource for advancing adaptive, intelligent, and materially innovative architectural practice.

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GENERAL AUDIENCE ABSTRACT

Buildings are usually seen as still and unchanging; but what if they could move and respond like living things? This thesis explores how a special type of smart metal, called Shape Memory Alloy (SMA), can be used in architecture to create buildings that adapt to people and their environment. These materials can "remember" shapes and return to them when heated, allowing walls, facades, or surfaces to shift in response to light, sound, or touch. While these materials have exciting possibilities, they are not widely used in buildings yet, partly because they are complex and costly. To help designers use SMAs more effectively, this research brings together technical knowledge, design strategies, and real-world experiments to create a practical guide. The result is a clear framework that helps architects design buildings that are more interactive, energy-efficient, and emotionally engaging. Ultimately, this work shows how smart materials can help shape the future of architecture, one that is more responsive, sustainable, and connected to the people it serves.

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1.Introduction

1 Introduction

Norberg-Schulz’s exploration of place emphasizes architecture as a communicative medium that fosters identity and orientation, suggests holistic embodied design principles. The integration of spatial configuration, cultural symbolism, and historical narratives serves not only as a visual guide but also as a sensory and existential framework, enabling users to navigate and internalize their environment through bodily engagement. In this way, architecture transcends its functional attributes to create meaningful places imbued with cultural and emotional resonance.

Architecture, when viewed through the lens of an "embodied" design perspective, emerges as a medium intrinsically connected to the sensory, cognitive, and corporeal experiences of its users. Rooted in theories of embodied cognition, this perspective challenges the conventional treatment of architecture as a static object and instead frames it as an active participant in human experience, shaping and being shaped by the movements, emotions, and perceptions of individuals within its spaces.

The enactive approach to architectural experience, as highlighted by Jelić et al. (2016), further supports this perspective by acknowledging the neurophysiological interplay between the body and built space. This approach underscores how architectural elements—textures, light, sound, and movement—elicit sensory and cognitive responses that shape users’ understanding and interaction with their environment.

Embodied design also prioritizes inclusivity and user-centricity, as discussed by Bhargav-Spantzel et al. (2007). By addressing diverse sensory and physical needs, architecture becomes an adaptive and accommodating framework that enhances belonging and accessibility. Such spaces evoke a profound connection by fostering interaction, emotional resonance, and identity.

Architecture through the lens of embodied design becomes more than a container for activity; it is an active participant in the human experience, shaping lived realities and creating environments that are responsive, inclusive, and deeply interconnected with human presence.

1.1 Motion signifies vitality

Kinetic architecture that incorporates dynamic building elements capable of movement has emerged as an important paradigm in contemporary architectural discourse and practice in perspective of bringing static built environment to life. There are several underlying motivations that render motion and transformative capacity in the built environment aspirational and advantageous. Incorporating kinetics enables structures to actively adapt to fluctuating external stressors and changes in their surroundings. On a basic functional level example, facades that passively track solar orientation like sun-following louvers or shading systems constructed using flexible materials can enhance thermal comfort and energy efficiency. Kinetics allows modulation of light, ventilation, insulation and other environmental factors in response to diurnal and seasonal variations. Buildings now account for a large portion of energy consumption and new methods for energy control and increasing natural ventilation help control that(Bagheri et al., 2023a) (Bagheri et al., 2023b). This capacity of SMAs for self-regulation improves building performance.

More importantly conceptually, kinetics aligns with the ontology of architecture, which rejects notions of buildings as static objects and embraces their inherent relationality to inhabitants and changing contexts. The vitality introduced into inert spaces through motion and transformation reasserts architecture's ontological linkage to the dynamism of lived experience. Kinetic operations can be designed to choreograph diverse spatial qualities that engender delight, mystery and engagement for occupants.

Socially and psychologically, motion signals life and invites participation. Kinetic structures exhibit vitality akin to natural organisms and prompt interaction. The animation of space through integrated kinetics can provide symbolic expressions, establish communicative gestures, and enrich spatial narratives. Kinetics holds potential to reaffirm architecture's role as a meaningful cultural expression.

Technologically, embedding kinetics requires innovating structurally performative systems and smart materials. This drives progress in design methodologies, manufacturing techniques and sustainable technologies. The growing pursuit of kinetic architecture fuels cross-disciplinary knowledge exchange and material innovation.

Thus, from the vantage points of experience, cultural expression, performance and technological advancement, the capacity for controlled movement and transformation allows conceiving architecture that is functionally responsive, experientially stimulating, culturally communicative and materially progressive. This multidimensional value underpins the desirable aspirations enveloped in kinetic systems. These technologies have the potential to enhance building morphology and suggesting new user experience in interrelation with spaces they occupy.

Furthermore, recent advancements in computational design (Gerber and Ibañez, 2014) have increasingly focused on the mobility of buildings, emphasizing interactive features of architectural forms and the responsive transformation of various building components such as the envelope, shading, and ceilings (López et al., 2017). These developments draw inspiration from innovations in materials science, robotics, and the growing accessibility of software and electronic hardware. As a result, architects and building engineers are now exploring new frontiers in the application of movable building elements across various aspects of design, fabrication, and control (Peters and Drewes, 2019)(Yi, 2019)(Holstov et al., 2017).

Despite substantial academic evidence highlighting the potential of adaptive building structures capable of kinetically responding to environmental stimuli—these concepts remain underutilized in architecture due to two key challenges. First, there is a technical gap in effectively integrating and operationalizing adaptive systems to ensure functionality and reliability. Second, their implementation often lacks a visionary approach that leverages these systems to foster awareness and transform architecture into a forward-thinking discipline. This transformation would create embodied spaces that not only serve human needs but also redefine architecture as a medium for future-oriented, adaptive, and responsive design.

This study aims to propose accessible and efficient methods adopting shape memory alloys to achieve embodiment spaces that when viewed a living space, transform into dynamic forces that not only serve functional needs but also foster emotional engagement.

By integrating adaptive systems, architecture becomes responsive, engaging the senses and evoking emotions such as wonder or comfort. This approach merges technology with thoughtful design to create inclusive, sustainable spaces that resonate deeply with users. As a medium of interaction and adaptation, responsive architecture evolves alongside people, enhancing both the built environment and human experience.

This represents a significant application of conscious building element design, focusing on the principles of kinematics. While some industrial efforts have introduced ideas and techniques for mostly performance related applications like responsive shading in buildings, resulting in the development of adaptive shading facades like those seen in the Al Bahr tower or

Q1 headquarters (Alotaibi, 2015)[1]; it is imperative to reevaluate current practices in responsive building design due to several observed challenges:

(i) The fabrication of mechanisms and components required for configuring movable parts and linkage systems is intricate and costly.

(ii) Electromagnetic motor-based kinetic systems often generate disruptive noise and vibrations within the building interior, demanding regular maintenance for reliable operation.

(iii) Reported performance assessments of kinetic designs in building simulations often do not adequately consider actuation efficiency (output force/energy or output force/weight), neglecting the additional electricity consumed by large-scale motors and components.

To address these issues, recent adaptive building studies have started to explore the use of self-shaping materials in kinetics, including smart materials like shape-changing alloys, polymers, or biomaterials (Peters and Drewes, 2019)(Holstov et al., 2017)(Loonen, 2014). These material-based kinetic systems offer the potential to make responsive buildings more adaptable, lightweight, and compact, while also reducing or eliminating the need for external power sources. While previous related studies and designs have been reported (Torres-Jara et al., 2010)(Boyraz et al., 2018), many of them do not yet meet the technological readiness required for practical application in the building industry, with only a few examples beyond the laboratory scale demonstrating limited practical feasibility (Peters and Drewes, 2019). Furthermore, the mechanical forces generated by soft material deformation are often insufficient for building-scale actuation, manufacturing processes are too intricate to be standardized for mass customization or production, and the comprehensive performance of dynamic buildings (in terms of energy efficiency, lighting, and life-cycle costs) remains largely unexplored in such approaches.

Shape Memory Alloy (SMA) actuators can offer a promising solution to address the existing gap in the body of knowledge within the field of architecture. The integration of SMAs can significantly contribute to and advance several aspects of architectural design and creating futuristic embodiment spaces for people that have previously lacked comprehensive solutions:

1. User-Centric Design: The use of SMAs in kinetic architectural elements can introduce user-centric design principles by creating interactive and adaptable spaces. This addresses the gap in providing architectural designs that respond to occupants' needs and preferences in real-time, ultimately enhancing the quality of the built environment.
2. Shape Memory Alloys have the unique ability to mimic the dynamic, responsive behaviors observed in living organisms and natural systems, making them a powerful tool for infusing architecture with life-like qualities. This motion, akin to the rhythmic breathing of a living creature or the Seismonastic movements of leaves, introduces a sense of vitality to architectural spaces. Such movements have an emotional resonance, offering a sense of comfort, curiosity, or connection to the users.
3. Reduced Noise and Maintenance: Unlike traditional electromagnetic motors, SMA actuators have the potential to operate silently and require less frequent maintenance due to their simplified mechanical structure. This addresses the gap in minimizing noise pollution within buildings and reducing the operational costs associated with maintenance.
4. Material Innovation: The utilization of SMAs introduces a new dimension of material innovation in architecture. These smart materials can change shape in

response to external stimuli, enabling the creation of dynamic, adaptable, and aesthetically pleasing building components. This bridges the gap in materials research and application within architectural design.

5. Accessibility and Mass Customization: The development of easily accessible and rapidly mass-customizable methods and frameworks for SMA-based kinetic building elements can democratize the adoption of responsive architecture. This addresses the gap in making advanced architectural technologies more accessible to general practitioners and non-professional building users.

6. Environmental Responsiveness: SMAs can contribute to the creation of buildings that are more in tune with their surroundings. By responding to environmental cues, such as sunlight, temperature, or wind, SMA-based elements can optimize energy use and reduce the ecological footprint of architectural designs. This addresses the gap in achieving architecture that is more environmentally responsive.

While shape memory alloys offer intriguing properties, there are certain constraints that have hindered their widespread adoption in the built environment. One major limitation is the high cost of most SMA materials, especially nickel-titanium alloys which are commonly used. The raw material and processing expenses make it currently prohibitive to use SMAs in large quantities needed for architectural-scale implementations like cladding systems or dynamic building components. There are also challenges with response time and response symmetry - SMAs have a relatively fast activation time when heated but slow deactivation when cooled passively. This asymmetry in response makes control and predictability difficult. Additionally, factors like thermomechanical fatigue, training requirements to fixate shapes, and susceptibility to overheating can reduce the lifecycle and reliability of SMAs as actuators. These drawbacks pose concerns regarding maintenance, safety, and stability when incorporated into permanent structures.

From a design perspective, there are still Questions remaining, regarding how to intricately program and control the complex thermomechanical behaviors of SMAs at an architectural scale. The relationships between SMA composition, building envelope and inside, and people living and interacting with it require further study and simulation to be translated into constructs that can be manufactured and customized cost-effectively. There is also a need for interfaces that allow designers to predictably tune SMA response for integration with buildings across varying contexts and senarios. Research on SMA responsive actuators design, improved training techniques, and hybrid systems can help address some of these challenges and unlock the potential of shape memory alloys in future human-centric responsive architecture.

My Contribution to expanding and consolidating knowledge on implementing shape memory alloys (SMAs) in architectural and design applications:

Michael Joroff and Stanley Morse in their book *A Proposed Framework for the Emerging Field of Architectural Research*(Joroff and Morse, 1983) suggest that architectural research requires a more structured and systematic approach to advance the field. It emphasizes the importance of creating **knowledge frameworks** to organize, guide, and standardize research methods and practices. These frameworks are seen as crucial for integrating new ideas and technologies into architectural design while ensuring that research outcomes are applicable and accessible to both academics and practitioners.

The book likely advocates for frameworks that enable researchers to better **analyze, categorize, and apply architectural knowledge** across different contexts, facilitating interdisciplinary collaboration. It also underscores the need for clear methodologies that can guide architects and designers in adopting **emerging technologies** (like SMAs) into their work, ensuring that innovations are not just theoretical but **practically implementable**. Through a structured framework, the book likely aims to bridge the gap between architectural theory and real-world applications, promoting more evidence-based, responsive, and sustainable design practices.

This thesis aims to provide a comprehensive reference on the effective integration of shape memory alloys into architecture and design to achieve designing living evoking architecture as a forward thinking paradigm for future. Despite growing interest in SMAs for kinetic structures and adaptive architecture, there is currently a fragmented understanding of how to leverage their unique properties in the built environment. Designers lack consolidated resources that map the capacities and limitations of different SMA materials and configurations with respect to functional objectives, manufacturing constraints, and performance goals. My research will gather dispersed knowledge across materials science, mechanics, and fabrication processes relevant to architectural SMAs. Through extensive literature review, patent analyses, and interviews with experts, I will synthesize actionable guidelines, simulation methodologies, and prototyping techniques for SMA-driven designs. My goals will be an open-access knowledge base equipping architects, engineers, and researchers to make informed decisions on selecting suitable SMAs, programming their thermomechanical responses, and integrating them into dynamic structures. This comprehensive framework distilling multi-disciplinary insights on architectural SMAs does not yet exist, and my thesis will fill this gap to facilitate their creative and rigorous adoption in future responsive and sustainable built environments. The knowledge resource developed through my research will aid in overcoming current barriers to SMA applications and catalyze innovation at the intersection of materials, kinetics, and design.

The objectives and methods: the goal of my thesis is to rigorously explore and document the integration of shape memory alloys (SMAs) as responsive actuators in human-centric architectural designs and prototypes to bring the sense of interactivity with alive conscious embodiment surrounding people. This will be accomplished through:

- An exhaustive review of scholarly literature and previous projects at the intersection of SMAs, smart materials, and responsive architecture. I will analyze the methodologies and outcomes of this prior work to identify promising avenues and open questions for SMAs in kinetic systems.
- Designing and fabricating multiple prototypes of SMA-activated components and surfaces at different scales. These prototypes will serve as working case studies and testbeds for my own experimental research.
- Capturing the insights and knowledge gained through prototyping in detailed documentation including journals, videos, and photographic records.
- Developing systematic flowcharts and guidelines that map relationships between SMA properties, mechanical design, actuation methods, and kinetic architectural responses.
- Creating an interactive architectural surface prototype actuated by SMAs and capable of real-time motion in response to diverse stimuli like human movement, sound, light, or touch inputs. This prototype will demonstrate how SMAs could be integrated into future responsive and participative spaces.

The outcomes of this multifaceted research will be a comprehensive framework and design resource for incorporating SMAs into kinetic and adaptive architectures for different purposes. My methodology combines literature synthesis, prototype fabrication, experimentation, and detailed documentation to expand the knowledge base around architectural applications for these fascinating smart materials.

2.Literature Review

2 Literature Review

2.1 Architecture as a communicative mean

Schulz in his renowned book Architecture: Presence, Language, Place(Norberg-Schulz, 2000) discusses The concept of language in architecture, not in a literal sense, but as a communicative medium that expresses cultural, historical, and existential meanings. Norberg-Schulz explores how architecture conveys a sense of identity, reflecting the values and narratives of a particular culture or society.

Place, as a fundamental aspect of architecture, is explored in terms of both physical and existential dimensions. The author investigates how the built environment contributes to the sense of place, creating a connection between individuals and their surroundings. He underscores the significance of understanding architecture beyond its functional attributes, emphasizing its role in creating meaningful places that resonate with human experience.

Norberg-Schulz's exploration of these themes lays the groundwork for a profound understanding of architecture as a lived experience, deeply intertwined with human presence, cultural expression, and the creation of meaningful places. The subsequent chapters likely further elaborate on these foundational concepts, providing a comprehensive exploration of the philosophical underpinnings of architecture.

Architecture plays a pivotal role in providing users with a sense of orientation and identity within a place, contributing significantly to the human experience of the built environment. The spatial configuration, formal language, and symbolic elements inherent in architectural design collectively serve as communicative mediums that guide users in navigating and interpreting their surroundings. Through careful attention to spatial organization and the establishment of distinct landmarks, architecture facilitates a legible and comprehensible environment, enabling users to orient themselves within a given space. Furthermore, the integration of cultural, historical, and contextual references in architectural elements fosters a sense of identity, anchoring users to the place and reinforcing a connection with the broader cultural narratives embedded in the built environment. In this academic context, it is imperative to recognize that architecture, as a form of environmental language, possesses the capacity to shape the user's perception of space, thereby contributing substantively to their orientation and identity within a given place. The intricate interplay of spatial configuration, symbolic representation, and cultural context establishes a framework through which architecture becomes a mediator of orientation and identity, transcending mere functionality to evoke a profound and meaningful sense of place. Architecture plays a crucial role in shaping the orientation and identity of users within a place. The design and spatial configuration of architectural environments can significantly influence how individuals perceive and interact with a space. The concept of place identity, as discussed by (Kalandides, 2011),is particularly relevant in understanding how architecture contributes to the orientation and identity of users. The physical characteristics, cultural elements, and historical context embedded in architectural designs can evoke a sense of place identity, providing users with a connection to the environment and a sense of belonging.

Furthermore, the enactive approach to architectural experience, as explored by,(Jelić et al., 2016) emphasizes the importance of considering the neurophysiological and embodied aspects of user experience in architectural design. This perspective underscores the significance of designing spaces that resonate with the sensory and cognitive experiences of users, thereby contributing to a strong sense of orientation and identity within the built environment.

User-centric design principles, as highlighted by (Bhargav-Spantzel et al., 2007), are instrumental in ensuring that architectural spaces are tailored to meet the needs and preferences of the users. By prioritizing user control, privacy, and personalized experiences, architecture can foster a sense of ownership and identity among individuals interacting with the built environment.

Moreover, the work of (Ma et al., 2017) underscores the importance of environmental experience design in architecture, particularly in the context of aged care facilities. This research emphasizes the role of design in contributing to user health, wellbeing, and overall experience within architectural spaces. By structuring the environmental experience design framework, architects can create environments that support the physical, emotional, and psychological needs of users, thereby enhancing their orientation and identity within the space.

In summary, architecture contributes to the orientation and identity of users by incorporating elements of place identity, embracing user-centric design principles, and prioritizing the holistic experiences of individuals within the built environment. By considering the sensory, cultural, and functional aspects of architectural design, spaces can be crafted to provide users with a strong sense of orientation, belonging, and personal identity.

2.1.1 Self-awareness through architecture

In the realm of architecture, the static nature of built environments, while undoubtedly influential, inherently presents limitations in its capacity to engage with and respond to the dynamic needs of its inhabitants. Traditional architectural forms, though aesthetically and functionally significant, lack a direct means of communication with human occupants. This rigidity, marked by a static existence, can hinder the establishment of a profound connection between individuals and their surroundings. However, the integration of kinetic elements within architectural spaces represents a paradigm shift, introducing a dynamic dimension that has the potential to foster a more profound and interactive relationship between individuals and their built environment.

The incorporation of kinetic elements transcends the conventional static nature of architecture, offering a means through which spaces can actively respond to human presence and engagement. By introducing dynamic components such as movable walls, interactive surfaces, or responsive structures, architecture becomes a participatory entity that, in real-time, adapts to the evolving needs and activities of its occupants. This dynamic responsiveness has the profound potential to instigate a sense of connection and belonging, as individuals witness and experience the environment's responsiveness to their presence and actions.

Furthermore, the incorporation of kinetic elements serves as a catalyst for heightened self-awareness among users. As architectural spaces engage in a reciprocal dialogue with individuals through kinetic features, occupants become more attuned to their immediate surroundings. This heightened awareness not only facilitates a sense of belonging but also enables individuals to identify with the space on a more personal and reflexive level. The interplay between kinetic architecture and human reflexes establishes a unique mode of interaction, prompting individuals to perceive themselves in relation to the responsive environment.

In essence, the integration of kinetic elements within architectural design transcends the conventional boundaries of static structures, ushering in a new era of spatial interaction. This innovative approach has the potential to cultivate a profound connection between individuals and their built environment, fostering a sense of belonging and self-awareness. By enabling architecture to engage dynamically with its users, kinetic design offers a transformative means of enhancing human experience, encouraging a deeper identification with and understanding of one's surroundings.

2.2 Shape Memory Alloy Structure

Shape-memory alloys exhibit a range of distinctive characteristics, including shape memory and superelasticity. Shape memory denotes their ability to return to their original configuration when subjected to heat, while superelasticity enables significant deformations with minimal or no lasting strain. These alloys display superior energy dissipation capabilities compared to standard metallic materials when they undergo repeated phase transformations. Shape memory alloys (SMAs), often referred to as "smart metals," offer a lightweight, solid-state alternative to traditional actuators and switches like hydraulic, pneumatic, or motor-driven systems. Shape-memory alloys (SMAs) are ferro-elastic materials characterized by their ability to exhibit the shape memory effect (SME). This phenomenon arises from thermomechanical behaviors within the material, leading to a sequence of crystalline structural deformations that allow it to memorize and subsequently recover its original shape. SMAs have two distinct solid-state phases: martensite (M) and austenite (A), which determine the material's elastic properties and geometric patterns. When an SMA is heated above the transformation temperature As, it becomes rigid and begins to revert to its initial shape. The shape change continues as the temperature rises to Af. Conversely, cooling the SMA to below Ms leads to a softer crystalline state known as twinned martensite. If the temperature decreases further to Mf while an external load is applied, the SMA undergoes hysteresis and remains in a detwinned martensite state. Nickel-titanium (NiTi) is the most widely utilized and industrially manufactured shape-memory alloy (SMA), accounting for approximately 90% of all SMA applications(Yi et al., 2020).

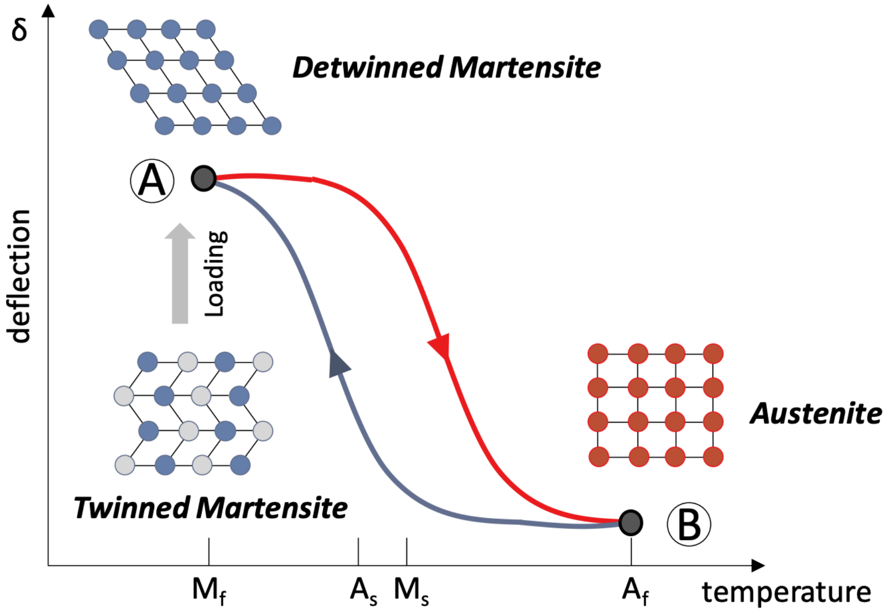

Figure 1-Schematic plot of SMA phase transformation: (A) maximum deflection at a 100% martensite (detwinned) state. (B) Maximum deflection at a full austenite state. Mf, MS, AS, and Af stand respectively for the material temperature of martensite finish, martensite start, austenite start, and austenite finish.

2.3 One-way vs. two-way shape memory

To operate effectively, SMAs require a process known as "training" to enable them to revert to a previous shape when subjected to heating.

Shape-memory alloys exhibit different shape-memory effects, with two common types known as one-way SMA and two-way SMA. These effects follow similar procedures, typically beginning with the martensite phase, introducing a deformation, heating the material, and then cooling it once more.

2.3.1 One way effect

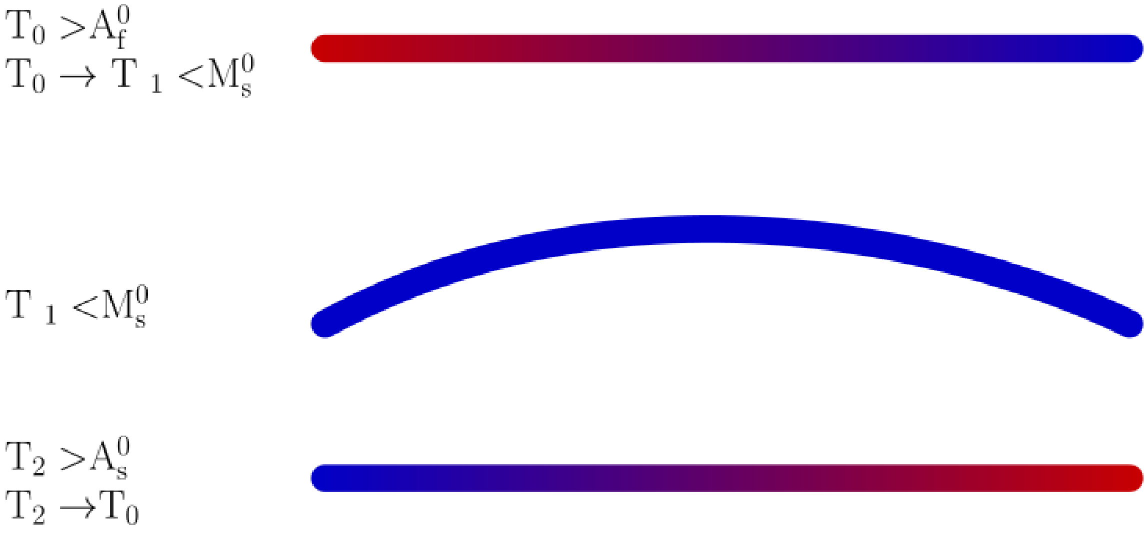

Figure 2- One Way Shape Memory Effect

In its cold state (below Mf), a shape-memory alloy can be bent or stretched and will maintain those shapes until heated above the transition temperature. Upon heating, the metal returns to its original shape. When it cools again, it retains the shape until deformed once more.

In the case of the one-way effect, cooling from high temperatures does not cause a macroscopic shape change. The low-temperature shape requires deformation to be created. Heating initiates transformation at As and completes it at Af, typically at temperatures ranging from 2 to 20 °C or higher, depending on the specific alloy or loading conditions. The value of As is determined by the alloy's type and composition and can vary between −150 °C and 200 °C.

2.3.2 Two way effect

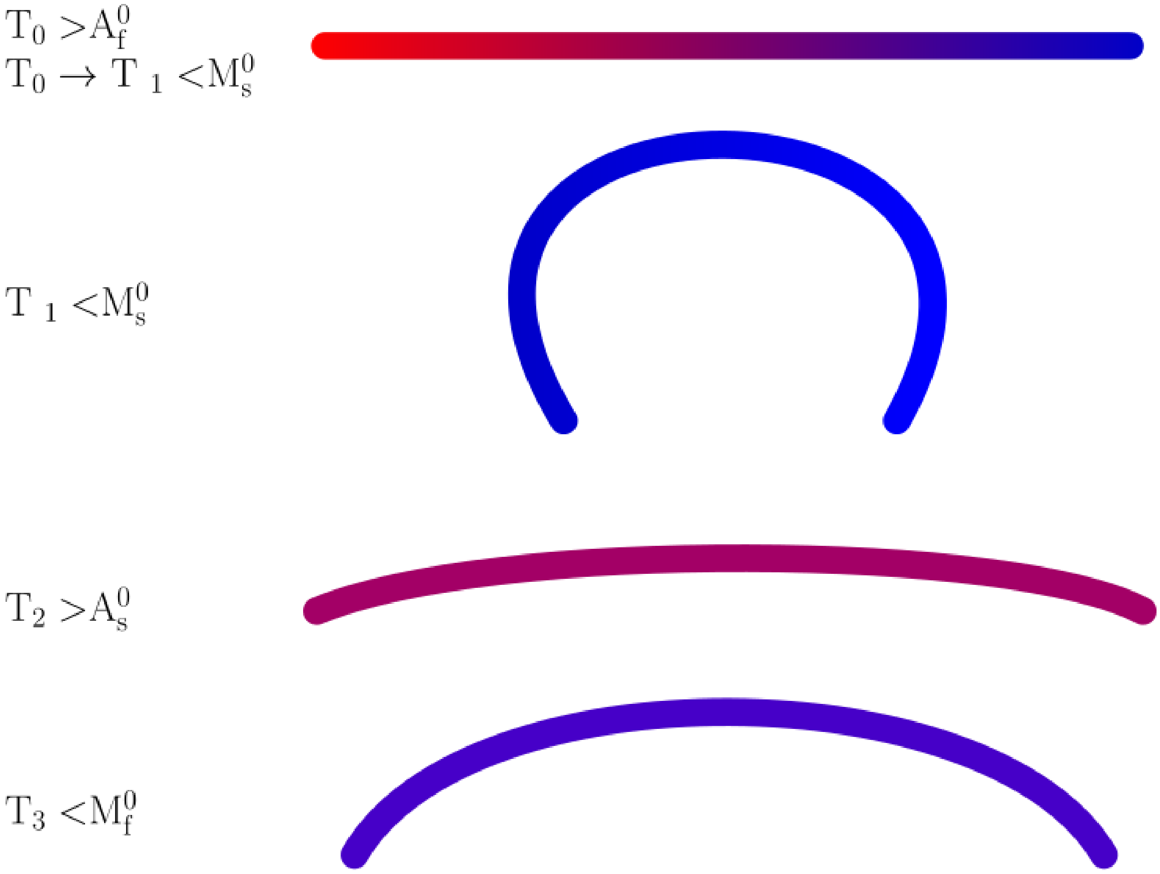

Figure 3- Two Way Shape Memory Effect

The two-way shape-memory effect is a unique property where a material remembers two distinct shapes: one at low temperatures and one at high temperatures. When a material exhibits this effect during both heating and cooling, it is referred to as having two-way shape memory. This effect can be intrinsic, meaning it occurs without the application of external force. Training is a critical factor in how the material behaves in these situations. Typically, a shape-memory alloy remembers its low-temperature shape but forgets it when heated to recover the high-temperature shape. However, training involves "teaching" the SMA to retain some memory of the deformed low-temperature shape in the high-temperature phases. This training process often involves applying cyclic thermal loads under a constant stress field, introducing internal defects into the microstructure that generate permanent internal stresses, facilitating martensitic crystal orientation. Consequently, when the trained SMA is cooled in the austenitic phase under no applied stress, it undergoes a shape change as the martensite detwins due to internal stresses. Upon heating back to the austenite phase, it regains its initial shape. There are several ways to train SMAs(“SMA Shape Training Tutorial,” n.d.). However, heating a trained SMA beyond a certain point will cause it to lose the two-way memory effect.

2.4 Training Shape Memory Alloy

A shape memory alloy is characterized by its dual crystalline structures and the unique phase transformations that occur between them. The high-temperature stable phase, known as austenite, transitions to a monoclinic crystalline structure called martensite when the alloy is cooled. This martensitic transformation is akin to that seen in iron-carbon alloys and is diffusion less by nature.

The shape memory effect is facilitated through these phase changes. Rapid cooling of the material in its austenitic state induces a spontaneous shift to the martensitic phase. Subsequently, the application of external stress can plastically deform the material, altering its crystalline lattice without inflicting irreversible damage. Although deformed, the material retains the ability to return to its pre-deformation shape upon reheating above the phase transition temperature, reverting to the austenitic phase.

For the material to 'remember' a particular shape, one must mold it at high temperatures—such as 400°C in the case of Flexinol 0.001 LT—and then swiftly cool it, ensuring the austenitic phase locks in the desired configuration, which is essential for the shape memory effect to manifest.

Shape memory alloys (SMAs) can be "trained" to remember specific shapes through two primary methods: one-way and two-way training.

1. One-Way Training: In one-way training, the SMA is programmed to remember one shape at high temperatures (austenite phase) and a different shape at low temperatures (martensite phase). The process involves heating the SMA above its transformation temperature to the austenite phase, deforming it to the desired shape, and then cooling it to "lock" in the martensite phase. Upon reheating, the SMA will return to its high-temperature shape. This method is common in applications where the alloy only needs to return to a predetermined shape from a deformed state.

2. Two-Way Training: Here are detailed methods for two-way training:

    1. **Simple Heating Cooling Cycles**: Two-way shape memory effect (TWSME) training in Shape Memory Alloys (SMAs) involves simple heating and cooling repeated in more than 50 cycles. To achieve TWSME, the material must be trained so that it "remembers" two distinct shapes: one at a higher temperature (austenite phase) and another at a lower temperature (martensite phase). A simple heating and cooling cycle for training a Shape Memory Alloy (SMA) typically involves the following steps:

    2. **Heating**: The SMA is heated to a temperature above its austenite finish temperature. This is the temperature at which the SMA fully transforms into its austenite phase, which is a high-temperature phase where the atoms are arranged in a parent cubic crystal structure. The SMA is held at this temperature until the transformation is complete.

3. **Cooling**: After the SMA has fully transformed into the austenite phase, it is allowed to cool down. As the temperature decreases, the alloy begins to transform into the martensite phase, which is stable at lower temperatures. This phase has a more complex crystal structure, often twinned.

4. **Deformation**: While the SMA is in the martensite phase, it can be mechanically deformed to a new shape. This deformation occurs easily since the martensite phase is softer and more ductile.

5. **Recovery**: Upon reheating the SMA, the deformed martensite phase reverts back to the austenite phase, and the alloy returns to its original shape, as remembered from the high-temperature phase.

6. **Repetition**: To strengthen the memory effect, the heating and cooling cycle is repeated several times. Each cycle involves heating the SMA above the austenite finish temperature, cooling it down to allow for martensitic transformation, and then reheating to recover the original shape.

7. This process "trains" the SMA by reinforcing the transformation pathways between the martensite and austenite phases, making the shape change more repeatable and reliable. The exact temperatures and the number of cycles needed can vary based on the composition of the SMA and the desired application.

8. **Mechanical Cycling Under Load**: This method involves repeatedly deforming the SMA while it is in the martensitic phase, then heating it above the austenite finish temperature to recover its original shape. The material is then cooled back to allow it to transform into martensite, and the process is repeated. The mechanical

cycling under an applied load helps the material to "learn" the shape at both temperature phases.

9. **Training with Bias Stress**: By applying a bias stress, which is a constant load during the thermal cycling, the SMA can be trained to remember the shapes associated with the martensitic and austenitic phases. The bias stress is maintained while the SMA is cycled through its transformation temperatures, facilitating the formation of oriented martensitic variants that correspond to the applied stress.

10. **Electrical Training**: For some SMAs, electrical current can be used as a method for training. Passing an electrical current through the SMA generates heat due to resistive heating, which can raise the temperature quickly and precisely to induce the phase transformation. The precise control allows for localized training and can be used to train specific sections of the alloy.

11. **Isothermal Holding During Transformation**: Another technique involves holding the SMA at a constant temperature at which both martensite and austenite phases coexist during transformation. This isothermal holding can help stabilize the two-way effect.

Each of these methods aims to rearrange the internal structure of the SMA in such a way that it creates stable martensite variants upon cooling and a single austenite phase upon heating. The detailed microstructural changes during this process often require optimization for the specific SMA composition and the intended application. Extensive research is typically necessary to determine the most effective training process for a particular SMA to achieve reliable and repeatable TWSME.

Both training methods exploit the inherent phase change properties of SMAs, but the specific training process and resulting memory effect depend on the application requirements and the characteristics of the particular SMA being used

Recent advancements have propelled these alloys into the realm of practical solutions for various applications in construction and infrastructure. In the following, an overview of the potential and constraints of shape-memory alloys in the Architecture and construction industry has been discussed.

Superelasticity refers to the remarkable property of certain alloys to display substantial, fully recoverable strain when subjected to stress. Various families of shape-memory alloys find application in diverse contexts due to their distinct ranges of transformation temperatures. For instance, aluminum-manganese and iron-nickel-cobalt-aluminum shape-memory alloys are well-suited for seismic applications because their operational temperature range spans from -50°C to 50°C. Various families of shape-memory alloys come with their own set of advantages and disadvantages. The development of shape-memory alloys has been ongoing since the early 1960s. Shape-memory alloys have found successful applications in diverse fields such as medicine, robotics, aerospace, and automotive industries.

2.5 Embedding shape-memory alloys in Construction:

The first practical application of the shape-memory effect for post-tensioning in a concrete structure occurred on a highway bridge in Michigan. This bridge had developed cracks due to inadequate shear resistance. To reinforce the bridge girder, shape-memory alloy rods made of iron-manganese-silicon-chromium, each with a diameter of 10.4 mm, were installed across the cracks on both sides of the web. These rods were heated using a 1000A current to reach 300°C, leading to a remarkable 40% reduction in the width of the cracks.(Bacha and Bourbia, 2016)

Shape-memory alloys have been employed in the restoration and reinforcement of architectural heritage structures. An example is the development of a shape-memory alloy device within the EU-funded Istech project. This device utilized nickel-titanium shape-memory alloy wires, pre-tensioned to enable two-way superelasticity when subjected to movement. The method of mounting these shape-memory alloy devices within structures depended on whether they were intended to prevent significant deformations in slender structures or to prevent the out-of-plane collapse of building facades.

In a notable application, several shape-memory alloy devices were utilized in the restoration of the bell tower of San Giorgio church in Trignano, Italy, which had suffered extensive damage during an earthquake in 1996. These shape-memory alloy devices were connected in series with steel bars within the bell tower to restrict horizontal movement, enhancing its earthquake resistance and structural integrity.(Indirli et al., 2001).

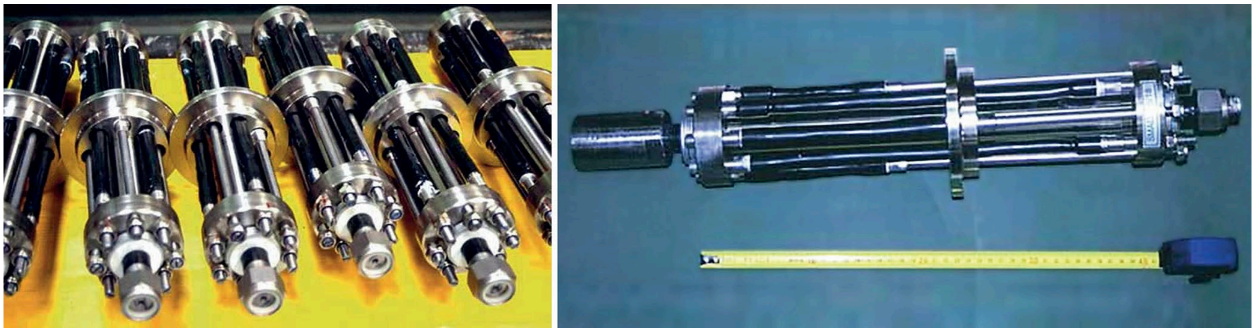

Figure 4-Shape-memory alloy device developed in Istech project

Figure 5-San Giorgio church and its bell tower, Trignano

Figure 6-Bell tower of Badia Fiorentina, Firenze

A similar approach was subsequently employed to enhance the seismic resilience of the bell tower of Badia Fiorentina in Italy before an anticipated earthquake. In 2006, this tower was fortified with the installation of 18 shape-memory alloy devices, following a methodology akin to that used in Trignano. While these devices couldn't prevent the occurrence of cracks in the tower or slender structures during an earthquake, they effectively curtailed excessive deformation, thereby reducing the risk of collapse during aftershocks.

This technique was further applied to safeguard several Italian cultural heritage sites that had suffered earthquake damage, including the Basilica of St. Francis of Assisi and the San Serafino church. A total of 47 shape-memory alloy devices were employed to restore the damaged facade of the Basilica of St. Francis, which had been impacted by an earthquake in 1997(Croci, 2001)(Martelli, 2008).

By 2008, it was reported that at least 19 buildings had been bolstered through the use of shape-memory alloy devices or energy-dissipation systems, showcasing the efficacy and adaptability of this approach in preserving architectural heritage and mitigating earthquake-induced risks(Benavent-Climent, 2008).

2.6 Embedding shape-memory alloys in structures

2.6.1 Concrete

Numerous projects have utilized shape-memory alloys in critical areas of concrete structures with the primary aim of minimizing permanent deformation(Saiidi and Wang, 2006). In seismic events, these alloys are anticipated to yield and dissipate energy in these regions while also recovering from deformation. They find application in concrete connections and beams, effectively reducing residual deformation under cyclic and reversed cyclic loading, as evidenced by hysteretic loops. It's important to note that while shape-memory alloys yield during an earthquake, they aid the structure in rebounding from deformation afterward.

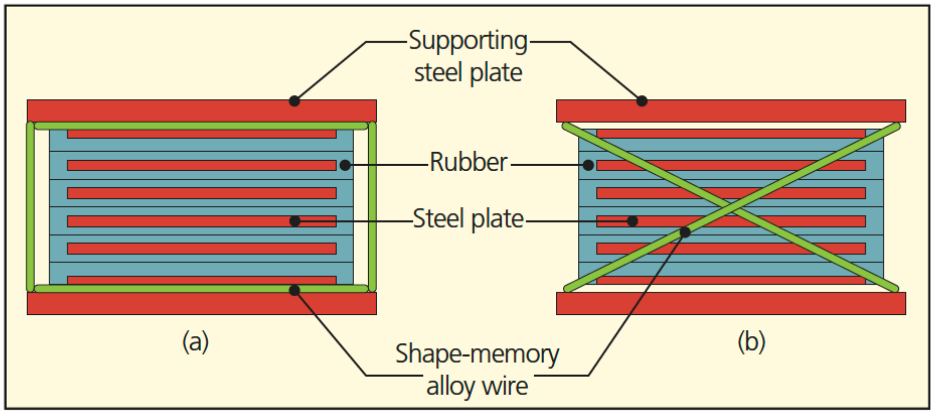

Figure 7-Details of shape-memory alloy–rubber bearing developed by (Das and Mishra, 2014)

Another application involves using shape-memory alloys in shear walls, with tests demonstrating their ability to reduce residual displacement(Effendy et al., 2006). However, there's a need to address potential buckling issues in the shape-memory alloy bars. The key advantage of this approach is cost reduction in post-earthquake repairs, facilitated by the superelasticity of shape-memory alloys, which grants structures self-centering capabilities.

2.6.2 Bracing

Incorporating shape-memory alloys into a bracing system proves highly effective in addressing the pinching observed in the hysteretic loop of a structure following significant deformation. This integration enhances the structure's capacity for robust re-centering.

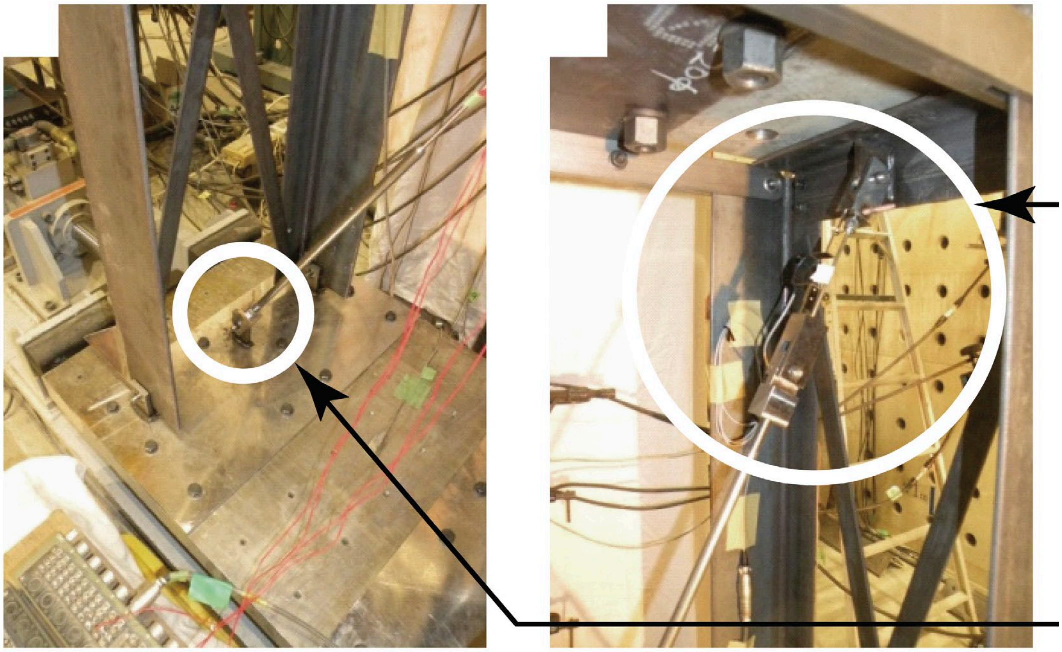

Figure 8-Bracing system design (Araki et al., 2014)

2.7 Embedding shape-memory alloys in Architecture

Shape memory alloys (SMAs) have gained significant attention in the construction industry due to their unique properties and potential benefits(Zhang et al., 2022). Iron-based shape memory alloys (Fe-SMAs) in particular have been studied extensively for their corrosion resistance, shape recovery capability, plastic deformability, and fatigue resistance. These properties make Fe-SMAs suitable for various applications in construction. However, the use of SMAs in the architecture field is not as prevalent as in the construction field.

One possible reason for the limited use of SMAs in architecture is the lack of awareness and understanding of their potential applications and benefits. SMAs are relatively new materials, and there may be a lack of knowledge and expertise among architects regarding their properties and how to incorporate them into architectural designs. This knowledge gap could be a barrier to the widespread adoption of SMAs in the architecture field(Zhang et al., 2022).

Another factor that may contribute to the limited use of SMAs in architecture is the cost. SMAs can be more expensive compared to traditional construction materials, which may deter architects and developers from using them in architectural projects. Cost considerations are often a significant factor in architectural design and construction decisions, and if the cost of SMAs is prohibitive, they may be overlooked in favor of more affordable alternatives (Zhang et al., 2022).

Shape-memory alloys can additionally play a role in the contemporary movement towards adaptable buildings, allowing these structures to react to shifts in their surroundings, such as alterations in lighting, temperature, and air conditions. In 2006, the 'Pixelskin02' project by Sachin Anshuman (S, 2008) employed shape-memory alloy wires as a non-motorized method for operating a facade. In this innovative project, each pixel tile comprised four triangular panels that were activated using 200 mA shape-memory alloy wires. These wires allowed for the controlled opening and closing of the panels by regulating the electric current supply.

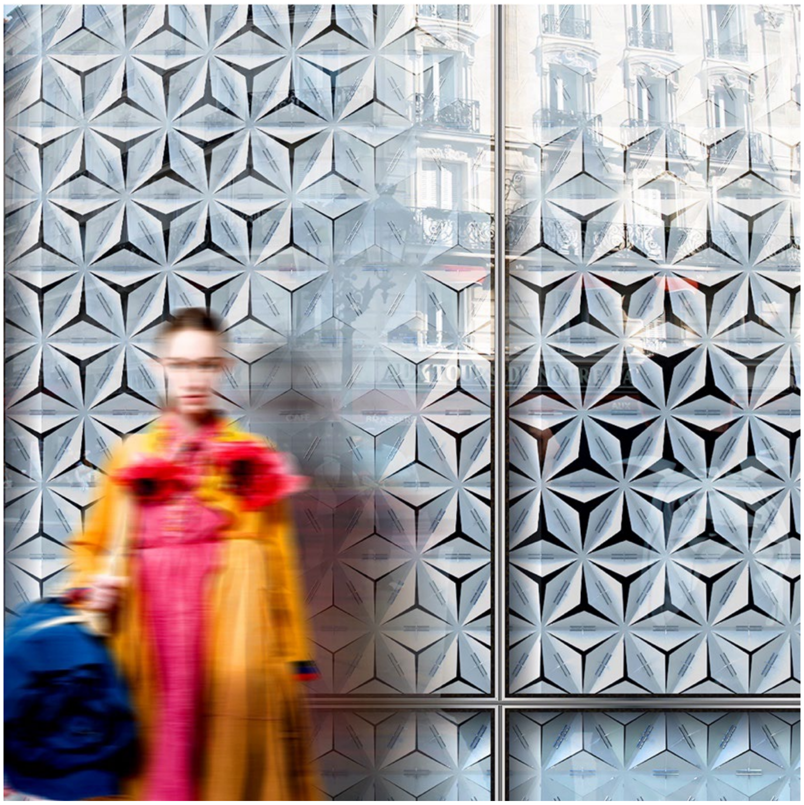

Figure 9-'Pixelskin02' project by Sachin Anshuman

Tashakori (Tashakori, 2014) has introduced a computer-controlled facade system capable of sun-tracking, utilizing shape-memory alloy wires. This facade system is activated through the application of an electric current. This thesis presents the development of a computer-controlled sun-tracking device model aimed at enhancing a building facade's environmental performance, encompassing aspects such as daylighting, shading, and energy harvesting. The project leveraged advanced computational tools like Grasshopper and Ecotect to create and assess an environmentally responsive building envelope featuring an integrated sun-tracking mechanism. Physical models of this system were constructed, incorporating light sensors to gather solar data for optimal solar radiation absorption. These sensors communicated with a micro-controller using SMA, which, in turn, adjusted the sun-tracking elements using micro-servos.

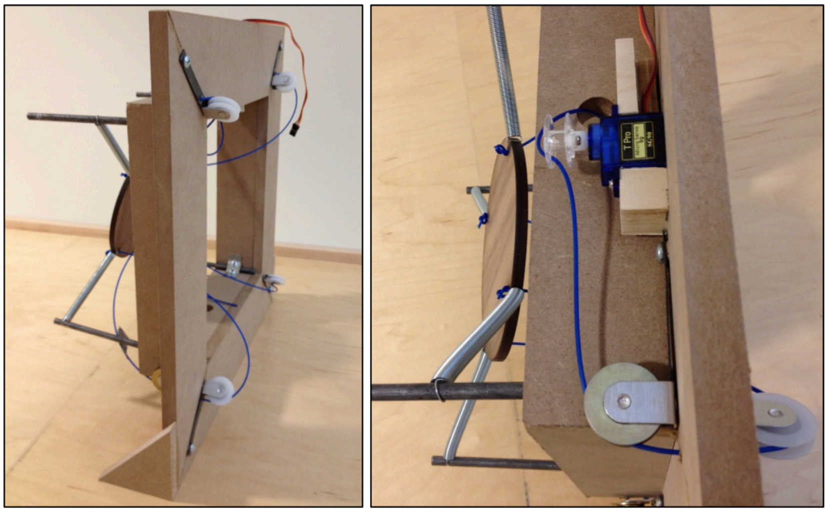

Figure 10-Physical prototype of sun tracking system using SMA(Tashakori, 2014)

Coelho and Maes (Coelho and Maes, 2009) introduced a shutter system designed to regulate both ventilation and lighting, operated through the use of motorized shape-memory alloy wires.

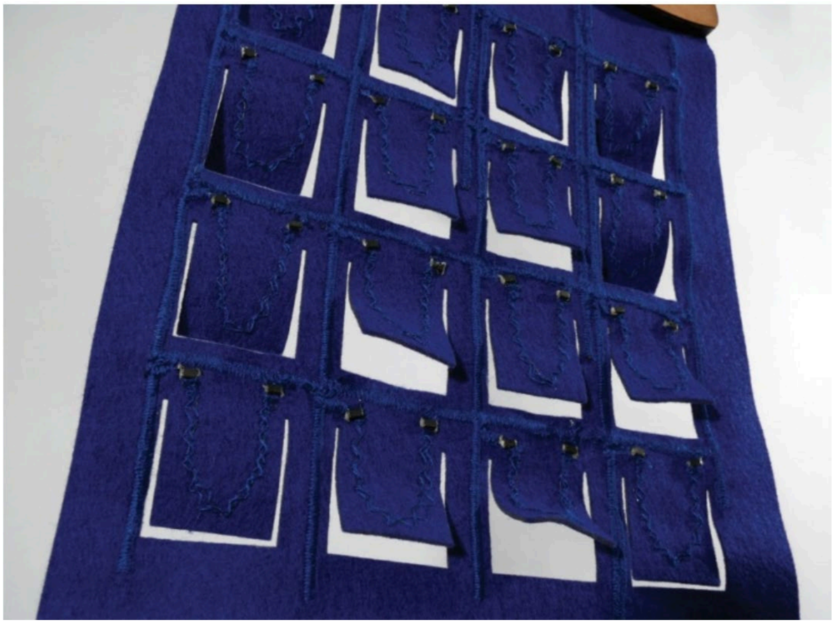

Figure 11-Shutters' louvers positioned at different angles(Coelho and Maes, 2009)

In Loonen's work (Loonen, 2014), a novel approach is suggested involving strips of shape-memory alloy that expand or contract based on carbon dioxide concentration. This innovative concept allows for achieving an optimal balance between facade opening, pressure difference, and immediate ventilation needs.

Lignarolo (Lignarolo et al., 2011) conducted research focused on studying the impact of wind on kinetic facades in tall buildings with the goal of improving the aerodynamic performance of high-rise structures. In their study, shape-memory alloys were employed to induce deformation in facade elements, effectively altering the roughness of the building's exterior surfaces.

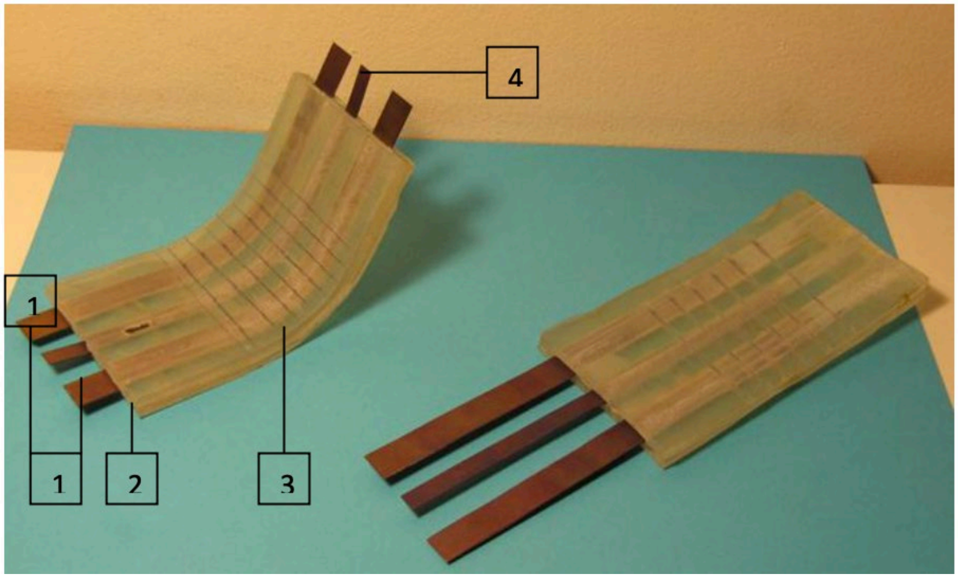

Figure 12-On the left, a smart composite material is depicted in a deformed state, while on the right, the integrated shape-memory alloy (SMA) strips are exposed.(Lignarolo et al., 2011)

While numerous designers and architects are intrigued by the prospect of creating systems incorporating shape-memory alloys to enable buildings to adapt to environmental changes, the actual implementation of shape-memory alloys in building design remains in its early stages, largely limited to demonstration projects. It is evident that greater efforts are required to facilitate market acceptance and adoption of these design concepts in order to fully realize their potential in the construction industry.

Behnaz Farahi has worked extensively with shape memory alloy (SMA) in her design projects. Farahi is known for her work in interactive architecture and responsive environments, and her use of SMA is a key element of her design approach.

One of her most notable projects is the "Caress of the Gaze" installation (Farahi, 2016). This project was an interactive installation that used SMA-based actuators to create a dynamic, responsive surface. The surface would change shape in response to the movement of people in the space, creating an immersive and dynamic environment. The project was widely recognized and was exhibited at several international events.

Another of her notable project is "Breathing Wall" that creates a responsive façade for a building using SMA actuators (Farahi, 2021). The facade responds to changes in environmental conditions, such as temperature and humidity, by changing its shape and creating different patterns of light and shadow. This creates a dynamic and interactive relationship between the building and its environment. Farahi has also developed a number of other projects that use SMA, such as "The Self-Adjusting Dress" and "The Self-Adjusting Chair" which both use SMA actuators to change their shape and form in response to different conditions(Leach and Farahi, 2018).

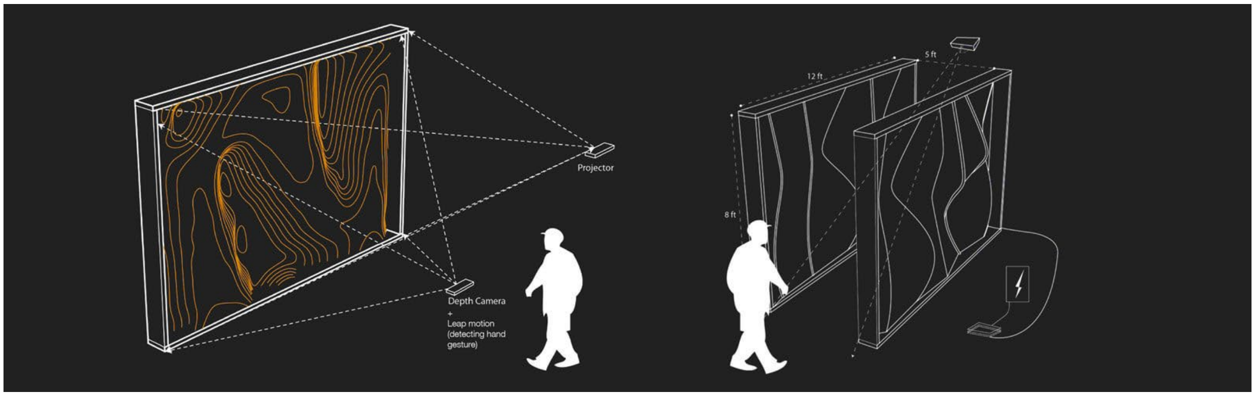

Figure 13-Motion sensors incorporated into the Living wall by Farahi

Figure 14- The Living Breathing Wall by Farahi

Philip Beesley is also another Designer renowned for his innovative projects incorporating shape-memory alloys (SMAs). "Hylozoic Ground," a standout installation initially showcased at the Venice Biennale of Architecture in 2010, features a floor adorned with thousands of SMA-based actuators. These actuators respond to the presence and movement of people, creating an immersive and interactive environment that encourages exploration(Beesley, 2009). Another notable project, "Luminous Veil," employs SMA-based actuators in an adaptive façade that adjusts louvers in response to changing light and temperature conditions, enhancing both energy efficiency and the building's connection with its surroundings. Beesley's exploration of SMA-based actuators extends to projects like the "Hylozoic Series," which delves into the potential of SMAs to create dynamic and responsive architectural designs (Beesley, 2023).

Figure 15-POEITIC VEIL: LIVING ARCHITECTURE by Philip Beesley

Architect Doris Sung has introduced innovative building envelope designs in several projects, such as "eXo," by incorporating NiTi sheets, also known as self-shaping structures. These responsive designs showcase the use of NiTi sheets in creating dynamic and adaptable building envelopes (Sung, 2014).

Formentini and Lenci (Formentini and Lenci, 2018) suggested a paneling system utilizing Shape Memory Alloys (SMA) for building envelopes, specifically ventilated facades, to enhance architectural and energy efficiency in buildings. The SMA serves a dual purpose, acting as energy-efficient thermal sensors and actuators. In the summer, the panels open to facilitate natural ventilation, while in the winter, they close to provide thermal insulation by trapping still air within the cavity between the external facade and the internal wall. This design offers a responsive and energy-efficient solution for building envelopes.

The practical application of Shape Memory Alloys (SMAs) in architectural design faces limitations in existing examples. In designs like Sung's, SMA-clad facades are environmentally inefficient due to the high cost of using NiTi in large quantities, the complexity of material programming for on-site construction, and the potential for solar-heated SMA shading panels to introduce excessive heat into interiors. Additionally, the work of Formentini and Lenci lacks validation of the building performance of SMA-actuated cladding systems. Issues such as discomforting metallic surface glare and limited movability of SMA sheets and wires are also noted. Importantly, both approaches do not clearly model the mechanical behavior of SMA deformation and its relationship with building geometry. In an effort to provide a cost-effective and adaptable solution for sustainable architecture, the authors (Yi et al., 2020) introduced a user-friendly 3D-printed kinetic shading device. This device can be switched between a geared DC motor and a thermomechanical shape memory alloy (SMA) actuator for selective activation. It utilizes additive manufacturing, SMA technology, and origami principles to create a lightweight and quiet kinetic building module with compact components. The focus is on user customization, with 3D-printed thermoplastic parts that allow self-supporting installation. An app-based remote control and sensor-based automation enhance user engagement. Through simulations and mockup tests, it was demonstrated that this thermo-responsive building module effectively manages solar radiation and light, leading to dynamic room temperature reduction.

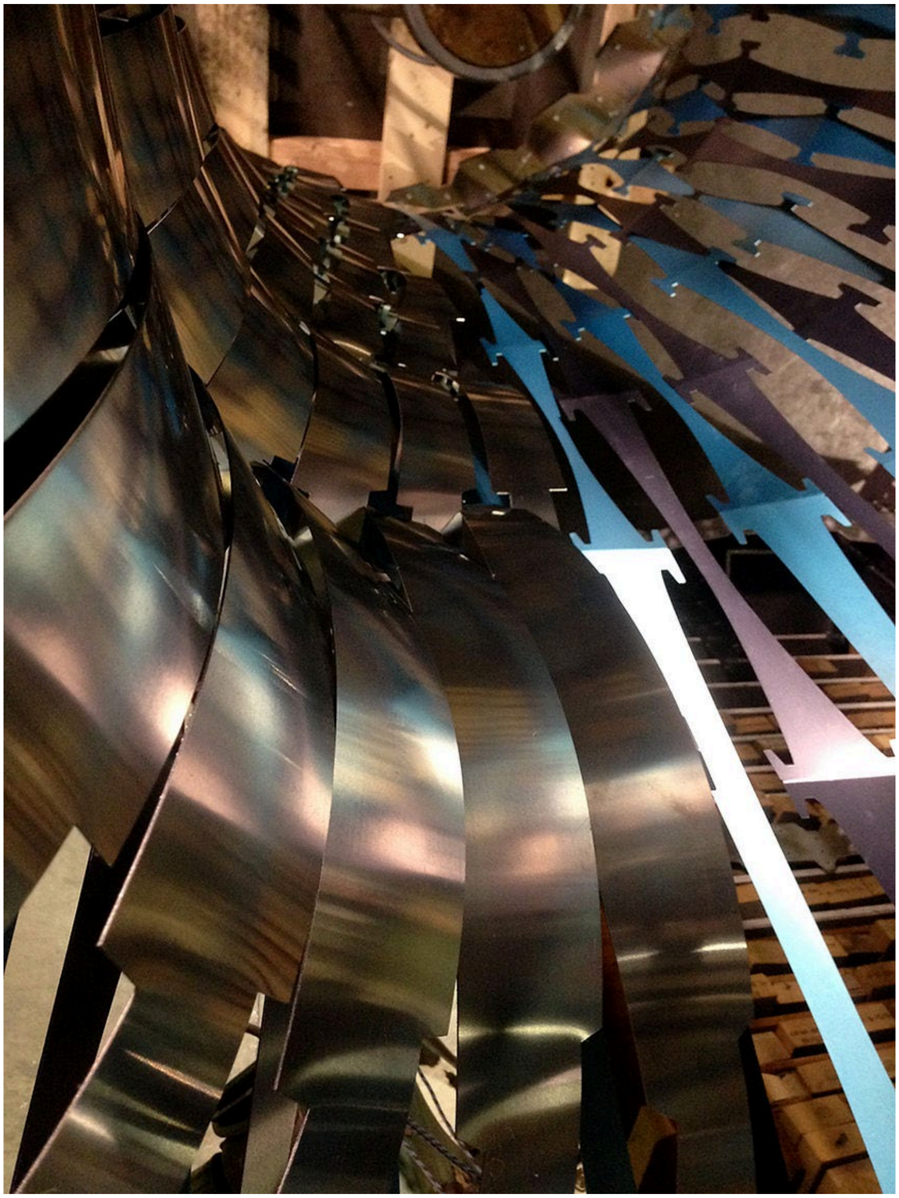

Figure 16-eXo by Sung incorporating NiTi sheets

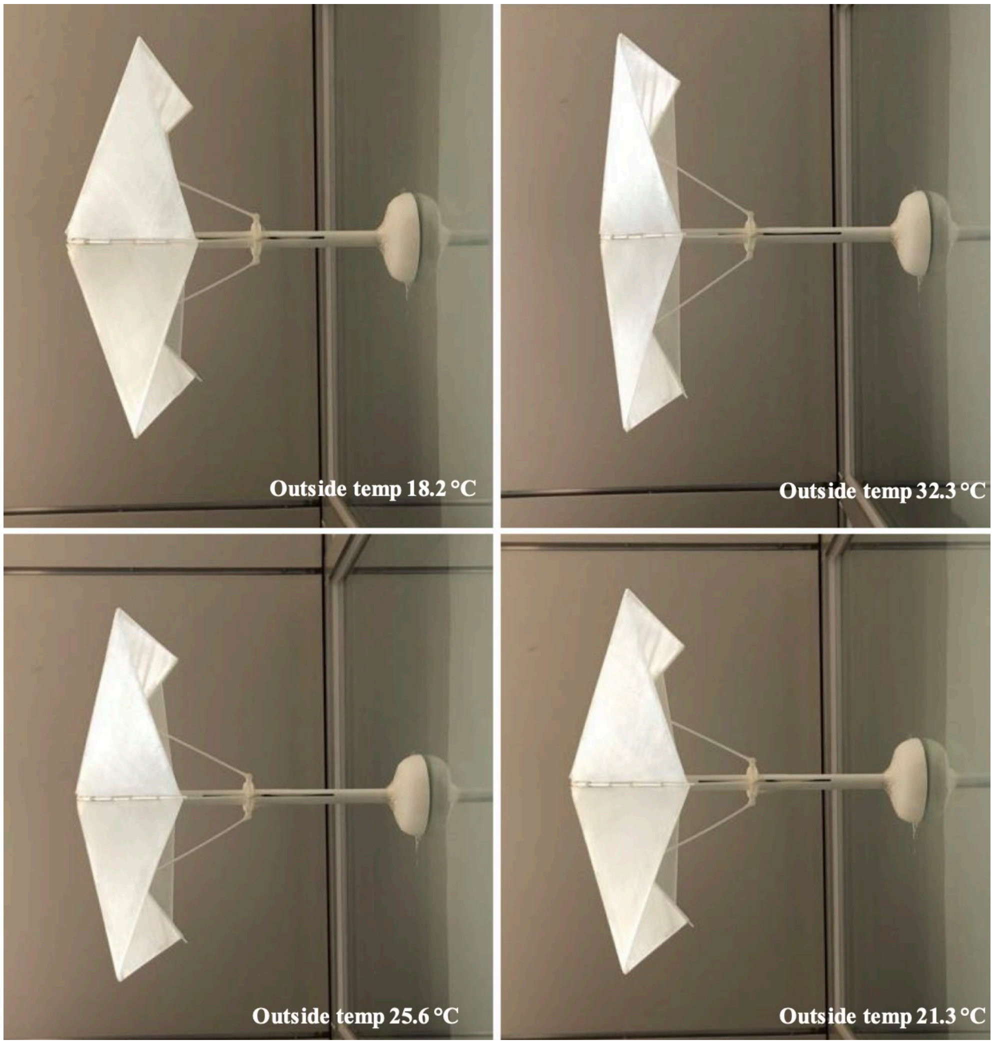

Figure 17- SMA actuator prototype(Yi et al., 2020)

2.8 Shape-memory Activation:

Shape-memory effect allows SMAs to change shape in response to changes in temperature. There are two primary methods for activating SMAs:

1. Temperature Change: The temperature change can be achieved by exposure to ambient temperature changes or by actively heating the SMA using external heat sources.

2. Electrical Activation: Another common method to activate SMAs is by passing an electric current through the material. This approach relies on Joule heating, where the resistance of the SMA to the electric current generates heat. This heat raises the temperature of the SMA, causing it to transition from the martensitic phase to the austenitic phase, which results in a change in shape. Electrical activation provides precise control over the activation process and allows for rapid shape changes.

Both methods have their advantages and are used in various applications based on the specific requirements of the SMA actuator. Temperature change activation is more passive and relies on external temperature variations, while electrical activation offers active and precise control over the SMA's response which can also include circuits using Arduinos and different sensors.

It takes several steps to build an Arduino circuit that can move a shape-memory alloy (SMA) actuator; As a general introduction, the following should be considered:

Supplies required:

1. Arduino board (such as the Arduino Uno or Nano)
2. SMA actuator or wire
3. MOSFET or H-Bridge motor driver, In order to manage the high current required by the SMA
4. Power supply (SMA-dependent demand for voltage and current)
5. Resistors, diodes, and capacitorIn order to protect the circuit
6. Breadboard and jumper wires (for prototyping)
7. SMA activation technique (either electrical current or temperature control)

Steps:

1. Understand the SMA: To start, ascertain if the project’s SMA is activated electrically or depending on temperature. For effective circuit design, one must be aware of the voltage, current, and power needs of your SMA.

2. Connect the SMA: Attach the positive terminal of the power supply to one end of the SMA wire, and the motor output (D) or drain (D) of your MOSFET or H-Bridge driver to the other.

3. Connecting to an Arduino: The following parts should be connected to the Arduino:

   i. Connect the ground (GND) pin of the Arduino to the source (S) terminal of the MOSFET/H-Bridge driver.

   ii. Connect the MOSFET/H-Bridge driver's gate (G) or control pin to one of the Arduino's digital output pins, such as digital pin 9.

   iii. Connect the Arduino's ground (GND) to the ground of the power supply.

   iv. To prevent voltage spikes when the SMA switches off, you might optionally connect a diode in parallel with the SMA actuator.

4. Program the Arduino: To control the MOSFET/H-Bridge driver and the SMA as a result, an Arduino sketch (code) should be written. The code will be determined by the particular specifications of the project’s SMA and the motion we desire. For instance, if electrical activation is being used, the SMA will be activated by sending a digital signal to the gate/control pin.

5. Power Supply: Make sure the power source has the necessary voltage and current to turn on the SMA. If necessary, use a suitable voltage regulator.

6. Testing: Test the setup by uploading the Arduino sketch. Make any necessary code or circuit adjustments based on the SMA's movement.

7. Safety: SMAs can become extremely hot upon activation, so use caution when interacting with them. Ensure adequate insulation and safety precautions to avoid hazards like burns.

8. Iterate and optimize: Depending on the specifications of the project, everyone might need to make minor adjustments to the code and circuit to ensure peak performance.

It should be noted that each project unique SMA and MOSFET/H-Bridge driver's characteristics and datasheet may differ greatly from other SMAs and components. Safety measures are essential, especially when working with high-temperature SMAs.

In order to include different sensors into circuit to trigger SMA using them, we need to connect the sensor to the Arduino and write code to read data from the sensor; following steps should be taken:

1. Arduino board (e.g., Arduino Uno)
2. Sensor of choice (e.g., temperature sensor, ultrasonic sensor, light sensor, etc.)
3. Jumper wires
4. Breadboard (if needed)

Steps:

1. Identify Your Sensor: Determine the type of sensor that is being used using and its pinout. Refer to the datasheet or documentation for the sensor to understand its electrical characteristics.

2. Connect the Sensor: Connect the sensor to the Arduino as follows:

- Connect the sensor's power (VCC) pin to the Arduino's 5V pin or 3.3V pin, depending on the sensor's voltage requirements.

- Connect the sensor's ground (GND) pin to the Arduino's ground (GND).

- Connect the sensor's signal (OUT) pin to one of the Arduino's analog input pins (A0 to A5) or digital input/output pins (2 to 13). The choice of pin depends on the sensor and its interface (analog or digital).

3. Install Necessary Libraries (If Required): Some sensors may require specific libraries to communicate with the Arduino. These libraries can be found in the Arduino IDE's Library Manager or on platforms like GitHub. Install the appropriate library if needed.

4. Write Arduino Code: Write an Arduino sketch (code) to read data from the sensor. Use the Arduino IDE for this purpose. The code will depend on the type of sensor is being used for each project’s purpose. Here's a basic example for reading data from an analog sensor connected to analog pin A0:

~~~
  ```arduino
void setup() {
    Serial.begin(9600); // Initialize serial communication
  }
  void loop() {
    int sensorValue = analogRead(A0); // Read sensor data
    Serial.println(sensorValue); // Print data to serial monitor
    delay(1000); // Delay for 1 second
~~~

~~~
}
```
~~~

The code to should be modified to match the project’s sensor's interface and data format.

5. Upload and Test: Upload the Arduino sketch to the Arduino board and open the Serial Monitor in the Arduino IDE (Tools > Serial Monitor). The sensor data being printed to the Serial Monitor should be seen.

6. Calibrate and Interpret Data: Depending on the sensor and its application, calibration of the sensor data or perform specific calculations to interpret the data correctly may be needed

7. Expand The Project: Depending on the project's requirements, the sensor data may be used to control other components, display information on an LCD, or send data to the cloud, among other possibilities.

It should be noted that refering to the datasheet and documentation of projects specific sensor for detailed wiring instructions and code examples is highly necessary, as each sensor may have unique requirements.

2.9 Response time and response symmetry

SMAs are commonly activated using electricity, which causes Joule heating. Deactivation, on the other hand, usually happens through the natural dissipation of heat into the surrounding environment, a process known as free convective heat transfer. As a result, SMA actuation tends to be asymmetric, with a relatively fast activation time and a slower deactivation time. Various techniques have been suggested to shorten the deactivation time of SMAs. These methods include using forced convection, which involves actively moving air or fluid to enhance heat dissipation, and adding a thermally conductive material around the SMA to manipulate the rate of heat transfer(Quintanilla et al., 2013).

2.10 Limitations:

One of the primary hindrances to the widespread adoption of shape-memory alloys in construction is the material's cost, which is particularly significant because construction materials are typically used in large quantities. The production cost of shape-memory alloys encompasses expenses related to raw materials, processing, heat treatment, and machining. To encourage greater acceptance of shape-memory alloys for construction purposes, it is imperative to develop cost-effective yet high-performance shape-memory alloy products. These alloys rely on various metallic commodities, the prices of which can fluctuate over time, and the cost of shape-memory alloy products is further influenced by factors such as shape, quantity, and manufacturing processes.

The fatigue of shape-memory alloys can be categorized into two main types: functional fatigue and structural fatigue. Functional fatigue involves a reduction in the mechanical properties of shape-memory alloys, such as superelasticity and the shape-memory effect, as a result of increased cyclic loading. On the other hand, structural fatigue refers to the gradual accumulation of damage within the microstructure of shape-memory alloys during cyclic loading, ultimately leading to fatigue failure(Eggeler et al., 2004).

The fatigue life of shape-memory alloys is influenced by several factors, including loading frequencies, stress levels, phase-transformation temperatures, and changes in microstructure. Research has shown that higher stress levels imposed on shape-memory alloys tend to result in shorter fatigue life. It's crucial to consider scenarios where prestressed shape-memory alloys are employed in structures, as temperature fluctuations can lead to variations in stress within the alloy, potentially causing long-term fatigue failure.

As discussed, this research synthesizes dispersed knowledge from material science, technology, coding, and design to construct an integrated framework, enabling architects to capitalize on shape memory alloys' vast potential. Despite these materials' transformative capabilities, technical complexities have inhibited adoption in architectural contexts. Through exhaustive inquiry across disciplines, this thesis elucidates the properties, fabrication processes, mechanical principles, and responsive behaviors that empower SMAs. Bridging these specialized domains, the resultant knowledge framework empowers designers to strategically incorporate SMAs into innovative constructions, kinetic systems, and adaptive facades. With barriers to entry diminished through this resource, the striking material agency and energy efficiency innate to SMAs can finally be harnessed to enact dynamic, intelligent architectures. By aggregating insights from leading experts, this thesis lays the foundation necessary to catalyze imaginative new directions in architectural design using these extraordinary alloys. while shape memory alloys, particularly iron-based SMAs, have gained attention and found applications in the construction industry, their use in the architecture field is not as widespread. Factors such as limited awareness and understanding of how to implement this fairly new material among designers, cost considerations, and differing design requirements may contribute to the limited adoption of SMAs in architecture. Further research, education, and exploration of the potential applications and benefits of SMAs in architectural design and creating a framework that sheds light on vague parts of the process of using SMA could help bridge this gap and promote their use in the field.

The integration of Shape Memory Alloys in architectural design holds great potential for creating adaptive, responsive buildings. However, several challenges prevent their widespread use. These include the complexity of programming and controlling SMAs' thermomechanical behaviors, the lack of predictive tools to model their performance at an architectural scale, and limitations in manufacturing processes, which are not yet cost-effective or scalable (Bagheri, 2024). Moreover, architects and designers do not have a solid, accessible source that outlines how to effectively use and implement SMAs in their projects. This knowledge gap leaves designers without the necessary tools and guidelines to integrate these advanced materials into real-world applications, thus hindering the broader adoption of SMA-based kinetic systems.

To address this gap, we propose developing a comprehensive knowledge framework for the practical application of SMAs in architecture. This framework would provide clear guidelines for material selection, design integration, and control systems, making it easier for architects to incorporate SMAs into building projects. It would include customizable tools for predicting SMA behavior, facilitating the design of responsive systems that adapt to different climates and architectural contexts. By offering practical, scalable solutions, the framework would enable architects and engineers to advance the field of adaptive architecture, making sustainable and innovative building designs more accessible and feasible.

In the following research, I intend to create an accessible repository of information, empowering architects, engineers, and researchers to make well-informed choices regarding the selection of appropriate Shape Memory Alloys (SMAs), configuring their thermomechanical behaviors, and seamlessly incorporating them into dynamic structures. This all-encompassing KNOWLEDGE FRAMEWORK, which distills insights from various disciplines related to architectural SMAs, is currently absent, and my thesis aims to bridge this gap. It aims to facilitate their imaginative and systematic incorporation into future responsive and sustainable built environments. The knowledge base created through my research will help surmount existing obstacles to SMA applications and stimulate innovation at the intersection of materials, kinetics, and design.

3.Methods

3 Methods

The use of Shape Memory Alloys (SMAs) in architecture has the potential to revolutionize building designs by creating adaptive and responsive structures. However, several barriers are limiting their widespread implementation. These challenges include the complexity involved in programming and managing the thermomechanical properties of SMAs, the absence of predictive tools to model their performance in architectural applications, and the high cost and difficulty of scalable manufacturing. Additionally, there is no comprehensive resource available for designers on how to effectively incorporate SMAs into building projects. This lack of accessible, practical information prevents designers from fully utilizing SMAs, which slows the adoption of these technologies in sustainable architecture.

To bridge this gap, I propose the development of a thorough knowledge framework to guide the integration of SMAs into architectural practice. This framework would provide detailed guidance on material selection, design strategies, and control mechanisms, making it easier for architects to apply SMAs in their projects. It would also offer predictive tools to simulate SMA behavior, enabling designers to create responsive systems that adapt to various climates and design needs. By providing these practical resources, the framework would help advance the adoption of SMA-based solutions, making innovative and energy-efficient building designs more achievable and scalable.

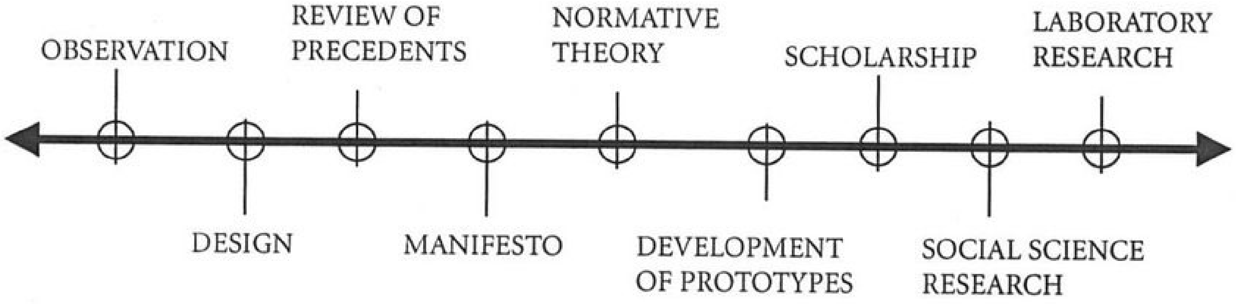

Figure 18- Michael Joroff and Stanley Morse's conceptual framework for architectural research(Joroff and Morse, 1983)

This research employs a subjective system of inquiry, with the investigative approach ranging from subjective to more objective as it progresses. The flowchart depicted as Figure 16 serves as a guide, illustrating the various sequential stages undertaken in this research. Additionally, it clearly delineates the research methodology employed.

The primary goal is to establish a framework that serves as a step-by-step guide for architects, interior designers, and industrial designers interested in incorporating SMA-actuated responsive elements into their projects. Given that the researcher is closely involved with the subject of study, the approach is largely qualitative. However, certain case studies involve a deductive process of inquiry to explore cause-and-effect relationships, while the qualitative approach focuses on clarifying multiple critical factors influencing the phenomenon.

The outcome of this research is the creation of a new architectural design framework that supports the integration of SMA-actuated responsive elements in buildings. This framework outlines key decisions at each stage of the design process to ensure the successful incorporation of these dynamic components. It defines the roles of team members, necessary resources, and the flow of decision-making. The research begins by exploring the significance of including dynamic SMA components in architecture, followed by an evaluation of the available tools and technologies to support this. Ultimately, a structured design framework for implementing SMA-based dynamic lighting designs was developed. In my research, I navigated through three distinct stages, with each stage resulting in a revised version of the framework. The initial framework, formed in the first step, underwent successive revisions in the subsequent steps. The third and final stage acted as a point of consensus, solidifying the framework. This multi-step approach was designed to ensure a well-rounded research design.

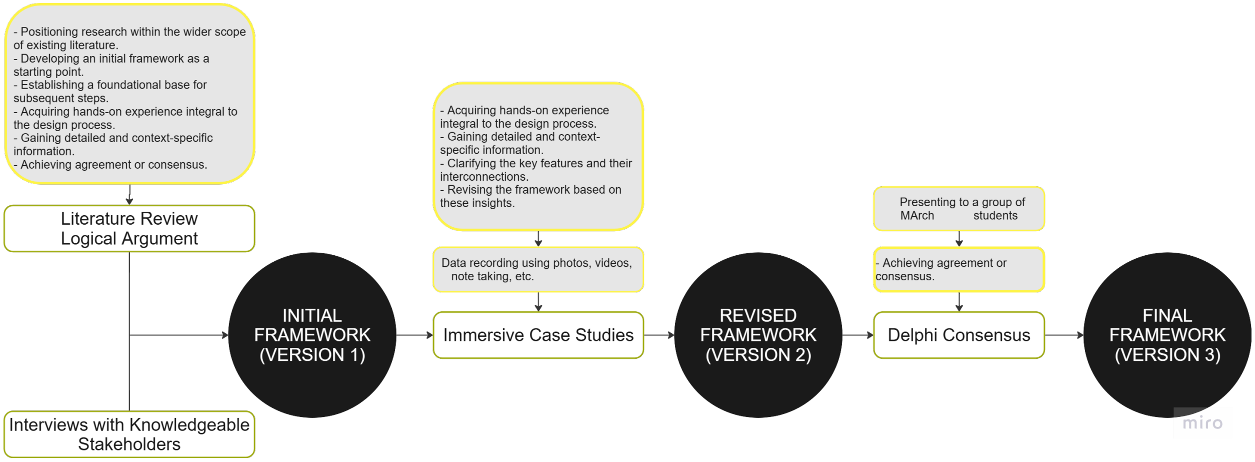

Figure 19 - General scheme of research methodology

Each of these steps will be explored in more detail in the upcoming sections. Additionally, Figure 17 illustrates the overall structure of the research design, which primarily employed qualitative methods of investigation. Consequently, the next section will justify the use of a qualitative research approach and discuss its philosophical underpinnings as they apply to this study.

3.1 Praxis vs. Theory

"Praxis" encompasses a range of interconnected themes that examine its application across disciplines, underscoring its importance in critical practice, cultural studies, and social action. These discussions emphasize how praxis acts as a link between theory and practice, enabling active engagement with societal challenges and enhancing insights into human agency.(Sami Qasim Alfartosi and Nasser Samari Jaafar, 2023; Smith, 2004) In contemporary art, praxis as a form of critical practice represents a procedural human activity aimed at practical functions rooted in a hands-on engagement with the physical world. The concept of **praxis** in Gramsci's thought identifies it as a critical practice rooted in human activity that encompasses various aspects of life, including artistic endeavors. This artistic practice is intertwined with the creative processes of artists, arising from a profound awareness and critical understanding of societal issues. Sami Qasim Alfartosi also discusses how to monitor artistic practices linked to praxis as a human activity aimed at societal change. It establishes the research's importance and objectives, particularly in exploring representations of praxis in contemporary art. He notes the theoretical framework, consisting of two topics: the compatibility of theory and practice within Gramscian praxis, and the effectiveness of praxis as a critical practice in society. Finally he emphasizes on research community and analyzes three selected artworks as representative samples.(Sami Qasim Alfartosi and Nasser Samari Jaafar, 2023)

Jaeger et el (Jaeger and Selznick, 1964) discussed Normative theory as a matter that establishes prescriptive frameworks that guide behavior and practice, providing standards for how things "ought to be." In artistic contexts, these frameworks inform decision-making processes and evaluate the effectiveness of creative outcomes. While theory remains in the realm of abstract thought and academic discourse, normative theory bridges the gap between pure theoretical understanding and practical application by establishing guidelines and principles.

The intersection of **normative theory**, **praxis**, and **prototyping** creates a comprehensive framework for artistic inquiry and practice. Normative theory offers a critical lens through which artists can assess the implications of their work within broader societal contexts, encouraging a reflective approach that goes beyond aesthetic considerations. Praxis, in this framework, ensures that theoretical insights are actively applied in the creative process, fostering an environment where practice informs theory and vice versa. Prototyping serves as an essential tool in this interplay, enabling artists to experiment with and iterate on their ideas, transforming theoretical concepts into tangible expressions. Together, these elements contribute to a nuanced understanding of artistic practice, facilitating a dialogue between ethical considerations, practical application, and innovative experimentation in the arts.

3.2 Qualitative vs Quantitative Methods

“Design is a way of inquiring, a way of producing knowing and knowledge; this means it is a way of researching” (Downton, 2003)

Qualitative and quantitative methods are two distinct approaches to research that serve different purposes and employ different techniques. Qualitative research focuses on understanding and interpreting subjective experiences, meanings, and social phenomena, while quantitative research aims to measure and analyze numerical data to identify patterns and relationships (Chapman et al., 2015; Krauss, 2015; Lewis, 2015)

Qualitative research methods involve collecting and analyzing non-numerical data, such as interviews, observations, and textual analysis, to gain an in-depth understanding of the research topic. This approach emphasizes the exploration of context, perspectives, and the subjective experiences of individuals or groups . Qualitative research often uses techniques like thematic analysis, grounded theory, and narrative synthesis to identify themes, patterns, and meanings within the data (Chapman et al., 2015)(Murphy, 2015).It is particularly useful for generating rich, descriptive data and exploring complex social phenomena.

On the other hand, quantitative research methods involve collecting and analyzing numerical data to test hypotheses, establish correlations, and make generalizations about a population(Ghosh et al., 2020; Prabhakararao Sampathirao, 2016). This approach relies on statistical analysis and employs techniques such as surveys, experiments, and statistical modeling to quantify and analyze data. Quantitative research aims to provide objective and measurable evidence, often focusing on variables, causality, and generalizability (Ghosh et al., 2020; Prabhakararao Sampathirao, 2016).

The main difference between qualitative and quantitative methods lies in their underlying philosophical assumptions, research questions, data collection, and analysis techniques. Qualitative research seeks to understand the subjective experiences and meanings of individuals, while quantitative research aims to measure and analyze numerical data to identify patterns and relationships. Qualitative research is often exploratory and inductive, while quantitative research is deductive and hypothesis-driven(Chapman et al., 2015; Krauss, 2015; Lewis, 2015).

In summary, qualitative research focuses on understanding subjective experiences and social phenomena through non-numerical data analysis, while quantitative research aims to measure and analyze numerical data to establish patterns and relationships. Each approach has its strengths and limitations, and the choice between qualitative and quantitative methods depends on the research objectives, research questions, and the nature of the research topic.

This thesis aims to elucidate the nascent applications of shape memory alloys in architectural design through an immersive qualitative inquiry. The qualitative approach is well-suited for the exploration of this intricate topic, which involves not only technical dimensions but also encompasses design considerations, user experiences, and potential aesthetic and functional implications within the built environment.

Qualitative research is particularly apt for the exploratory nature of this investigation, where the primary objective is to gain a comprehensive understanding of how SMAs can be effectively employed in architectural design. Through qualitative methods such as interviews, observations, and content analysis, this study aims to capture the richness and diversity of perspectives held by architects, designers, and users, thereby informing the development of a holistic framework.

Furthermore, qualitative research offers the flexibility necessary for a nuanced exploration of the topic. The approach permits the examination of real-world cases, consideration of cultural and contextual factors, and the discovery of challenges and opportunities that may not be amenable to quantitative measurement but hold paramount importance for the integration of SMAs into architectural practice.

In particular, in-depth interviews with architects and designers will serve as a pivotal methodological choice. These interviews are poised to yield invaluable insights into the intricate thought processes, decision-making criteria, and creative strategies that underpin the utilization of SMAs in architectural design. By delving into the subjective experiences and perceptions of individuals with practical exposure to SMAs, this research endeavors to unravel not only the technical facets but also the emotional and experiential dimensions that are intrinsic to the engagement with this material.

While it is acknowledged that qualitative research may not furnish data readily amenable to quantitative generalization, it is posited that this method offers a profound depth of insight, contextual understanding, and a holistic grasp of the subject matter—attributes that align closely with the aims and objectives of this thesis, particularly in the context of developing a comprehensive framework for SMA usage in architecture.

3.3 Epistemological Basis

In developing a comprehensive knowledge framework for the implementation of Shape Memory Alloy (SMA) actuators in architectural and design practices, it is pivotal to delve into the epistemological foundations underpinning this multidisciplinary endeavor. Epistemology, the study of knowledge, its origins, methods, and validity, provides a crucial lens through which the convergence of material science, technology, and architectural knowledge can be critically examined and integrated.

This framework predominantly utilizes three types of knowledge: empirical, theoretical, and practical. Empirical knowledge, gained through observation and experimentation, is crucial in understanding the physical properties and behaviors of SMA materials. Theoretical knowledge, drawn from scientific and architectural theories, guides the conceptualization of how SMA actuators can be innovatively applied in design. Practical knowledge, grounded in hands-on skills and real-world applications, translates theoretical insights into feasible design practices.

Here is a suggestion for discussing epistemology and types of knowledge in an academic yet straightforward way for your thesis framework on implementing shape memory alloy (SMA) actuators:

This research conceptualizes the proposed SMA framework as embodying designerly ways of knowing that integrate technical knowledge with application-based architectural knowledge. The framework consolidates both:

(a) Propositional knowledge on material composition, mechanical principles, and performance parameters transferred from materials science and engineering fields

(b) Procedural knowledge on fabrication techniques, integration logics, and design methodologies gleaned from direct prototyping experience with SMAs

While propositional knowledge establishes technical "knowing that", procedural knowledge conveys applied "knowing how" for incorporating SMAs in spatial and structural contexts. The framework synthesizes these two interconnected ways of understanding.

Furthermore, the combined inductive (from particulars to general principles) and deductive (applying existing theories) reasoning underpinning the framework reflects the abductive logic of design processes. This aligns with designerly epistemologies that integrate scientific and intuitive ways of knowing. By consolidating insights from both specialized analysis and open-ended making, the framework mirrors the construction of architectural knowledge itself through the dialectic between abstract and experiential modes of inquiry.

So in summary, the multi-disciplinary knowledge framework advanced here is grounded in an epistemology embracing technical propositional insights and practice-based procedural guidance as interlinked, and aesthetically synthesizes broader concepts with contextually attuned application, making it a robust tool for architects and designers working with SMA actuators.

This study is an attempt to bridge the gap between design and research by utilizing an inductive approach, characterized by an intensive, open-ended, and iterative process that encompasses knowledge acquisition through the design process, fabrication, and the exchange of ideas. The research prominently relies on a "knowledge capture through design" approach, specifically drawn from the design process of SMA actuator systems. This knowledge capture process is cultivated through an immersive case study, involving firsthand experience and practical application. The insights garnered through this process will be amalgamated with information extracted from existing literature, culminating in the development of a preliminary procedural model for the design of dynamic shading systems.

3.4 *Dynamics of divergence and convergence*

3.4.1 after Bela H. Banathy (1996)

Banathy's model highlights the repetitive pattern in design of divergence and convergence, analysis and synthesis. First, we broaden perspective by considering different inquiry scopes, various major design options, core values and ideas. Then we narrow down as we select and craft a vision of the future system. This divergence then convergence repeats in generating design solutions. For each key design domain – core definition, specifications, functions, enabling systems, systemic environment – we start by diverging as we create multiple alternatives. Then we evaluate and select the optimal alternative, converging on promising solutions. So design progresses through cycles of opening up possibilities then narrowing down selections, iterating between divergent and convergent thinking to synthesize analyzed alternatives into preferred solutions.

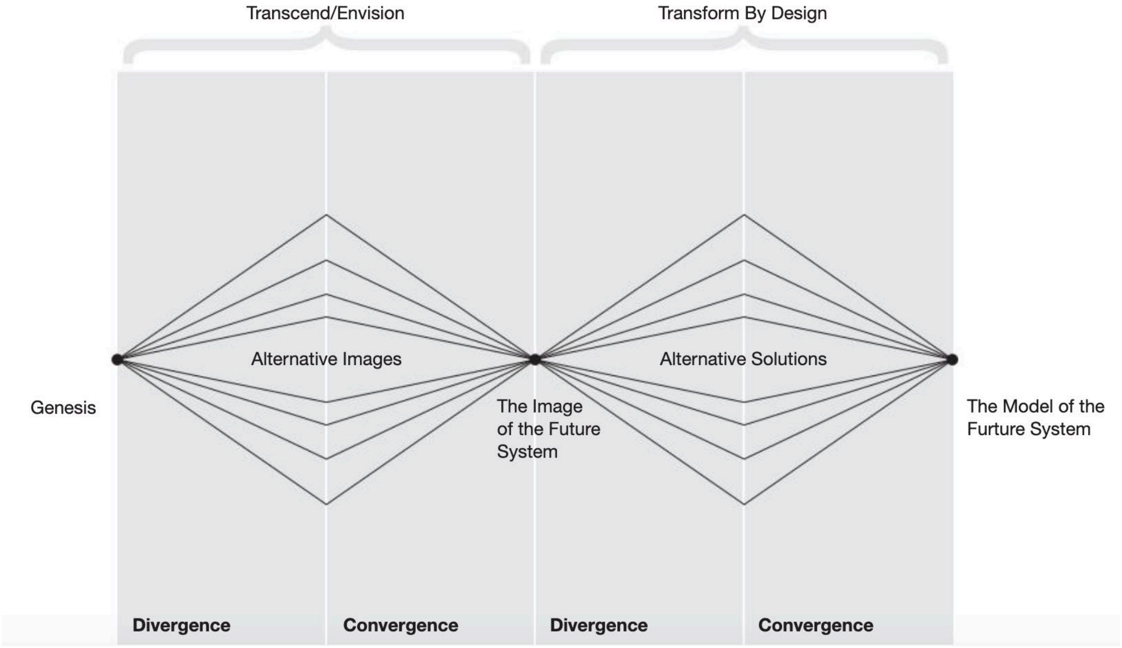

Figure 20- Double Diamond is the name of a design process model popularized by the British Design Council in 2005, ***and adapted from the divergence-convergence model proposed in 1996 by Hungarian-American linguist Béla H. Bánáthy***

3.4.2 after Nigel Cross (2000)

Typically, a design strategy aims to ultimately converge on a final, thoroughly evaluated and detailed design proposal. However, in working towards that end goal, there will be appropriate and necessary times to diverge, widening the search or seeking new conceptual starting points. While the overarching objective is to focus in on an optimal proposal, the process involves periods of intentionally broadening exploration and ideas along the way.

Therefore, while the overall design process is convergent, focused on an end result, it will incorporate deliberate periods of divergence as well.

The cyclic, iterative nature of convergence and divergence in Banathy's and Cross's models is analogous to the iterative design processes described by Marcus and Maver, and the iterative spirals put forth by Boehm and others. There is alignment across these models that design progressed through repetitive cycles of broad exploratory thinking and focused narrowing down in order to arrive at optimal solutions.

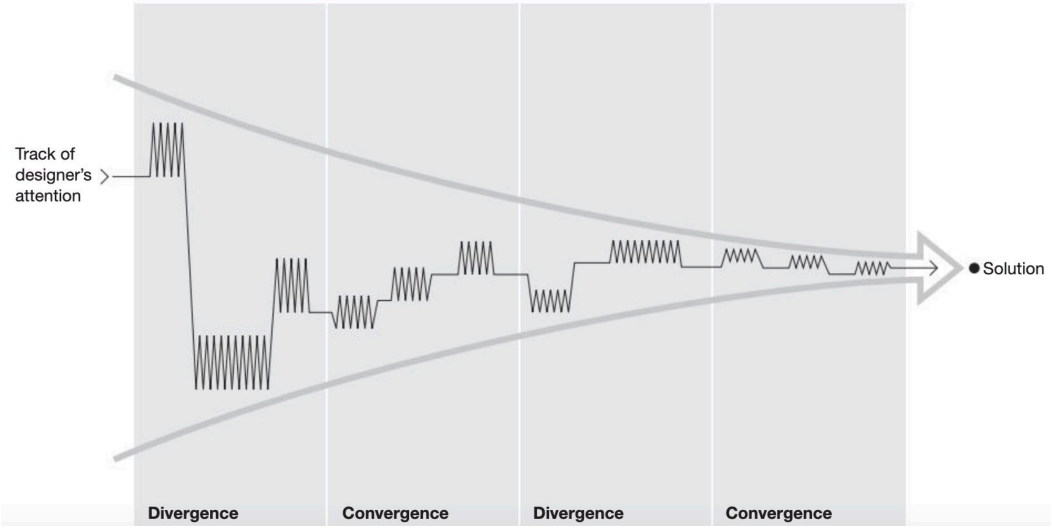

Figure 21- Nigel Cross's divergence and convergence model of overall folding

This study employs both divergent and convergent thinking, as Cross explains. Overall, the design process aims to narrow down to a final, evaluated design solution. However, within the process, there are times when broadening the search or exploring new concepts is appropriate and essential. So while the overall arc is convergent, focused on honing in on an optimal design, there are intervals of intentional divergence to widen the idea generation and possibilities considered. This study will mirror that larger creative flow - converging toward proposed frameworks but diverging during the qualitative data gathering and analysis to encompass architectural insights and experiments that may catalyze innovative applications of shape memory alloys.

3.5 Theoretical Grounding of the Research

In architecture, theory refers to discourse that describes and reflects on architectural practice and production, including identifying issues facing the field. Architectural theory can take different forms - prescriptive, proscriptive, affirmative, or critical. Prescriptive theory puts forth new or renewed solutions to particular problems, establishing norms to guide practice. It advocates positive standards, at times even proposing a design methodology. This research engages with prescriptive theory, aiming to present an innovative proposition in design research. As Groat and Wang describe, architectural theory can be categorized as explanatory theory, normative theory, or design-polemical theory. This study aligns with prescriptive, normative theory in working to develop a framework to inform architectural design and education.

This study aligns with design-polemical theory, which guides and evaluates design choices based on value-driven convictions about how a problem ought to be solved. From this lens, designers' approaches stem from personal convictions regarding their designs, though ultimately wider adherence to their perspective is sought. Here, theory can be applied to the architectural envelope design outcomes. Since translating theory into formal outcomes involves interpretation, the design workflow proposed in this study may elucidate designers' decisions. Extensive literature examines passive shading design or design constraints, yet little examines the design process or attributes for transformable SMA actuated systems. This study helps address that gap through a proposed framework rooted in design-polemical theory.

The research methods used can influence the design process development. As an architect with over fifteen years of experience researching, designing, and constructing kinetic structures, the researcher believes this work signals a shift in transformable design studies and anticipated outcomes. This study diverges from conventional architectural research expectations. Here, research and practice interrelate more fluidly, aiming to advance both architectural practice and scholarship. Bridging these two often disparate realms is a core research motivation. Through firsthand expertise, this study pursues research methods that entwine with and enhance the design process to jointly elevate academic inquiry and applied practice.

3.6 Design Decision Research Strategy

3.6.1 Action Research

"Action research" refers to studies that closely investigate a specific, real-world situation, particularly the logic of how factors within that setting interconnect as the process progresses toward a defined experimental objective. The focus is on contextualized knowledge generated from a localized setting, as opposed to abstract knowledge derived from multiple environments. Action research emphasizes insights emerging from examination of a concrete scenario as it unfolds toward a targeted goal.

A more specific type of action research is "design decision research." In traditional action research, the researcher remains outside the concrete situation, observing the iterative cycles of actions taken. Design decision research immerses the researcher within the actual process. Here, the "researcher" can include the various participants in the design process. In this sense, "researchers" and "designers" are one community, not two separate groups. The researcher becomes a new kind of practitioner who not only makes design decisions but also analyzes those decisions through a research lens. Design decision research integrates the researcher into the unfolding scenario as both decision-maker and assessor (Groat and Wang, 2013).

3.6.2 Reflective Theory

This study is influenced by reflective theory, which focuses on integrating theory and practice through iterative cycles of experience and conscious application of that learning. The concept of experiential learning centers on transforming information into knowledge and abstract theory into practical knowledge. It is critical that the researcher grasps the significance of experimental knowledge gained through hands-on testing and incorporates it into practice. In experiential learning, reflection on action by the researcher/practitioner is crucial for active engagement in the process. Reflection entails reconsidering and evaluating one's experiences. The reflective approach emphasizes learning by doing, examining general understandings in new contexts, and self-regulating one's learning. This study embraces experiential learning through iterative hypothesis testing and reflection to synthesize theoretical concepts with experimental findings and evolve an integrated understanding to inform architectural practice.

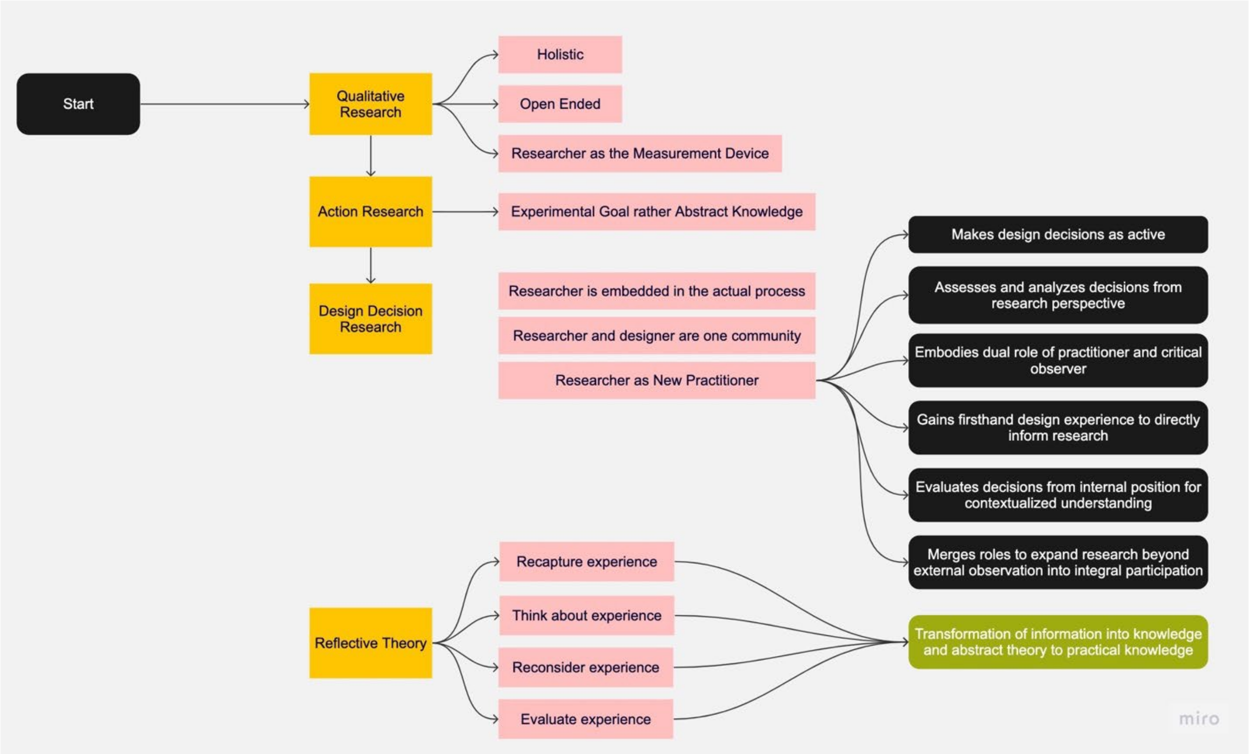

Figure 22- Reflective Theory Framework

3.7 *Knowing In Action: Immersive Case Study*

An immersive case study approach holds significant potential for architectural research aimed at elucidating the tacit knowledge or "knowing in action" embedded within design practice. By positioning the scholar as an insider through participant-observation within a contextualized design scenario, immersive strategies allow firsthand access to the nuanced interactions, experiential knowledge, and reflexive decision-making that characterize architectural work. As both practitioner and critic, the scholar-as-researcher gains crucial lived perspectives on how skilled expertise guides actions and judgments in the immediacy of problem-solving. Despite limitations in objectivity, immersive methods enrich architectural epistemology by capturing the relationships between contextual factors, tacit knowledge, and design decisions as they unfold. The scholar is thus immersed directly within the ecology of practice, gaining insights into architectural knowing in action from within its native context.

With thoughtful implementation, immersive case study techniques hold meaningful potential to advance architectural understanding.

Heidegger's philosophical perspective, as evident in works like "Being and Time," underscores the importance of immersive case studies in illuminating the intricacies of human existence and its connection to the world. Immersive case studies, he contends, are essential for understanding how individuals engage with their surroundings, construct meaning, and navigate their existence. Heidegger's emphasis on phenomenology and hermeneutics aligns with the use of immersive case studies to provide a deep and contextually rich exploration of lived experiences, making them a valuable method for architectural research.

In this research, the investigator takes an embedded, participatory role rather than a distanced observational one. As active participant, the researcher makes design decisions within the process and assesses those choices through a critical lens. This enables firsthand experience capturing, evaluating, and reconsidering various facets. Given the scarcity of information on kinetic solar shading design processes, coupled with the very limited number of experts exploring this niche area, an immersive approach leverages the researcher’s background as both architect and long-time practitioner to provide otherwise inaccessible perspectives. With few designers working on kinetic solar shading, traditional data collection methods would have restricted insight into the decision-making sequences. Therefore, this study implements an embedded, experiential methodology to expand understanding of this specialized domain through the researcher’s dual position as designer and analytical critic.

3.7.1 Research through an Immersive case study

Through conducting the research via a project based approach, the author will be enabled to to identify how particular outcomes guided each stage. Through cycles of exploration, interventions, and gathered insights, new exploratory directions emerged. Conducting research via this design project expands current motion-focused investigations by elucidating the development process itself. With emphasis on design sequencing, this study delineates a process model from initial concept to fabricated prototypes, revealing how motion possibilities using shape memory alloys actuators evolved into physical artifacts. By embedding research within creation of the prototypes, the progressive design decisions and influences shaping each phase become traceable and analyzable. The project methodology grounds the study in practical outcomes while expanding understanding of kinetic design processes.

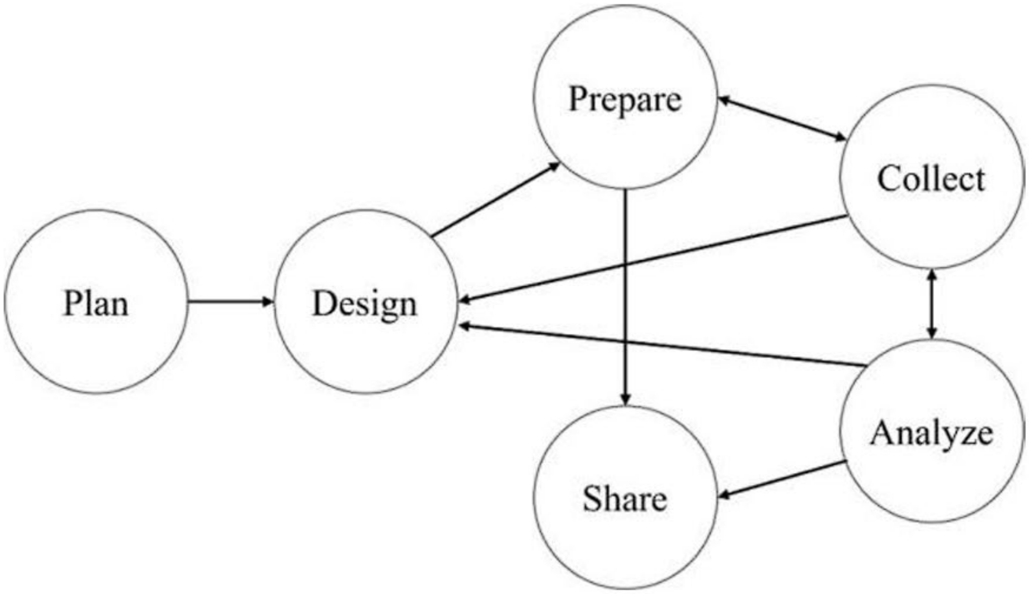

Figure 23- Case study research design(Yin, 2009)

3.8 Evolving the Design Process Model for SMA Actuated Systems

This study seeks to develop a design process model through creation of the SMA actuated prototypes, with the goal of informing a broader framework for transformable design. The research maps the influential factors, challenges, and knowledge areas within the process of designing a transformable solar shading system. Mapping the design workflow elucidates the most impactful variables in kinetic development. By framing the decision sequence undertaken in the design, the study aims to identify key elements in transformable design processes more broadly. Delineating this case study's progression could clarify drivers and dependencies applicable to other adaptive, kinetic systems.

3.8.1 Attributes of SMA Actuated Systems Design Process Model

This research seeks to develop a design process model for shape memory alloy (SMA) actuated systems. Establishing such a model is critical to elucidate the interconnected information and hidden relationships within the design process. The model describes design methodologies and pathways through different design phases. By breaking down the sequences into activities and decision nodes, the model provides context for evaluating the design approach for SMA systems. While each project has unique aims, the model captures the process to enable improvement. This model provides designers with accelerants, deterrents, iterations, considerations and rationalizations.

The SMA design process model is cyclic, enabling continuous refinement through prototyping, feedback and assessment. The model facilitates communication between users, designers, engineers and fabricators. It represents a shared understanding of the design flow. This model adopts a design-led perspective rather than research-led. With research-led models, the problem is fully defined before solutions are developed. The design-led model begins with tentative solutions that clarify the problem over time. Here, analysis and synthesis are integrated, not sequential. Without fixed answers, the process involves iterative loops between solutions and problems. This aligns with addressing ill-defined problems containing inherent uncertainties.

This research concentrates on the envision phase where possibilities are generated, evaluated and prioritized. Models aid idea generation by combining solution aspects. Prioritization frameworks allow concept comparison. Design representations depict abstract solutions. Roadmaps outline development sequences from current to future states. Scenarios and prototypes demonstrate functionality. Through making, solutions become tangible.

The problem-solution relationship is two-way; solutions help further define problems. Similar sub-problem and sub-solution interactions occur. Creative loops for novel concepts are embedded within the process. Communication enables discovery through conversations with collaborators. Feedback provides continuous improvement.

The SMA design process integrates multiple disciplines including engineering, fabrication, and environmental assessment. Making through prototypes is research that informs design thinking. Hands-on exploration elucidates intricacies for fabrication, installation, operation, and maintenance. Prototypes visualize concepts, reveal performance, and prompt discoveries. By interlinking design and making, errors and malfunctions are reduced.

In summary, this research delineates a cyclic, integrated SMA design process model foregrounding:

3.8.1.1 Multidisciplinary collaboration

The SMA actuated system design process integrates multiple disciplines, requiring collaboration between various experts. Engineers provide technical guidance on feasibility and performance. Fabricators contribute material and construction knowledge. Environmental analysts assess sustainability impacts. Architects synthesize aesthetics with functionality. By bringing together various lenses early on, the design is strengthened. Different perspectives reveal overlooked aspects, prompt new directions, and negotiate tradeoffs. This multidisciplinary approach is crucial for balanced, holistic development during converting theory into praxis in case of incorporating SMA into design as shown in Figure 21

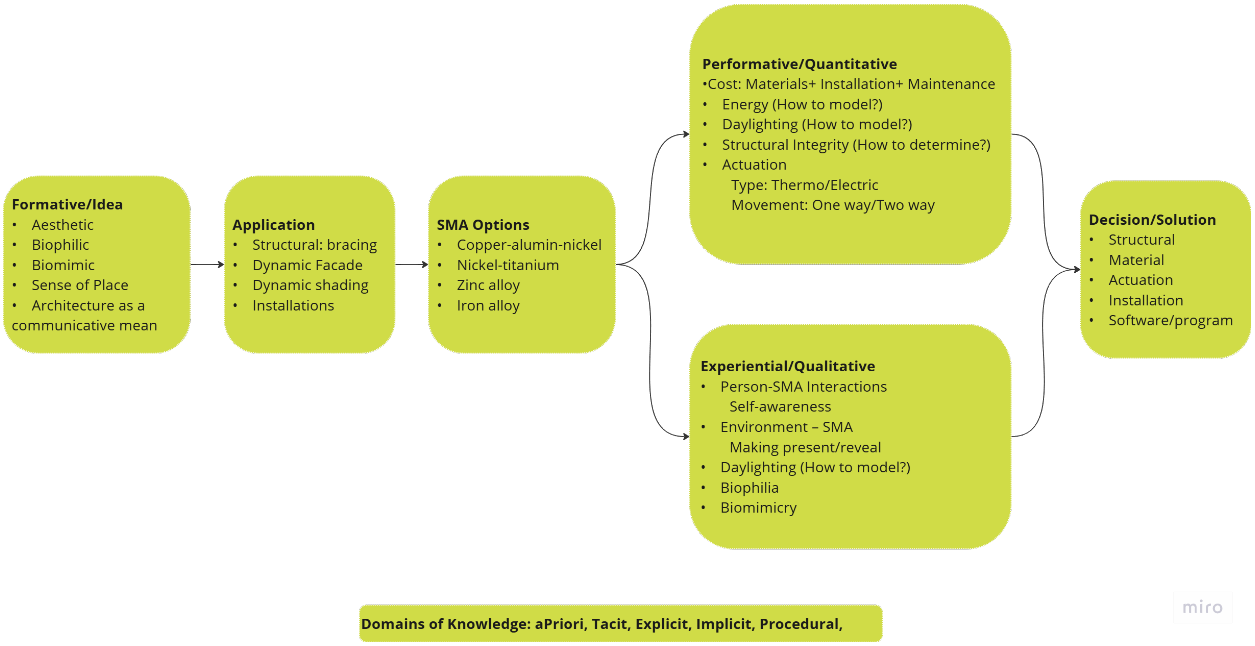

Figure 24- SMA process flow

3.8.1.2 Design-led framing

Unlike research-led processes starting with fully defined problems, this model adopts a design-led perspective. The design process begins with tentative solutions that provide a framework for clarifying the evolving problem over time. Design-led framing treats the problem as ill-defined, filled with uncertainties. Solutions become tools for understanding through an integrated analysis and synthesis approach. The process involves ongoing loops between solutions and problems, enabling flexible refinement as new insights arise.

3.8.1.3 Envisioning creative solutions

The model focuses on the envisioning phase where creative possibilities are generated, assessed and refined. This phase entails conceiving novel realities grounded in research. Various techniques aid ideation, from brainstorming to biomimicry. Evaluation frameworks prioritize innovative concepts with the most promise. Creativity is integrated throughout the process, not isolated. Envisioning is critical for pushing SMA actuated systems in new aesthetic and functional directions.

3.8.1.4 Prototyping through making

Making through prototypes and models is built into the design process as a vital mode of inquiry. Hands-on exploration elucidates physical behaviors, material interactions, fabrication methods, and performance. This tangible engagement prompts discoveries and clarifications. Prototyping enables visualization, testing under simulated conditions, and refinement of concepts. By linking making and design, errors are reduced and intricacies revealed.

3.8.1.5 Bidirectional problem-solution refinement

Rather than a linear path, the model involves bidirectional refinement of problems and solutions. Solution conjectures clarify problems, while (re)defining the problem shapes solutions. There is symmetry between sub-problems and sub-solutions. The design process progresses through interconnected iterations, not discrete steps. This fluidity enables responsive integration of new constraints and opportunities.

3.8.1.6 Communication and feedback loops

The model incorporates communication channels and feedback loops at multiple points. Conversations enable collaborative knowledge sharing and evaluation. Feedback from prototyping and testing provides critical insights to guide refinements. Design thinking develops through dialogue with materials and processes. Communication and feedback enhance discovery and avoid missteps throughout the cyclic design process.

The model aims to capture flows, activities, and decisions within the design process. By mapping the sequences, influential factors and knowledge domains are revealed to provide designers with an evaluative framework. While focused on SMA actuated systems, discoveries could elucidate patterns applicable to other transformable designs. Further research is needed to validate and refine the proposed model through design practice. This serves as an initial model laying the groundwork for mapping the intricacies of the SMA actuated system design process.

3.8.2 Research Design

Architecture is evolving into an information-based realm where technology and the built environment intersect, forging a new design paradigm. This emerging model creates solutions tailored to changing conditions over time, actively identifying issues and opportunities. While technology-driven active design has proven tremendously effective, it demands substantial energy and diverges from passive approaches, widening the divide between technological and traditional architectural solutions. As architecture shifts into the information age, new technology-integrated models are arising that go beyond static design to create intelligent, adaptive built environments. However, this increasing reliance on energy-intensive technology distances contemporary active architecture further from passive techniques deeply rooted in the field's history. The challenge is integrating high-performance active systems while retaining architecture's connection to passive solutions refined over centuries.

3.8.3 Knowledge Capturing Process

The author thoroughly documents the experiments and prototyping evolution through notes, images, videos, and journaling. This qualitative data provides a platform to assess the model's comprehensiveness and clarity. Monitoring a range of students as the delfi group and navigating the design process illuminates gaps in the model's completeness that can then be addressed. Additionally, points of confusion or ambiguity become visible so the model's clarity can be strengthened. By embedding evaluation within the student design process through observational data, the model is iteratively improved based on insights from fresh perspectives applying it in practice.

The proposed framework serves as a comprehensive knowledge framework for the design and development of Shape Memory Alloy (SMA) systems. By employing immersive case studies, iterative prototyping, and interdisciplinary collaboration, this framework aims to capture and integrate diverse types of knowledge essential for advancing SMA-based design. Acknowledging the multifaceted nature of design processes, the framework recognizes that knowledge manifests in different forms, each contributing uniquely to the innovation and realization of SMA systems.

3.8.3.1 Explicit Knowledge

Explicit knowledge encompasses codified information that is easily documented, stored, and communicated. In the context of SMA systems, this includes the physical and mechanical properties of SMAs, such as thermal actuation thresholds, fatigue resistance, and stress-strain behaviors. It also covers standardized design principles, computational models, and fabrication methodologies. By organizing and documenting explicit knowledge in technical manuals, research papers, and open-access repositories, the framework ensures accessibility and fosters collaboration across disciplines. Explicit knowledge forms the foundation for evidence-based decision-making and guides the development of innovative SMA applications.

3.8.3.2 Tacit Knowledge

Tacit knowledge refers to the intuitive, experience-driven understanding that practitioners gain through direct engagement with SMA systems. Unlike explicit knowledge, tacit knowledge is challenging to articulate but critical for mastering the nuances of SMA behavior and its integration into dynamic systems. This knowledge emerges during hands-on processes such as prototyping, testing, and iterative refinement. For instance, understanding the subtle thermal response of an SMA wire or the precise calibration required for actuation often relies on the practitioner's experiential insights. The framework emphasizes the need for immersive, practical experiences to cultivate and transmit tacit knowledge among designers, engineers, and fabricators.

3.8.3.3 Procedural Knowledge

Procedural knowledge focuses on the sequence of steps and methods necessary for the design, fabrication, and deployment of SMA systems. This includes processes such as geometric optimization for actuation efficiency, integrating SMA elements with structural components, and establishing control mechanisms for responsive behaviors. Procedural knowledge ensures that the design workflow is repeatable, scalable, and adaptable. By codifying these methods, the framework supports designers in systematically navigating complex design challenges while maintaining flexibility for innovation.

3.8.3.4 Relational Knowledge

Relational knowledge examines the interplay between components within SMA systems and their interaction with external environments. It addresses systemic considerations such as thermal and mechanical dependencies, energy efficiency, and user-system dynamics. For example, understanding how an SMA actuator interacts with its supporting structure and ambient conditions is vital for optimizing performance. The framework integrates relational knowledge to foster holistic design approaches that align individual components with the broader objectives of functionality, sustainability, and adaptability.

3.8.3.5 Heuristic Knowledge

Heuristic knowledge emerges through iterative experimentation and problem-solving during the design process. It includes strategies, decision-making shortcuts, and creative solutions developed by practitioners as they encounter and overcome design challenges. For instance, heuristics might guide the selection of SMA materials for specific applications or the adaptation of actuation mechanisms to unexpected constraints. By capturing and sharing heuristic knowledge, the framework promotes innovation and empowers teams to navigate the uncertainties inherent in SMA system design.

3.8.3.6 Integration of Knowledge Types

The framework's strength lies in its ability to integrate these diverse types of knowledge into a cohesive model for SMA system design. Explicit knowledge provides a scientific foundation, while tacit and procedural knowledge enhance practical understanding and operational efficiency. Relational knowledge ensures that designs are contextually relevant, and heuristic knowledge drives creative exploration. Together, these knowledge types create a robust foundation for designing adaptive, innovative, and sustainable SMA systems.

By structuring the framework around these knowledge types, the study not only advances SMA technologies but also fosters a shared understanding among interdisciplinary teams. This integrated approach bridges gaps between theory and practice, enabling designers, engineers, and researchers to collaboratively address complex challenges and create transformative designs. The framework underscores the importance of knowledge diversity, iterative learning, and collaboration in pushing the boundaries of what SMA systems can achieve.

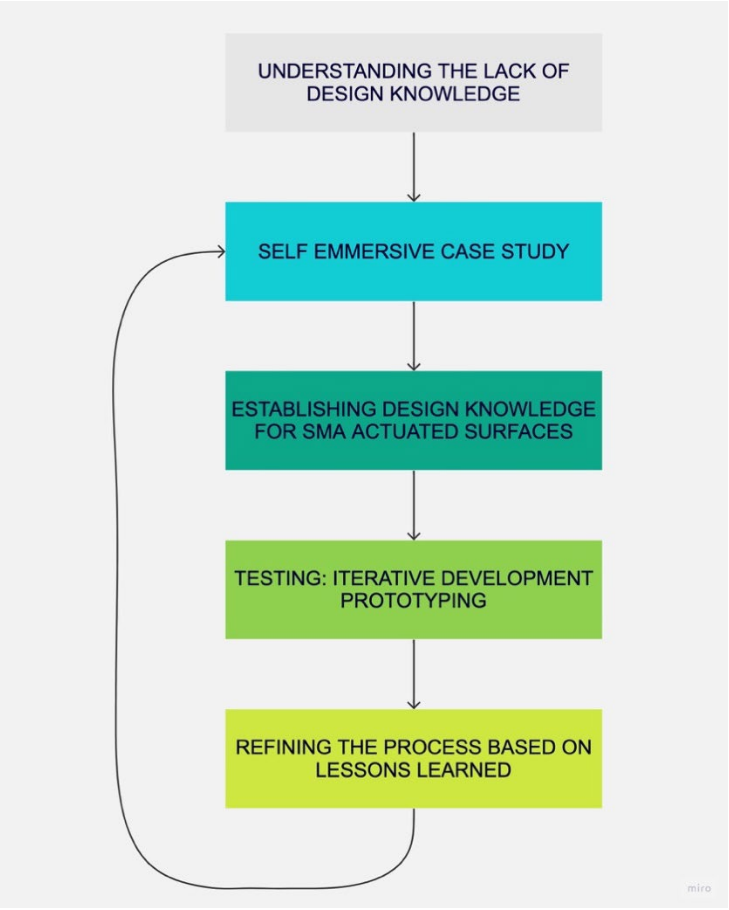

Figure 25- SMA Knowledge Flow

3.9 SMA Utility Scenarios:

The integration of Shape Memory Alloys (SMAs) within the realm of architectural design presents a transformative paradigm, affording unique opportunities across the dual dimensions of sustainability and aesthetic enhancement. The inherent characteristics of SMAs, with their ability to undergo reversible shape changes in response to external stimuli, offer a versatile toolkit for the realization of kinetic architecture, particularly in the domains of interior shadings and exterior facades.

From a sustainability and performance standpoint, the incorporation of SMAs into building design introduces a dynamic element that can significantly enhance energy efficiency. For instance, in the context of interior shadings, SMAs can be strategically employed in responsive shading systems that adapt to changing external conditions. By intelligently modulating the aperture of shading devices based on real-time factors such as solar intensity and occupant preferences, SMAs contribute to optimized energy consumption and indoor comfort. Similarly, in exterior facades, the integration of SMA actuators enables the creation of adaptive surfaces that respond to environmental stimuli, enhancing the building's thermal performance and reducing reliance on mechanical systems.

Beyond the realm of sustainability, the aesthetic dimension emerges as a compelling arena for the application of SMAs. By leveraging these alloys as kinetic interactive elements within architectural spaces, designers can infuse dynamism and interactivity into the built environment. The experiential quality of interacting with SMA-actuated architectural elements not only introduces an engaging aesthetic but also cultivates a heightened sense of self-awareness among users. The tactile and visual feedback generated through user interaction with these dynamic elements creates an immersive experience, prompting individuals to reconsider their relationship with the built environment. This sensory engagement becomes a catalyst for a deeper understanding of space, architecture, and one's own presence within the designed context.

In this academic discourse, the integration of SMAs into architectural design emerges as a multifaceted approach, wherein sustainability and aesthetic considerations converge. The versatile application of SMAs, spanning from responsive shading systems to interactive architectural elements, signifies a nuanced and innovative endeavor that not only aligns with the imperatives of sustainability but also transcends conventional aesthetic boundaries. This symbiotic relationship between form and function, sustainability and aesthetics, positions SMA-embedded architecture as a pivotal frontier in the ongoing evolution of kinetic design within the built environment.

Beyond simply enabling mechanical motions, the inherent liveliness of shape memory alloys (SMAs) - with their organic, muscle-like contractions - opens possibilities to imbue architectural spaces with a sense of vitality and dynamism. The almost animate materiality of SMAs invites their application as reactive components that ripple, bend, and reconstitute themselves in response to human presence and activities. In this way, SMA assemblies can translate individuals' movements and proximities into shifting material reconfigurations that unfold in real-time. Such responsiveness fosters stronger connective experiences between inhabitants and architecture, aligning with paradigms of sentient, affective environments. Experimental designers have only begun tapping the potential to leverage SMAs not just for kinetic performance but also more poetically as instruments that make space feel alive to human participation. Further inquiry into SMA systems as mediums for sensitively revealing people's impacts on their surroundings could yield new architectural vocabularies. Here built forms move, morph, and emote as inhabitable participants in an enlarged conversation between bodies and spaces in motion. Overall, the organic agency and reaction-capacity encoded in SMAs offers uncharted possibilities for imbuing buildings with a fluid, lively sentience - if fabrication scalability and design methodologies can be refined through additional research.

1. Exterior SMA Actuated Shading for Passive Temperature Response:

The integration of Shape Memory Alloys (SMAs) in exterior shading systems represents a pioneering approach to passive thermal regulation in architectural design. By leveraging the inherent property of SMAs to undergo reversible shape changes based on temperature variations, the exterior shading elements dynamically respond to ambient conditions. As temperatures fluctuate, the SMA actuators adjust the position and configuration of the shading system, optimizing solar heat gain and mitigating overheating within the building envelope. This intelligent and passive response to environmental cues not only enhances the energy efficiency of the structure but also aligns with sustainable design principles, contributing to the reduction of artificial cooling demands and promoting thermal comfort within the interior spaces.

Having multiple scenarios have been considered for this purpose:

2. Interior SMA Actuated Shading Aligned with User Health Metrics:

The application of SMAs in interior shading systems extends beyond conventional considerations, introducing a novel dimension that intertwines architectural dynamics with human well-being. In healthcare facilities, for instance, SMA-embedded interior shading becomes a responsive element, directly linked to users' health metrics. Utilizing sensors to monitor physiological parameters such as heartbeat, the shading system discerns variations in user anxiety levels. In response, the SMA actuators delicately modulate the shading configuration, creating a visually dynamic and comforting environment. This nuanced integration not only enhances the spatial aesthetics but also contributes to patient well-being by fostering a responsive and adaptive architectural milieu that aligns with the principles of patient-centered design.

3. Sound-Responsive SMA Wall at Home Entrances:

The incorporation of SMAs into architectural elements extends into the realm of auditory interaction, particularly at the entrance of residential spaces. A SMA-actuated wall, responsive to sound stimuli, serves as a welcoming element that engages occupants and visitors in a multisensory experience. As sound patterns change in the vicinity, the wall undergoes subtle shape modifications through SMA actuators, creating a visually intriguing and responsive architectural feature. This dynamic response to auditory cues not only introduces an aesthetic dimension but also establishes a unique form of spatial interaction, enhancing the entry experience and fostering a sense of connectivity between individuals and their living environment.

4. SMA-Actuated Wall Responding to Movement in Hospital Hallways:

In healthcare settings, the incorporation of SMA technology into wall systems within hallways introduces an innovative approach to human-centric design. The SMA-actuated wall, responsive to movement patterns, creates a companionable effect as individuals traverse the hospital corridors. As occupants move through the space, the wall subtly adjusts its configuration through SMA actuators, offering a responsive and engaging architectural experience. This dynamic interaction with the built environment not only contributes to wayfinding and spatial orientation within the hospital but also addresses the psychological aspects of patient experience by introducing an element of companionship and dynamism to often clinical and static spaces.

3.10 Summery

Chapter 3 outlines the **methodology** used to explore and develop an architectural design framework for integrating **Shape Memory Alloy (SMA) actuators** in kinetic building systems. The research adopts a **qualitative approach**, which emphasizes an in-depth, first-hand exploration of how SMAs can be applied to create adaptive and responsive architectural designs. In qualitative research, the researcher engages directly with the design context to understand and interpret the dynamic relationship between materials, design strategies, and environmental factors.

The research falls within the realm of **prescriptive praxis**, as it aims to develop a **design framework** that informs architects and designers on how to use SMAs to enhance building performance, adaptability, and energy efficiency. The methodology includes **logical argumentation**, **immersive case studies**, and the **development of a dynamic design framework** that integrates multidisciplinary knowledge.

- The chapter details the step-by-step development of the design framework, starting with **logical argumentation** to gather relevant data and technical knowledge from fields such as materials science and architecture.
- **Immersive case studies** are then conducted, where the researcher actively participates in the design and prototyping of SMA-actuated systems. These case studies are designed to test the initial framework and provide insights into how SMAs can be effectively integrated into real-world building designs.
- Each case study is iterative, allowing for refinement of the framework based on practical outcomes and feedback from design experiments. By immersing in the design process,

the researcher leverages both theoretical and practical knowledge to address the challenges of implementing SMA-based systems.

The chapter also includes a discussion on the **documentation strategy**, where techniques such as **process mapping, flow charting, and visual overlays** are used to present the evolving design framework. These tools help illustrate the relationships between SMA properties, design requirements, and the dynamic behavior of building components.

The objective of the methodology is to provide a **comprehensive and accessible framework** that enables architects and designers to effectively incorporate SMAs into **responsive and sustainable building designs**. Through the use of **qualitative methods** and **hands-on prototyping**, the chapter advances the understanding of how SMAs can transform the future of adaptive architecture.

4.RESULTS

4 Results

4.1 Initial Framework

To successfully implement Shape Memory Alloy (SMA) components into interior or exterior architectural pieces, a structured, step-by-step approach is necessary. This process integrates various types of knowledge, including material science, design methodologies, engineering principles, and prototyping techniques. Here's a detailed mapping of the implementation process, outlining the types of knowledge required at each stage.

1. Identify the Architectural Objective

- Objective: Define the functional and aesthetic goals of the SMA system.
  - Examples: Adaptive facades for solar shading, dynamic partitions, or responsive louvers.
- Knowledge Needed:
  - Architectural Design: Understand the spatial, functional, and aesthetic needs.
  - User-Centric Design: Consider the impact on occupants in terms of interaction and comfort.
  - Environmental Knowledge: How the system will respond to environmental factors like sunlight, temperature, or wind.

2. Understand SMA Material Properties

- Objective: Choose the right type of SMA (e.g., NiTi) based on its thermomechanical characteristics.
- Knowledge Needed:

- Material Science: Study the properties of SMAs, including shape memory effect, superelasticity, phase transformation temperatures (e.g., martensite to austenite), and fatigue limits.

- Mechanical Engineering: Understand how SMAs will behave under thermal and mechanical loads, such as the activation temperature range and actuation force.

3. Design the SMA-Activated Component

- Objective: Develop the initial concept for integrating SMAs into architectural elements, such as facades, interior partitions, or adaptive louvers.

- Knowledge Needed:

- Architectural and Interior Design: Design the component in line with spatial requirements, aesthetic goals, and functional needs (e.g., shading, ventilation, or partitioning).

- Mechanical Design: Create mechanisms that leverage SMA actuation, ensuring the component can deform and return to its original shape when activated.

- Kinematics and Dynamics: Analyze the movement and response of the SMA component within its designed range of motion.

4. Prototype and Simulation

- Objective: Create small-scale prototypes and simulate the behavior of the SMA component before full-scale implementation.

- Knowledge Needed:

- Prototyping Techniques: Fabricate prototypes using 3D printing, CNC milling, or other methods to test designs. SMAs may be embedded in custom-made molds or integrated into existing architectural elements.

- Computational Design: Use simulation tools (e.g., finite element analysis or parametric design software like Grasshopper and Rhino) to predict how the SMA will respond to different environmental stimuli.

- Thermal and Structural Analysis: Model the thermal and mechanical behavior of the SMAs under varying conditions to ensure performance durability.

5. Develop the Control System

- Objective: Design the system that controls the activation and deactivation of the SMAs.

- Knowledge Needed:

- Electronics and Control Systems: Implement electrical activation systems (e.g., Joule heating) that trigger the phase transformation of SMAs. This could involve an Arduino or similar microcontroller to regulate current and temperature.

- Sensor Integration: Use environmental sensors (e.g., light, temperature, or motion sensors) to automate the activation of the SMA system based on real-time data.

- Software Development: Develop control algorithms and user interfaces to allow for manual or automated operation.

6. Full-Scale Fabrication

- Objective: Manufacture the full-scale architectural component and integrate the SMA system.

- Knowledge Needed:

- Manufacturing Processes: Utilize appropriate fabrication techniques for the architectural element (e.g., metal bending, injection molding, 3D printing) and ensure proper integration of the SMA materials.

- Material Compatibility: Ensure that the SMA and other materials (e.g., the building envelope or interior structure) are compatible and that heat transfer does not damage surrounding materials.

7. Testing and Evaluation

- Objective: Test the functionality, reliability, and efficiency of the SMA component in real-world or simulated environments.

- Knowledge Needed:

  - Testing Protocols: Establish performance tests for actuation speed, durability, and response time, ensuring that the SMA responds as expected to environmental stimuli.

  - Energy Efficiency Analysis: Evaluate the energy consumption of the SMA system and its impact on overall building performance, especially when used for shading or climate control.

  - User Interaction Studies: Assess how users interact with the SMA system, ensuring that it meets user expectations for functionality, comfort, and aesthetics.

8. Installation and Integration

- Objective: Integrate the SMA component into the building system, ensuring proper installation and alignment with other architectural elements.

- Knowledge Needed:

  - Construction Techniques: Collaborate with construction teams to ensure that the SMA system is correctly installed within the building structure (interior or exterior).

  - Building Systems Integration: Integrate the SMA system with other building technologies, such as HVAC or lighting systems, ensuring a seamless and energy-efficient design.

- Regulatory Compliance: Ensure that the SMA system meets local building codes and safety regulations, particularly regarding fire safety and electrical systems.

9. Post-Installation Monitoring and Maintenance

- Objective: Monitor the performance of the SMA system over time and provide guidelines for maintenance.

- Knowledge Needed:

  - Long-Term Performance Analysis: Track the performance of the SMA over time, monitoring for issues like fatigue, response degradation, or thermal cycling.

  - Maintenance Protocols: Establish a maintenance schedule to inspect the SMA system, check for wear and tear, and replace components as needed.

  - Optimization for Longevity: Implement adjustments based on real-world feedback to ensure long-term durability and performance of the SMA system.

Types of Knowledge Needed Throughout the Process

- Material Science: Understanding the properties of SMAs (phase transformations, thermal cycling, fatigue) and their behavior in architectural applications.

- Mechanical and Electrical Engineering: Designing actuation mechanisms and control systems, and ensuring the proper integration of SMAs into structural systems.

- Architectural Design: Ensuring that SMA components fit within the aesthetic, functional, and spatial goals of the project.

- Environmental Knowledge: Assessing how SMAs respond to environmental factors like sunlight, temperature, and wind, and their impact on energy efficiency and sustainability.

- Prototyping and Testing: Iteratively designing, fabricating, and testing SMA components before full-scale implementation.

- Software Development and Control Systems: Developing systems to control and automate the SMA behavior based on real-time data from the environment.

- Regulatory and Compliance Knowledge: Ensuring that the system complies with local building codes, safety standards, and energy efficiency regulations.

By following this comprehensive step-by-step process, designers and engineers can successfully integrate SMA technology into both interior and exterior architectural elements, contributing to a more adaptive, energy-efficient, and responsive built environment.

The Initial framework can be mapped out as following.

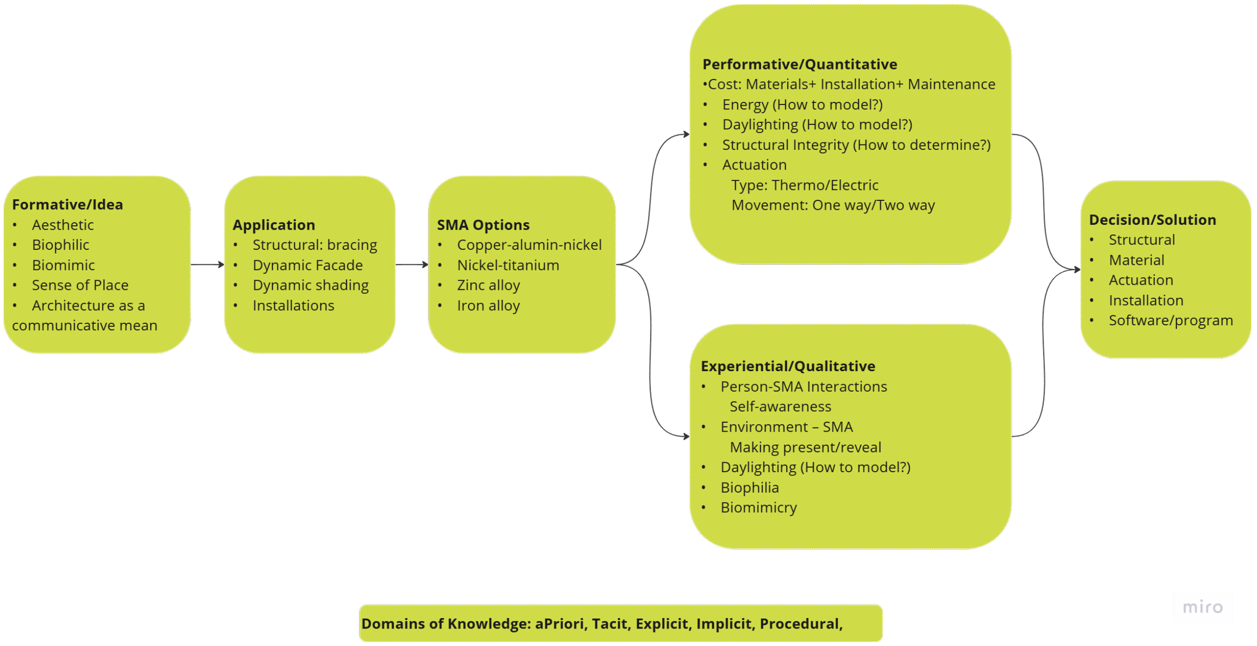

Figure 26-Initial Framework Based on Early Findings by author

Based on the information provided in Chapter 3, the first version of the framework is developed. This initial version addresses and introduces the themes identified in the available literature related to Shape Memory Alloy (SMA) applications in architecture. However, certain missing themes have been noted and will be explored in the following chapters. The themes introduced and addressed in this chapter, which will be added to the framework, include:

1. Material Properties of SMAs: Understanding the thermomechanical behavior of SMAs, including shape memory effect and superelasticity, and how these properties influence their architectural applications.

2. Design Integration of SMAs: Exploring how SMA actuators can be embedded into building components such as facades, shading systems, and kinetic elements to enhance responsiveness to environmental stimuli.

3. Energy Efficiency: Investigating how SMAs can contribute to more sustainable and energy-efficient building designs by dynamically regulating factors such as light, temperature, and ventilation.

4. User-Centric Design: Examining how SMA-based systems can be designed to improve user experience by creating interactive and adaptable environments that respond to occupants' needs and behaviors in real-time.

5. Prototyping and Testing: Introducing the process of creating physical prototypes of SMA-actuated systems to evaluate their performance, behavior, and feasibility in architectural contexts.

6. Challenges and Limitations: Addressing technical challenges, such as the cost of SMA materials, complexities in programming their behaviors, and issues related to maintenance and scalability.

7. Mapping out step by step implementation of SMA pieces into interior or exterior pieces and addressing all type of knowledge needed to do so.

The missing themes identified in the chapter, such as deeper exploration into the response time and symmetry of SMAs, long-term performance in building environments, and design strategies for mass customization, will be further studied and refined in the upcoming chapters.

4.2 Learning Objectives

1. Understand the Potential of Shape Memory Alloys (SMAs) in Architecture: Gain a comprehensive understanding of SMAs and their unique properties, including shape memory effect and superelasticity, and how these can be applied to create dynamic, adaptive architectural designs.

2. Explore the Role of Kinetic Architecture: Recognize the importance of kinetic architecture in modern building design, focusing on how dynamic elements can improve environmental responsiveness, sustainability, and user experience within the built environment.

3. Identify Technical and Design Challenges: Analyze the technical challenges associated with integrating SMAs into architecture, such as material cost, energy efficiency, fabrication processes, and the complexities of programming thermomechanical behaviors at an architectural scale.

4. Synthesize Multidisciplinary Knowledge: Learn how to integrate knowledge from materials science, mechanics, computational design, and architectural theory to develop responsive and adaptive building systems using SMAs.

5. Apply a Comprehensive Design Framework: Acquire the skills to apply the proposed knowledge framework for the practical implementation of SMA-based kinetic systems in architecture. This includes selecting appropriate SMA materials, designing actuators, and integrating them into building components like facades and shading systems.

6. Design Sustainable and Adaptive Buildings: Develop the ability to design buildings that dynamically respond to environmental changes (e.g., temperature, light, wind) using SMA technology, thereby improving energy efficiency and reducing the ecological footprint of architectural projects.

7. Understand Prototyping and Experimental Methods: Gain insights into the prototyping processes used to test SMA-based components, including fabrication techniques, material testing, and performance evaluation under real-world conditions.

8. Contribute to Innovation in Architectural Practice: Explore how the findings and frameworks from this research contribute to the broader field of architectural innovation, particularly in creating more interactive, adaptive, and sustainable building designs.

9. Critically Evaluate Responsive Design Solutions: Learn how to critically assess the effectiveness of SMA-based systems in architectural applications, considering

both practical feasibility and theoretical implications in achieving responsive and intelligent architecture.

10. Advance Future Research and Applications: Identify areas for future research and potential advancements in the use of SMAs in architecture, promoting continued exploration and adoption of smart materials in sustainable architectural practice.

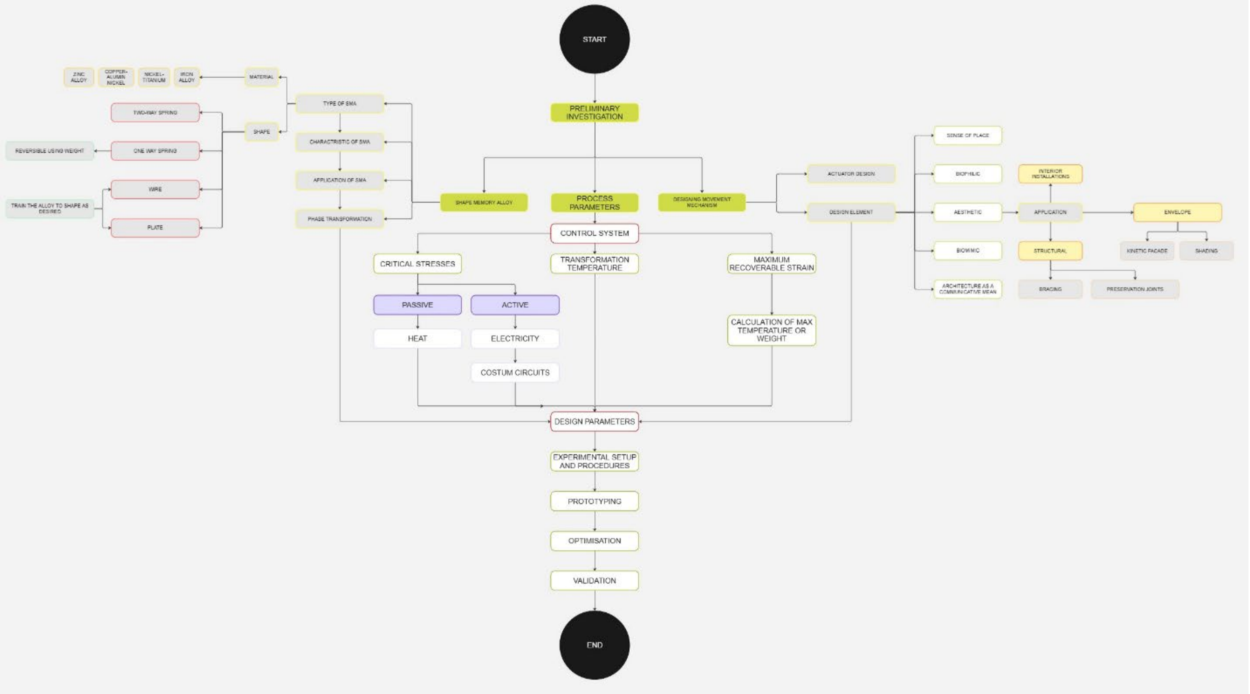

Figure 27-PRELIMINARY SMA IMPLEMENTION FRAMEWORK

The Initial Framework for SMA-Integrated Architecture (Figure 22) serves as a comprehensive guide for designers seeking to explore and implement Shape Memory Alloys within responsive architectural systems. Rooted in interdisciplinary research and iterative prototyping, this framework is designed to bridge the gap between advanced material science and architectural practice. It outlines a clear, step-by-step methodology that begins with material selection and performance mapping, advances through design integration strategies and control system development, and culminates in practical implementation protocols and evaluation metrics. Each phase is supported by modular decision-making pathways, offering designers a range of technical options—including sensors, microcontrollers, and activation triggers—based on project-specific criteria. By translating complex technical knowledge into a visually navigable and actionable flowchart, this framework empowers architects to experiment with and realize kinetic, adaptive environments that respond intelligently to their users and context.

5.CONCLUSION

5 Conclusion

5.1 Restatement of the Research Problem

This research begins by addressing a fundamental question in the field of responsive and intelligent architecture: how can Shape Memory Alloys (SMAs) be meaningfully and practically integrated into architectural design to facilitate human-centric, adaptive environments? The built environment, traditionally perceived as static and inert, is undergoing a conceptual transformation. Today, architects and designers are called to create spaces that are dynamic, interactive, and responsive to environmental stimuli and human presence. This shift necessitates a reevaluation of conventional materials and construction methods, especially when aiming to imbue buildings with vitality and performative capabilities.

SMAs, known for their thermomechanical actuation and unique phase-changing behavior, offer significant promise in this regard. Their ability to revert to a pre-defined shape upon heating, combined with their relatively silent and compact operation, positions them as potential enablers of a new architectural paradigm. Yet, despite their potential, the adoption of SMAs in architectural applications remains limited. Several barriers impede their integration: a fragmented knowledge base, limited accessibility to interdisciplinary insights, lack of standardization in design processes, high material and implementation costs, and insufficient understanding of control mechanisms and long-term performance in building-scale contexts.

This research identifies and interrogates these barriers. It argues that what is needed is not merely additional experimentation, but a comprehensive, accessible, and scalable knowledge framework that bridges material science, architectural theory, and practice. The lack of such a framework represents a significant gap in the current discourse on responsive architecture. This study seeks to fill that gap by offering a research-based, design-oriented, and practically informed model that enables architects to confidently explore and implement SMA-based systems in their work.

5.2 Summary of the Research Steps Taken

To develop a rigorous understanding of the integration of SMAs in architectural design, this study adopted a multifaceted methodological approach that combined theoretical inquiry, empirical prototyping, and design research methodologies. The process unfolded through the following major phases:

5.2.1 Literature Review and Conceptual Grounding

An extensive literature review was conducted to establish the epistemological, theoretical, and technical contexts of this research. The review covered architecture as a communicative and embodied medium, the enactive approach to design, and the philosophical underpinnings of motion and interactivity in the built environment. This was juxtaposed with a scientific and engineering-focused investigation into the principles governing SMA behavior, including their crystallographic transformations, thermal activation thresholds, and mechanical output capacities. The review laid the foundation for understanding the role of kinetics in architecture and positioned SMAs within the broader discourse of smart and responsive materials.

5.2.2 Technical Investigation of SMA Properties

This phase detailed the behavior of one-way and two-way SMA effects, training protocols, and activation strategies, including Joule heating and environmental stimuli. Detailed analysis was provided on the hysteresis behavior, response asymmetry, actuation fatigue, and the implications of such behaviors on architectural scale implementations. Critical issues such as SMA scalability, precision of motion, control systems, and lifespan were also explored. These insights were synthesized into a database of material behavior which informed later phases of design development.

5.2.3 Documentation of Precedents and Case Studies

Building upon the literature and technical analysis, the study conducted an in-depth survey of architectural and industrial case studies involving SMA applications. Projects such as Farahi's "Living Wall," Beesley's "Hylozoic Ground," and Sung's "eXo" were examined not just as aesthetic experiments but as sites of knowledge production. Each case provided data on performance, activation methods, user interaction, and design outcomes. The limitations of current implementations, particularly in terms of control, material quantity, heat management, and user experience, were critically assessed.

5.2.4 Methodological Structuring and Prototyping

The research adopted a design-based methodology, employing immersive case study techniques, action research, and reflective practice. A qualitative approach grounded in praxis and informed by normative theory guided the investigation. Through iterative prototyping of SMA-actuated architectural elements, the research generated procedural knowledge about integration, performance, and feedback loops. The prototypes served not only as proof-of-concept explorations but also as epistemological tools to interrogate the gaps between theory and implementation.

5.2.5 Iterative Framework Development

Drawing on Banathy’s divergence-convergence model and Cross’s iterative design cycles, a preliminary framework was constructed and refined through multiple stages. Each iteration incorporated findings from literature, precedent analysis, technical experimentation, and designerly reflection. The framework evolved into a structured system capable of supporting designers in the selection, integration, and control of SMA components in a variety of architectural contexts.

5.3 Proposal for an Initial Framework for SMA-Integrated Architecture

The proposed framework is conceptualized as a dynamic, transdisciplinary tool for architects and designers aiming to incorporate SMAs into responsive environments. It is organized into four core modules, each addressing a distinct phase of the design-to-deployment continuum:

5.3.1 Material Selection and Performance Mapping

This phase entails a rigorous assessment of functional goals and contextual parameters. The framework offers guidance on selecting SMA types (e.g., NiTi vs. Fe-based), identifying transformation temperature ranges, evaluating force output, and assessing environmental compatibility. It includes charts and decision trees that help correlate actuation requirements with SMA properties, thereby ensuring alignment between material behavior and design intent.

5.3.2 Design Integration Strategy

Here, the focus shifts to embedding SMAs into architectural components such as facades, shading systems, structural elements, or interactive furniture. Parametric modeling tools are recommended to simulate SMA behavior in relation to spatial deformation. Design logics are introduced for achieving reversible, kinetic morphologies that align with human movement, environmental rhythms, or programmed stimuli. The section also addresses issues of structural embedding, spatial implications, and interface design.

5.3.3 Control and Activation Systems

This module details the development of responsive control systems using sensors, microcontrollers (e.g., Arduino), and embedded logic. It outlines activation pathways (thermal, electrical, or hybrid), discusses real-time responsiveness, and offers coding templates for integrating sensors (light, touch, temperature) into architectural circuits. Particular attention is paid to issues of latency, symmetry, and feedback modulation. Scenarios of passive vs. active control systems are also compared.

5.3.4 Implementation Protocol and Evaluation Metrics

In the final module, the framework provides a step-by-step guide for fabrication, installation, and evaluation. This includes SMA training protocols, actuation cycles, safety guidelines, and fatigue testing. Performance metrics are introduced to assess energy efficiency, user engagement, thermal resilience, and lifecycle costs. Designers are equipped with criteria to evaluate success not only in mechanical terms but also in experiential, aesthetic, and ecological dimensions.

5.4 Concluding Thoughts and Future Directions

This research proposes that SMAs are not merely functional materials but are agents of architectural expression, capable of bridging the technological and the emotional, the scientific and the poetic. The integration of SMAs into architecture signals a paradigmatic shift: from buildings as static enclosures to environments as living, adaptive participants in human experience.

The framework developed in this study aims to demystify SMA integration and render it accessible to a broader audience of practitioners. By consolidating fragmented knowledge into a systematic, interdisciplinary model, it facilitates more informed design decisions, fosters innovation, and lays the groundwork for future experimentation. It is a first step toward a more conscious, responsive, and materially intelligent architecture.

Future work will expand this framework into a digital toolkit, incorporate simulation plugins, and collaborate with material scientists and control engineers to refine the system for real-world deployment. With sustained research and cross-disciplinary collaboration, SMA-based design can redefine the spatial, performative, and symbolic vocabulary of architecture in the 21st century.

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