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# Utilizing Systematic Design and Shape Memory Alloys to Enhance Actuation of Modular High-Frequency Origami Robots

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# UTILIZING SYSTEMATIC DESIGN AND SHAPE MEMORY ALLOYS TO ENHANCE ACTUATION OF MODULAR HIGH-FREQUENCY ORIGAMI ROBOTS

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ABSTRACT

Shape memory alloys (SMAs) describe a group of smart metallic materials that can be deformed by external magnetic, thermal, or mechanical influence and then returned to a predetermined shape through the cycling of temperature or stress. They have several advantages, such as having excellent mechanical properties, being low cost, and being easily manufactured, while also providing a compact size, completely silent operation, high work density, and requiring less maintenance over time. SMAs can undergo sold-to-solid phase transformations, and it is because of these phase transformations that they can experience shape memory effect (SME); or the ability to recover from a deformed shape to an initially determined shape through the cycling of temperature. However, since SME requires the cycling of temperature to actuate SMAs, the actuation frequency of these materials has been slow for small-scale applications, as actuation speed is limited by the time it takes to transition from a higher temperature (actuated, pre-determined state) to a lower temperature (flexible, reconfigurable state). While SMAs are known to be highly advantageous, their main drawback is that they are one of the slowest actuation methods in the field of origami robotics. SMAs cannot actuate quickly enough cyclically due to the long cooling times required to get from their austenite (higher temperature, actuated, pre-determined state) phase to their martensite (lower temperature, flexible, reconfigurable state) phase. Researchers have attempted to achieve a higher actuation speed in previous projects by using active cooling agents. However, this study investigated the use of SMAs to initiate high-frequency cyclic movement through a small-scale origami fold without an active cooling source. This study used a combination of different system design parameters

to mechanically hasten the actuation speed of a folding hinge with no cooling component present. Through only design and a complete understanding of the SMAs, this study achieved consistent and relatively high results (>1.5 Hz) of an actuation speed for a system of this size. This study discovered knowledge regarding the composition, material properties, and actuation limits of SMAs, and a new systematic design method was proposed for creating origami robots.

# DEDICATION

To my mother, who has never failed to show up for me. In both the big ways and the small ones, you have been by my side, no matter what. I could not be more grateful to have you in my life, and I know that without your constant love, support, friendship, and belief in me and my success, I wouldn't be half of the woman I am today. Thank you for everything.

To my father, who has taught me the importance of education and has never once doubted my success. Thank you for teaching me to pursue something more than myself and to not give up on my dreams, despite how crazy they sound. You have taught me the value of hard work, and I am genuinely grateful. Thank you for your constant support.

To my brother, Cooper, who has shown me what it means to believe in myself and who I am, even after I've failed. You are a living, breathing example of everything I could ever hope to be in this world. Thank you for your unwavering courage.

To my brother, Brady, who reminds me daily of what it means to love and be loved. Without your constant love, on the good and bad days, I don't know if I would be where I am today. Thank you for your wonderful heart.

I've said this once, and I will say it a million times again: being your daughter and your sister are the two things I am most proud of in this world.

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CHAPTER ONE

# 1. INTRODUCTION

## 1.1 Origami

Origami is the age-old Japanese practice of folding paper or other materials to create art in the form of three-dimensional shapes or figures. The most recognized origami structures were originally modeled based on ordinarily occurring folds in nature, as folding is nowhere short of the quotidian in almost all forms of life. Some of the most well-known origami assemblies include cranes, birds, flowers, and frogs, illustrating the importance of typically occurring folds in nature. Beyond these, some of the most common examples of folding are processes that worms, birds, bats, insects, and even human beings employ without a second thought. It has been found that worms contract or fold segmented parts of their bodies to perform peristaltic locomotion to move [1, 2]. Similarly, birds, bats, and insects fold their wings to propel their bodies through the air in aerodynamic ways [2]. Additionally, on a molecular level, folding occurs in DNA packaging and the organization of three-dimensional structures that proteins must assume for proper functioning [3]. Folding processes are relied on in almost all forms of life, and each life form uses folding differently, which has piqued the interest of many looking to harness the power of folding through the practice of origami [4].

After discovering the importance of folding in nature, researchers found that origami provides an opportunity to create structures that can be used in a multitude of applications in several different fields. Origami-inspired manufacturing allows for affordable rapid prototyping and customization of compact systems that can adjust their

compliance from soft to rigid and vice versa [5]. Recently, research on origami has been done to explore applications in the design of infrastructure, furniture, and devices for the medical field, to name a few [6, 7, 8, 9]. However, although origami structures provide the opportunity to design numerous systems, the real benefit of utilizing origami comes from harnessing its bistability at both its soft and rigid states rather than just at one, which is impossible to achieve without movement. To harness the bistability of an origami structure, researchers have been led to the field of origami robotics.

Origami robots are controllable multistable structures made from flat composite sheets which can achieve several tasks that a robotic system might implement, such as self-assembly through actuation, sensing and computation through shape change, and applying power for locomotion and manipulation of a system [6, 11]. Combining origami and the field of robotics allows engineers to innovate new solutions to problems by harnessing the unorthodox relationships between geometry and mechanics to create robust yet compact structures with a high frequency. Although the applications of origami robots seem numerous – from current engineering applications in the design of medical devices, space exploration, and aerospace systems – the study of using origami in a mechanical structure is relatively new, leading to an increased level of complexity when it comes to the design of such structures [12, 13, 14, 15, 16].

## 1.2 Design

When designing and fabricating an origami robot, several components must be considered. Careful deliberations about factors such as folding patterns, sensing techniques, system mechanics, actuation methods, controls, and power sources require a

multifaceted design process and solution to create an origami robot that can meet all predetermined constraints and criteria. As many considerations must be prioritized throughout the duration of fabricating an origami robot, several design methods and tools have been established to offer the field a little uniformity and ease of practice in the way these multistable structures are created. While these approaches have worked in some instances, the complexities and broadened scope associated with origami, robotics, and design limit these practices from establishing a promising model to follow in the field of origami robotics.

Historically, trial-and-error processes, computational modeling, and building upon previously established solution sets highlighted the extent of the design methods used to create origami robots. As this field expanded, origami-inspired robots were made through one of two design methods: direct or inverse design. While these design methods are not known or typically used by name, and with the exception of a few instances, most origami robots can be fabricated through these processes. Within this field, direct design refers to a researcher or a designer selecting a specific origami fold pattern and then modularly designing all aspects of the robot around that fold. Alternatively, inverse design refers to a process in which the components of a robotic system are created first, followed by the integration of an origami fold pattern. Of the two, direct design is most commonly used due to a lack of design tools such as software, modeling systems, and kinematic equations to define new or more complex origami designs.

The lack of a uniform design method within this field has posed some real issues for researchers. Often, the design of a new origami robot is slow-moving. Designers in this

field typically make minor corrections to current systems and optimize their abilities rather than attempt to create something new. Designing a system from scratch is rather difficult in this field because very few design tools are available. Additionally, although most researchers take either a direct or inverse approach to designing an origami robot, almost all origami systems require some trial-and-error, which can be very time and resource-consuming. Evermore, origami robot systems aim to harness the bistable nature of origami. To do so, however, integrating different components is required, which can often limit the natural bistable advantages of origami. Finally, optimizing an origami structure necessitates very detailed theoretical calculations and computations, which can be challenging to pursue. Overall, the current design methods can lend to a very frustrating and time-consuming process for a researcher in this field, typically leading to a non-original solution with many flaws.

As the field of origami robotics is new and everchanging, it has been found that the current and historically used design processes have been lacking somewhat of a systematic approach, which is believed to be something that can revolutionize the way origami robots are created. Design methods in this field are constantly evolving in a sporadic way to account for the intricacies involved in the combination of numerous diverse components required by all these origami structures. Additionally, trial-and-error practices and direct or inverse design still provide many limitations that could be ameliorated by implementing a single, systematic, and uniform approach. The most important aspects of a systematic design approach that are otherwise lacking in previously used techniques are that the process is both iterative and continuous. In other methods for designing and fabricating

origami systems, once a decision is made about a specific component, it is more difficult to go back and change that decision to advance the entire system. Previous methods are completed as a series of tasks or decisions, where decisions are rarely changed. However, a systematic design process would allow a designer to continuously make decisions and change them to proactively improve the robotic system at every step of the process.

### 1.3 Shape Memory Alloys

Shape memory alloys describe a group of smart metallic materials that can return to a predetermined shape through cycling temperature or stress after being deformed by external magnetic, thermal, or mechanical influence. They have several advantages, such as being low-cost, easily manufactured, and having great mechanical properties. Compared to other traditional actuation methods in origami robots, such as hydraulic and pneumatic actuators, SMAs provide a compact size, completely silent operation, high work density, and less maintenance over time [13]. They also offer several distinct mechanical advantages at various strains and temperature ranges, which provides an increased level of versatility in applying this actuation method.

Shape memory alloys can undergo sold-to-solid phase transformations, which is why they offer such a high level of versatility. These transformations consist of changes from an austenite, or “parent,” phase and a martensite phase, and vice versa, invoking movement used in soft robotics as a method of actuation. In SMAs, the austenite phase exists at relatively high temperatures and low stresses and takes the form of a cubic crystal lattice structure. In contrast, the martensite phase illustrates a tetragonal or monoclinic crystal structure while usually existing at a lower temperature or a higher stress. It is due

to these phase transformations that shape memory alloys can be characterized by one of two unique working principles: shape memory effect (SME) or pseudoelectric (PEE)/superelastic effect (SEE). These working principles result in the same motion but are achieved through slightly different means [14]. SME can be described as the ability of an SMA to recover an initially determined shape through the cycling of temperature. Inversely, the superelastic, or pseudoelectric, effect occurs when stress is cycled, rather than temperature, through an SMA to invoke movement to a predetermined position.

In projects that utilize SMAs for actuation, SME is most often used. However, because SME requires the cycling of temperature to actuate the SMAs, the actuation frequency has been relatively slow due to the need to reset to a lower temperature once the higher temperature has been achieved. Therefore, actuation speed is limited by the time it takes to transition from a higher temperature (actuated, pre-determined state) to a lower temperature (flexible, reconfigurable state). To combat this, researchers have found ways to hasten the actuation speed of SMAs by cooling them after their high-temperature cycle. While cooling the SMA allows for a higher frequency and longer lifetime, methods to cool SMAs have been extensively researched within the field of origami robotics. In contrast, the actuation of SMAs without a cooling source has been relatively untouched.

## 1.4 Research Motivation and Problem Statement/Application

The primary motivation of this research project was to investigate methods of embedding compact actuators into origami to achieve high-frequency folding on a small scale. In addition to the principal motivation, multiple secondary goals were established. Those secondary goals included further introducing and integrating modular design

concepts into origami systems and exploring and improving upon current design methods, tools, and practices utilized in the field of origami robotics. As the project gained traction and SMAs were selected as the actuation source to be used, it also became essential to understand the behavior of SMAs in an origami system fully, to broaden the scope of research of SMAs on projects of a smaller scale and investigate ways of implementing these SMAs at a high frequency, without any form of a cooling source. Combined, these goals created the motivation for this project. To achieve these goals, the focus of this project revolved around creating a modular 3D-printed fold, which would actuate at a high frequency through SMAs and joule heating.

### 1.5 Paper Outline

This paper will follow a similar progression to that of the research performed. It will begin with an introduction and historical discussion of design methods that have previously been used within the field, then move into current design methods and practices that are more regularly used but less often identified in projects encompassing origami robotics. Following this review and discussion, a systematic design concept will be presented. This new systematic design method will be proposed as a possible practice for future projects in this field. To conclude the design discussion, the paper moves through the steps of the proposed systematic design process to create a modular origami fold that would use SMAs to actuate at a high frequency. The stages of this process will outline the different sections of this report: SMAs, power, mechanical testing, hinge design, and integration. The results, recommendations, and future work will be discussed to conclude the paper.

CHAPTER TWO

# 2. SYSTEMATIC DESIGN

## 2.1 Introduction

Design requires established knowledge about a particular topic or problem being solved. The design process can start at any point and is not limited to a specific method. But, through the design process, engineers continuously grow their knowledge of a subject upon the basis of discussion, complex thought, research, observation, or mechanical practice; this expansion of knowledge then subsequently aids them in conceiving new ideas that will have actual or perceived, positive impacts on the world [15]. Within the field of origami robotics, design can be seen similarly. However, within this field, a uniform design process has not been accepted, nor has a methodical design method been highly regarded or paid attention to. While there are several proposed reasons for this, it is most likely that the novelty and ever-changing nature of the components in this field have made such design processes hard to adopt.

This section will further introduce, discuss, and expound upon the details of design approaches, methods, and tools used in creating origami robots, both historically and presently. Following the literature review of these design approaches, a proposed systematic process of designing robotic origami systems will be introduced and explained in detail to establish a more uniform operation of creating fully functional, high-frequency origami structures. This section will culminate with a discussion of possible issues associated with the systematic method presented. The presented systematic procedure will

then be used throughout the duration of this paper to illustrate its usefulness through the fabrication of a high-frequency origami fold.

## 2.2 Historical Design Methods of Origami Robots

Historically, there has been a sincere lack within the field of origami-based design of any one established, uniform, or shared design method. As robotic origami systems became popularized, it has since been found that there is no straightforward method of designing origami robots. Early design "processes" included origami researchers relying on previous knowledge or skills gained through practice or observations. This knowledge allowed them to use traditional trial-and-error methods and scaled models to create solutions for their specific intended applications [16]. Most of these historical methods fell into the category of using trial-and-error processes to integrate several individual pieces. Generally, before the field of origami robotics increased in size, most discoveries were made through minor adjustments to previously determined solutions rather than through specific design methods resulting in novel solutions because these trial-and-error methods traditionally proved to be more complex and time-consuming than initially expected [21, 22].

While scaled models, trial-and-error methods, and elaborate theoretical calculations can be helpful when creating an origami robot, they currently don't provide the most efficient solution for design researchers in this field [18]. Robotic origami systems require several different components, which all include a variety of intricacies that require a series of difficult decisions from the designer. At each decision that must be made for these systems, there remains a consistent concern about the efficacy of the synonymous nature

of modular components within an active origami system. Researchers have found that specific features or components of a design would work independently when utilizing elaborate trial-and-error methods. However, the integration of these components led to an entire system failure, illustrating an inefficient way of creating even the simplest of origami robots.

While in simple systems, methods of integrating individual components can work, systems requiring more intricate designs due to the complexity of their functions have shown that experimentation is not always the best method of creating origami structures [17]. In the past, there has been no rhyme or reason as to why or how researchers found their solutions, as the field was still new, and there was much to be uncovered. Although modular-based trial-and-error methods worked historically, researchers quickly realized other more efficient ways of establishing complex origami robots.

## 2.3 Current Design Methods

An extensive review of established design methods found that there are currently two fundamental design approaches in almost all cases where an origami robot was invented. As is typical in the design industry, it has been found that the two most common methods of designing an origami robot are direct and inverse design [19]. While these design approaches are rarely named in papers and seldom seem intentional, they still manage to describe how origami robots are typically created. Categorizing most methods used in making these robotic systems into one of these two design approaches allows this field to move towards design organization and uniform design methodologies, which

provides a great starting point in ascertaining a newly proposed uniform design method for this field.

### *2.3.1 Direct Design*

Within origami robotics, direct design is a method that includes using a predetermined origami pattern to present a solution for an intended application [16]. With this design method, a researcher is limited to the design constraints set by the specific origami pattern and geometry they have previously selected. This method ensures that the most critical decision made by the design engineer is that of their origami pattern and assumes that all subsequent decisions will fit within the bounds set by that pattern. With direct design, an origami pattern must be presented early in creating a robotic origami system so that all other components may be joined without necessitating any changes to the original origami structure. This method is the most well-used design approach in the fabrication of origami robots. Although most researchers don't readily acknowledge their use of this method, it can be identified easily, as it involves applying known folds, geometries, and origami patterns at the start of a research problem based only on the perceived ability of that design to solve the research goal. This method has been used and will be used in several origami-based design projects. It has been recognized as one of the most efficient and intuitive ways of integrating the components associated with sensing, actuation, and movement into an origami pattern [20, 21, 22, 23]. It has proven advantageous in allowing design engineers to work their components directly into the size, shape, and geometry they set at the beginning of their project. This maintains clear guidelines for every element and decision that must be made throughout their work.

However, its advantages come with some severe limitations. Using this method requires all mechanical system components to be created around a predetermined origami structure, leaving little to no room for error when assembling all aspects of the system at the end of the project. Another limitation associated with this method is the possibility of the researcher suffering from design fixation. Design fixation refers to a designer being unable to move forward with a project in a way different from a solution that has already been seen [24]. Since this approach relies entirely on deciding the origami pattern before any other components are created, a design engineer might only attempt to formulate answers to the problem using the specific origami fold type already selected. While there exists nothing to state that a design engineer cannot actively resort back to making different selections of the fold pattern to fabricate these systems, it has been found that once a single origami fold pattern has been selected, the majority of researchers keep it consistent throughout their work [16].

While several decisions must be made to construct a working origami robot, it can be argued that one of the most critical decisions is the origami pattern. The selection of the origami pattern is important because it not only defines the working system that all other components must occupy but also determines the number of applications in which the origami robot can be used. Even though the direct design approach highlights the importance of selecting the origami fold pattern by making that decision a significant step in the process, it also limits the possibility for other components that can be used during the entire design process.

### *2.3.2 Inverse Design*

Alternatively, the inverse design method is one by which origami patterns are generated to meet design requirements that are already in place [25]. This method effectively involves selecting or, most times, creating an origami fold pattern at the end of a project that will fit the already identified or constructed components. However, although the inverse design method can offer a design engineer quite a bit of freedom and flexibility while producing all of the components of an origami robot [25], very few researchers in this field have approached origami systems with this being their only method of finding a solution [26]. Inverse design is not as standard or readily accepted as direct design because it requires complex computations and design tools [27].

The concept of inverse design is quite impressive and, if accomplished for complex systems, would allow for incredible design opportunities in the field of origami robotics. Before optimizing a design's geometry, this method could enable designers to advance their solution by optimizing every aspect of their robot, including the actuation method, power source, and digital components. With the inverse design method, many possibilities may become available within the field of robotics. However, despite the numerous advantages associated with utilizing the inverse design method, a few practicalities exist that make this method less beneficial and less optimal overall. The nature of this method, along with the balance between crease pattern topology, manufacturability, and the complex algorithms and mathematical models required, has made standardization of this method more complicated than recent attempts have managed to achieve [26]. While the inverse design method can and has been used for simple systems of elementary geometry, such as rigid

Miura-based designs of symmetric fold patterns, the inability to use this method for other projects has left it relatively untouched in this field [28].

## 2.4 Systematic Design

Many have recommended that design researchers in any field take a systematic approach to increase the uniformity and efficiency of the fabrication of specific solutions; the field of origami robotics is no different [19]. A systematic design approach outlines an iterative process that includes planning, conceptual design, embodiment design, and detail design that can all be used to generate a system that will address a specific need [29]. From the lack of success that has come from design methods that have previously been used in this field up to this point, it can be assumed that this approach might allow for more order and organization in the design processes of origami-based systems. A systematic approach would allow for the opportunity to work on different aspects of robotic origami systems in conjunction with one another. This approach emphasizes the importance of making decisions at every step of the process that would be best for the overall system solution [30].

Utilizing systematic design methods would open the possibility of making slight adjustments to previously made decisions without risking the complete system's function or the smaller components' capabilities. However, although this approach would work well, a few issues with this method present themselves in ways such as being challenging to implement on a large scale and difficult to maintain on a smaller scale. This approach would require significant planning, concentration, and awareness at each process step on an individual scale. In addition, it has seldom been used in the past, which would contribute

to it being less readily accepted. However, a continuous and iterative process like the systematic design method would help organize how these origami robots are designed and fabricated.

## 2.5 Proposed Design Method

A defining aspect of origami robotics is that they have several components. Each component works independently and synonymously to accomplish a single, more significant task, such as moving in a pre-defined manner, deploying rapidly while providing bistability to a system, or acting as an essential part of a more extensive system, such as a medical device or spacecraft [28, 31, 32, 33]. In the same respect, however, each of these components must also be able to work with the elements around it, as they all depend on one another to form the complete system. Every aspect of these robotic systems must be considered in whichever method is selected to adequately and efficiently create high-frequency origami robots.

While historically, previous knowledge of origami patterns, trial-and-error procedures, scaled models, and modular-based design methods have assisted in creating and adjusting discoveries of simple origami structures, they have not proven to be methodical enough to apply to more complex systems that have a multitude of different components. Additionally, although current practices of direct and inverse design methods have illustrated a slight impact on the field, the progress and versatility of other solutions are lacking due to the impracticalities and limitations that exist from the absence of any standardized, systematic, or integrated approach to designing such systems. In part, this lack of availability of a systematic design approach is due to the field's novelty. However,

a principal reason for this lack of a uniform design method is that origami robots are incredibly complex systems, and systematic design approaches have been difficult to implement, although researchers have tried [30].

To date, and the author's knowledge, there have been only two formulations of a systematic design approach for the origami robotics [30]. These methods outlined major categories and subcategories to explain the process that should be used when creating an origami system. However, the presented design cycles appeared to leave out certain aspects that might be deemed necessary for possible applications. While these systematic design methods gave detailed models for geometry design, mechanism design, functional materials design, and 2D fabrication, known factors of origami robots were left out. Considerations such as power sources, controls, electronics, and sensing technologies were nowhere to be found in these other iterative models.

This paper presents a new goal-oriented, actuation-centered, systematic design approach for the field of origami robots, which will provide an iterative process that can assist in creating multiple types of origami robots. This design is a true combination of both direct and inverse design, trial-and-error methods, and systematic design approaches. This new approach would allow design researchers within the field of origami robotics to harness the advantages and minimize the associated disadvantages of each design process mentioned above. As illustrated below, the presented process makes good use of the direct design approach by highlighting a specific first decision that must be made. From an origami perspective, the geometry of the origami pattern that is used is one of the most critical decisions that must be made. However, from a robotics perspective, the actuation

method and several other components are limited when the origami pattern is determined first. This systematic design model highlights the importance of the actuation method by making the first decision in the design process. The careful consideration to place the decision for the actuation method first provides the advantages of narrowing the design method down as are provided through the direct design method while also working forward from one of the most challenging decisions in the process.

Similarly, certain advantages of the inverse design method are provided to this model in that the fabrication methods, manufacturing practices, and analyses are all presented as the last steps in the process, which will allow the researcher to keep in mind and effectively work backward from predetermined goals set forth by their intended goal or application of their project. Additionally, trial-and-error methods are scattered into the systematic design method around each process step by integration, optimization, or mechanical testing done at each main category. The time required through traditional trial-and-error methods for these origami robots will be reduced by implementing a less procedural design approach. Meanwhile, all the advantages of using trial-and-error methods to provide proof-of-concept will remain. In addition to providing the design researcher with all the benefits of direct design, inverse design, and traditional modular-based design methods, this systematic approach will also give them the ability to design continuously and make changes while keeping the intended application in mind.

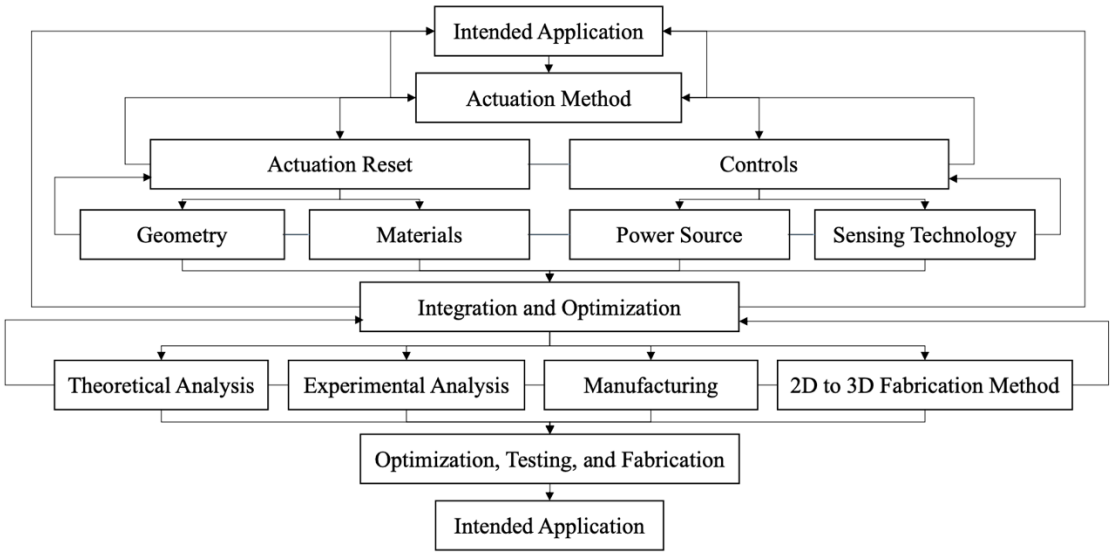


Figure 2.1: Proposed Systematic Design Method for Origami Robots

By creating a design approach that maintains a goal-oriented strategy, design engineers within the field of origami robotics can ensure that they meet their intended application in every step of the process, which is often forgotten or adapted to fit specific design constraints in typical projects. It is predicted that the systematic design approach will encompass most factors of traditional origami robots while encouraging more extensive changes and growth within the field of origami robotics.

### *2.5.1 Actuation Methods*

In any robotics field, when a specific material must move for a predetermined application, an actuation method is required to create that movement. The most common actuation methods for origami-based designs are pneumatic, electric, hydraulic, piezoelectric, chemical, and magnetic sources. However, a design engineer within this field is not limited to these main categories. Previously used origami methods have extended past these main categories and created origami structures with biological, optical, and

thermal actuation methods as well [30]. Regardless of which actuation method is selected, it drives the movement in an origami robot and remains one of these structures' most critical and limiting factors. Therefore, holding this decision in high regard is essential to achieve minimal limitations while working towards the goal of any project.

### *2.5.2 Actuation Reset and Controls*

As mentioned above, selecting an actuation method is extremely important, as it will drive most, if not all, of the motion of a system. A critical follow-up decision that must be made after and during the decision to select an actuation method is the possible method of resetting the movement driven by a robot's actuator. In most known cases, actuation is made in one direction. For shape memory alloys, motion is drawn inward; for pneumatic actuation, movement is pushed outward, and so on. Thus, it is vital to consider not only the actuation method itself but also the intended application of a project. Most actuation methods are fast to act on their own. However, the real issue with using actuation methods in origami robots is their ability to reset. Using the previous examples stated above, shape memory alloys can quickly heat up to actuate but typically require a cooling method to reset; similarly, most pneumatic actuators can be rapidly actuated through a large influx of fluid, but resetting the system requires the fluid to drain, which can be relatively slow. If a project needs to create quick movement, the second most important decision that must be made in designing an actuation method is its reset method.

Another important consideration that must be made when designing an origami robot is the nature of the controls of the system. At this point in the design process, the researcher should start thinking about the system's movement and where that movement

will come from. Here, the researcher will decide whether the system will be self-folding or rely on external stimulation to fold. While this decision won't drastically impact how the system is designed, it is directly related to the actuation reset method and can impact the robot's success concerning its intended goal or application. Determining how the system will be controlled will also affect future decisions, so this is a crucial decision to ponder, which is why it is placed so early in the design process.

### *2.5.3 Geometry, Materials, Power Source, and Sensing Technology*

Around approximately the third level of the decision-making process, a researcher will begin to work on their origami robot's geometry, materials, power source, and sensing technology. These four considerations are essential to how an origami robot works. They are all important to create together so that the integration of these components can be as seamless as possible.

The geometry of an origami robot should be contemplated on a smaller scale at first. This should include the introduction of an origami pattern and how this geometry might work with the selected actuation method. Specific geometrical properties to consider might also include the intended size, shape, angles, joints, stiffness calculations, or kinematics of the established origami fold. When designing the system's geometry, it is crucial to understand how the origami works on a smaller scale before integrating it into a much larger scale. It is recommended that geometry calculations are made with only a few folds at first.

Simultaneously, while establishing the system's geometry, the design researcher must also decide which material they want to use for their robot. Deliberations about the

material selection so early in the design process and at the same time as the decisions made about the geometry of the project allow a researcher the opportunity to solidify their calculations about their geometry. Most geometrical properties can be coagulated with specific material properties.

In parallel, the researcher should also establish the project's power source and sensing technology. Here, a power source refers to any method of powering, applying a force, or assisting in actuating the chosen actuation method. It has been found that most actuation methods require bulky equipment and technology, and being aware of this early on allows for the optimization of size and efficiency later.

Finally, the design engineer must consider the origami robot's sensing technology. A few of the most critical measurements associated with origami robots are the unrestricted stroke, the block force, and the speed or frequency of the device. These measurements have become some of the only tangible ways of establishing a basis for comparing different origami structures within this field. Therefore, a sensing technique is essential to install and integrate early in the design process.

### *2.5.4 Analysis, Manufacturing, and Fabrication*

After integrating all the previous components, this proposed systematic design method does something different than other methods presented in this field. Instead of placing the manufacturing, fabrication, and analysis decisions at the beginning of the project, these take place at the very end. This maximizes the efficiency of the time dedicated towards finding a solution and highlights the importance of physical yet educated trial-and-error methods in mechanical origami designs. At this point in the process, most

of the theoretical calculations on geometry, material properties, and integration of power and sensing sources will have already been completed, allowing for the optimization of fabrication rather than a redesign of components after these processes have already been established. This will enable the design researcher to only perform theoretical and experimental calculations on the possibilities that work, which will assist in creating specific models and equations for origami solution sets.

Finally, as most of the more challenging parts of the design process will have already been completed by this point, design engineers can effectively optimize the manufacturing and fabrication processes, making it easier to mass-produce and apply the solution to the intended applications as set forth at the beginning of the project. The idea behind the systematic design approach is that each decision is made methodically while keeping in mind the overall goal along with the previous, parallel, and future steps in the design process. This method allows critical decisions to be reversed, changed, or adapted without significant consequences to the entire system. While some of these items in the proposed systematic process may not apply to every project, this outline can be used as a starting point or template when other similar factors should be considered in the design process of origami robots.

## 2.6 Design Tools

A more systematic design method would be quickly corroborated through the development and availability of fully functional, versatile, and broad design tools that can be used for any application. However, in the current age and progress of origami robotics, design tools have been challenging to create and modify, especially with the complexity of

the geometric properties of origami and the modularity with other components [26]. From a design standpoint, while model-based design and trial-and-error processes can be valuable, those methods, along with other methodical design tools for manufacturability applications, have proven not to be as widely used as specific software programs in this field [17, 27].

Due to the complex nature of these origami systems, most design tools, when opted for, are computational in nature and often require multifaceted simulations to solve for the best origami pattern and its subsequent geometrical properties for specific applications. Within this field, there are a few well-known finite element simulation models [34], a few software tools for designing proper fold patterns [5], and multiple devices that can assess the kinematics of different crease patterns [16]. Meanwhile, although some of these simulation tools have proven helpful in this field, a disadvantage is that they can only be applied to specific models and cannot be integrated with other necessary system components. Another issue is that software and other design tools are relatively hard to create for such complex systems. Many have attempted to develop these design tools to assist the origami community with standardizing the design process but to no avail [35]. In the future, a standardized design approach might assist researchers in searching for and creating new design tools that can further help expand the field and applications of origami robots in daily life.

CHAPTER THREE

# 3. SHAPE MEMORY ALLOYS

## 3.1 Introduction

A source of actuation is required in any robotic system that necessitates active movement. Specific actuation methods can differ significantly, and such differences can also be heightened or minimized, depending on the application in which the actuation method is used. To meet the goals and motivations outlined at the beginning of this project, a group of smart materials, known as shape memory alloys (SMAs), were selected to present a possible solution for actuating a simple origami fold. As such, this section will further explain, define, discuss, and expand upon the reasons behind the selection of SMAs as an actuation source over more traditional methods, the different types of SMAs, their related composition and material properties, and a way of testing that was used to corroborate this information. Results from the associated testing will be presented, and the importance of the testing on the overall project's progress will be discussed in detail.

## 3.2 Selection of an Actuation Method

Most origami robot applications define goals through parameters such as successful application, actuation speed, block force, and free stroke. Of these parameters, researchers in this field are specifically expected to push the boundaries of actuation speed. As is typical of most robotic systems, the rate at which a robot operates effectively is an important characteristic or measure of success. Since origami robotics has become more popularized, many different actuation methods have created active origami structures that can achieve a high speed of actuation. Some of the more common actuation methods

include but are not limited to pneumatic, magnetic, chemical, and electric actuation. These actuation types have been presented in research time and time again through projects that stress the importance of using composites and soft pneumatic actuators (SPAs) to initiate actuation with a large block force and reliability [36, 37]; working with magnetic fields to control smooth actuation by way of elastomers and gels [37]; creating and maintaining a low profile yet high-speed electromagnetic system [20, 38]; self-folding to initiate actuation through smart materials such as shape memory polymers and electroactive polymers (EAPs) [39, 10, 40, 41, 42]; and utilizing electric fields to fold and unfold origami in response to external stimuli [43, 44].

While those projects include some of the most common methods within this field, researchers have been innovating actuation sources for several years and have since broadened the scope of these methods. Recently, within the field of origami robotics, engineers have even started to use photo-origami to thermally fold polymers using light [45, 46, 47, 48], cell traction within cell-laden microstructures to promote self-folding [49], electrochemical actuation [50], and flexible composite actuators to increase the resonance frequencies of origami folding [51].

### *3.2.1 Selection of Shape Memory Alloys*

The primary goal of this project was to find a way to embed compact actuators into origami to achieve high-frequency folding. This was to be done through the implementation of components into a small origami fold which could present a modular solution for future projects in this field. After much research and deliberation into the multitude of actuation methods that could have been used to initiate cyclic movement for this project, it was found

that the best actuation method for the intended application was actuation through SMAs. SMAs describe a group of smart metallic materials that can return to a set original shape after being deformed by external magnetic, thermal, or mechanical influence. They have several advantages, such as being low-cost, easily manufactured, and having great mechanical properties [52]. Compared to other traditional actuation methods in origami robots, such as hydraulic and pneumatic actuators, SMAs provide a compact size, completely silent operation, high work density, and less maintenance over time. They also offer several distinct mechanical advantages at various strains and temperature ranges, which provides an increased level of versatility in applying this actuation method [53].

For this specific project, it was found that SMAs offered the most viable solution compared to other, more traditional actuation methods in this field. In addition to finding a way of embedding an actuation method into an origami robot, two of the main constraints of this research were that the actuation method must be compact and allow for high-frequency actuation. While several other actuation methods were considered, SMAs provided the most significant number of benefits for a compact, multistable robot. It was found that most research projects that utilized pneumatic actuation provided an extensive free stroke range and large block force but fell short in that they were often not quickly actuated and were not compact [36, 54]. Conversely, it was found that although electric and magnetic fields provided frequencies of up to 10 Hz, they only allowed for relatively small amounts of free stroke and block force and were not generally described as compact [44, 39, 43, 41, 48, 20]. Once those were considered and rejected for this application, attention was shifted to smart materials, where both shape memory polymers (SMPs) and

SMAs were investigated. Although both provided tremendous advantages, SMPs fell short because they offered a slow actuation frequency compared to any other actuation method considered. SMPs also required a significant heating source to actuate, which took away from their ability to remain compact [10, 55, 56]. They also fell short in that they were not made for cyclic movement.

Similarly, SMAs could not provide a perfect solution for the intended application of this project. Some sincere disadvantages of SMAs include their associated reliability and the complexity of their mechanical properties. In addition to these disadvantages, and as mentioned previously, one of the main issues with SMAs is that they have historically provided slow actuation within this field. However, although SMAs did have some drawbacks, it was believed that they would give the largest number of benefits for an application requiring an embedded, quick-moving, compact, cyclic, and high-output force solution.

| Possible Actuation Types | | | | | | |
|---|---|---|---|---|---|---|
| | Free Stroke | Block Force | Compact | High-Speed | Cyclic Abilities | Easily Embedded |
| Composites and Soft Pneumatics | ✓ | ✓ | ✗ | ✗ | ✓ | ✗ |
| Electromagnetic Fields with Elastomers and Gels | ✗ | ✗ | ✗ | ✓ | ✓ | ✓ |
| Chemical and Electrochemical Actuation | ✗ | ✗ | ✓ | ✓ | ✗ | ✗ |
| Shape Memory Polymers (SMPs) | ✓ | ✓ | ✗ | ✗ | ✗ | ✓ |
| Shape Memory Alloys | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |

Figure 3.1: Possible Actuation Types

SMAs have been used in the past to assist in the biomedical, aerospace, and automotive industries, and it is anticipated that an active understanding of their properties

could extend their influence on several other sectors as well. Therefore, SMAs were selected and worked with throughout this project.

### *3.2.2 Shape Memory Alloy Type*

Contrary to the other proposed actuation methods, shape memory alloys offer several different subsets of smart materials. While other actuation methods, such as pneumatic or electric methods, are characterized by the way they work (i.e., an influx of fluid or the initiation of an electric field), SMAs are characterized by their mechanical properties. These mechanical properties can ultimately change the way they work for several applications, offering researchers more flexibility and versatility in their design process. Additionally, since SMAs are technically categorized as materials, they can be configured differently to highlight their specific material properties for applications. To date, SMAs have been used for linear, rotational, and torsional applications; they have been configured in the form of thin films and ribbons [57, 58, 59], torsion SMA coils and wires [11, 60], and mesh matrices composed of embedded thin wires [61, 62, 63, 64]. In certain instances, thin SMA wires have also been used independently for smaller applications. Utilizing thin SMA wires is less popular a practice than the preceding methods, as it is limited to mainly microscale applications. Still, it was hypothesized that its concept could be helpful for this project.

While certain SMAs have distinct advantages for specific applications, it was found that linear helical SMA wires would provide the maximum number of advantages for this application. The goals of this research project demanded that the selected shape memory alloy be small, lightweight, able to exert a high force, have a high free stroke, and be quick

to actuate. Of these goals, the most important aspects would be the compactness and speed of the selected actuation method. While SMA films were highly considered, they would not provide a large free stroke, a high force, or quick actuation. In the same regard, although mesh matrices made from thin SMA wires could provide good tensile strength, they are not always compact and were found to be even slower to actuate than any other SMA type [65]. Of the SMA actuation types, helical SMA wires presented the most significant number of benefits according to the constraints listed above.

| Possible SMA Types | | | | | | |
|---|---|---|---|---|---|---|
| | Small Size | Lightweight | High Free Stroke | Quick Actuation | High Force | Easily Embedded |
| Thin Films | ✓ | ✓ | ✗ | ✗ | ✗ | ✓ |
| Mesh Matrices | ✗ | ✗ | ✓ | ✗ | ✓ | ✓ |
| Linear SMA Wires | ✓ | ✓ | ✗ | ✗ | ✓ | ✓ |
| Helical SMA Wires | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| Torsional SMA Wires | ✓ | ✓ | ✗ | ✗ | ✓ | ✓ |

Figure 3.2: Possible SMA Types

Helical SMA actuators were found to exert a high force and have a high free stroke while being small and lightweight [60, 66]. Coil-type SMA springs can also generate a large displacement compared to wire-type SMAs. In previous projects, it has been found that helical SMA springs can generate a displacement over 100% their original length, compared to the 6-8% generated in wire-type SMAs [66, 67]. The only associated drawback with this actuation method is its inability to actuate quickly. However, actuation speed is an associated disadvantage for almost all applications that require SMAs, regardless of their type [68].

## 3.3 Material Properties

Following the selection of shape memory alloys as the actuation method used to achieve the goal of embedding compact actuators into a simple origami fold to promote high-frequency actuation, it became essential to pursue the goal of fully understanding the behavior of SMAs in an origami system. To do this, extensive knowledge on the composition and material properties of the SMAs to be used was required. This knowledge would prove to be helpful in describing the behavior of SMAs on their own and their behavior once introduced to the overall system (i.e., the fold).

Shape memory alloys can undergo sold-to-solid phase transformations. These transformations consist of changes from an austenite, or "parent," phase and a martensite phase, and vice versa, invoking movement, which is used in soft robotics as a method of actuation. In SMAs, the austenite phase exists at relatively high temperatures and low stresses and takes the form of a cubic crystal lattice structure [69]. In contrast, the martensite phase illustrates a tetragonal or monoclinic crystal structure, normally existing at a lower temperature or a higher stress [11]. It is due to these phase transformations that shape memory alloys can be characterized by one of two unique working principles: shape memory effect (SME) or pseudoelectric (PEE)/superelastic effect (SEE). These working principles result in the same motion, but they are achieved through slightly different means. Shape memory effect can be described as the ability of an SMA, in its deformed low-temperature martensite phase, to recover an initially determined shape in its high-temperature austenite phase through the cycling of temperature. On the other hand, the

superelastic, or pseudoelectric, effect occurs when stress is cycled through the SMA, rather than temperature, to achieve the same predetermined shape.

In projects that utilize SMAs for actuation, shape memory effect is most commonly used, as it is often easier to cycle temperature through a system than to cycle stress. The cycling of temperature to transition SMAs from their martensite to austenite phases, and vice versa, allows for a more compact method of actuation and a level of versatility, depending on what a project or application demands. SME principles can be used in several ways to actuate a robotic system, as there are several different types of this working principle that can be taken advantage of. Shape memory effect can be used in one of three ways. These methods have been referred to as "One-Way," "Two-Way," and "All-Round" shape memory effect. In one-way shape memory effect, heating is applied to achieve a pre-determined austenite shape, but a force is necessary to deform the material in any way when it is in its martensite phase. Two-way shape memory effect describes the ability of an SMA to achieve a preset shape once heated to its austenite phase, but also to return to a set shape when its temperature drops it back down to its martensite phase [70]. All-round shape memory effect describes a type of shape memory effect that is like two-way shape memory effect, but it offers a greater amount of shape change because the shapes at the high and low temperatures are a direct inverse of one another [71].

For this project, the one-way shape memory effect principle was utilized to reduce the number of variables in the system, specifically when the single fold was to be implemented into a larger origami robot. In two-way and all-round shape memory effect, large amounts of irrecoverable transformation-induced plastic strain can occur and have

large effects on the overall system [72]. Additionally, the requirement of setting two initial shapes for two-way shape memory effect, one at a martensite and one at an austenite phase, would reduce the manufacturability of the final solution. That, combined with the necessity of additional power and temperature regulation components, which would increase the overall size of the system, led this project in the direction of one-way shape memory effect.

It was predicted that by implementing a natural bias force and supply of heating to the simple fold, one-way shape memory effect could be taken advantage of in this project. With the heat being applied to the system, the austenite phase would be achieved. Then, once the temperature of the SMA achieved its martensite phase, an inherent bias force could deform the SMA once again, preparing it to be actuated through another round of heating, and so on, with the hopes of creating movement through this cyclic process.

## 3.4 Hastening Actuation

Since one-way SME requires the cycling of temperature to actuate SMAs, the frequency of actuation has been relatively slow for small-scale applications because of the need to reset a heated SMA to its lower temperature. Therefore, the actuation speed of any SMA undergoing shape memory effect is strictly limited by the time it takes to transition from a stronger, higher, actuated temperature (austenite phase) to a lower-temperature (martensite phase) due to a limiting factor of heat transfer rates.

### *3.4.3 Actuation Reset Method*

In the past, to combat the lengthy time required to return an SMA to its lower temperature, researchers found ways of hastening the actuation speed by cooling them after their high-temperature cycles. The application of pre-stress and heat sinking were also

investigated as possible options of reducing the actuation time required for SMAs. However, the introduction of any cooling method in general was found to reduce the actuation time by a factor of three on average [73]. In addition to research done on the integration of a heat sink to a system using SMAs, researchers have examined the effect of using fluid mediums to actively cool SMAs after they have been actuated to their austenite phase. Previous research has illustrated that operating frequencies of 40 Hz, 20 Hz, and 10 Hz can be achieved in thin SMAs with the integration of fluids such as water, silicon oil, and air, respectively, to cool the SMAs [74, 75, 76].

While cooling SMAs allows for a higher frequency and longer lifetime, methods to cool SMAs have been extensively researched within the field of origami robots. Additionally, even with an active cooling source, the actuation frequency for these projects typically remains under 10 Hz, with this value decreasing significantly when no cooling source is present. Thus, a new goal of investigating ways of implementing these SMAs at a high frequency, without any form of a cooling source, was established.

To the knowledge of the author, most projects utilizing SMAs without a cooling source are done at a microscale level [77]. One of the most well-known methods of increasing the actuation speed of a system including an SMA is to decrease its wire size. Using smaller, thinner wires has been found to be one of the best methods of dissipating heat quickly into the area surrounding the SMA. However, decreasing the size of an entire origami system to a microscale is not a practical choice for a modular origami building block. Assuming that this simple fold would be integrated into a larger origami system, scaling down the system became obsolete as an option. Therefore, it became important to

keep the simple fold configuration at a small scale. The main issue that existed with maintaining a small-scale application and use of SMAs without an active cooling source consequently became the ability to quickly, and cyclically, actuate the system. Up until this point, research done on SMAs at a small or larger scale had been hastened through cooling, and research done to promote high frequency actuation on SMAs without cooling had been done on only microscale applications.

### *3.4.4 Design Methods used to Increase Actuation Speed*

In previous projects, researchers have attempted to achieve higher actuation speeds using active cooling agents. This study, however, attempted to use a combination of different design parameters to mechanically hasten the actuation speed of a folding hinge configuration with no cooling component present. The idea behind using design to hasten the speed, rather than a cooling method, was that design parameters could be translated, scaled, and optimized for a wide variety of compact systems, whereas active cooling methods could not. If necessary, these design parameters could also be used in combination with active cooling methods to further enhance the actuation speed, even if only slightly. It was hypothesized that there would be several different design parameters that could be optimized to ensure the quickest actuation speed possible at a smaller scale. Through an understanding of SMAs, their material properties, and their consequent behaviors, it was predicted that the use of several different design parameters in tandem to create the desired high-frequency actuation of SMAs without a cooling source would be the best method. In the past, mechanical design to hasten the speed of actuation in these systems has been

limited. But seldom, it has worked. It was believed that if methods to hasten actuation mechanically could be devised and combined, actuation frequency could accelerate.

### *3.4.5 Smaller, Thinner Wires*

The most logical design decision that was made to increase the actuation speed of this project was to use smaller, thinner wires. Even at a small scale, it made sense to use smaller, thinner wires to allow for a quicker return of the SMAs to the ambient temperature of the room after being heated above their known transition temperature. A drawback of using thinner wires exists in that these wires do not have the ability to maintain as much force as the thicker wires do. However, this would be combatted by using helical wires, which can maintain a higher force at both their austenite and martensite phases, and by selecting a thickness that would be just right for the scale of this specific application.

### *3.4.6 A Bias Force*

In addition to using thinner wires, a bias force, to mechanically reset the SMA to its deformed state to be actuated again, was also used to achieve a quicker actuation speed. This bias force came from the design of a hinge, which would apply just enough stiffness to act similarly to a spring. As the SMA was actuated to its austenite phase, forcing the origami fold inwards, the stiffness of the hinge would force the SMA back to its original martensite shape, outwards, even if its temperature had not yet returned to the temperature of the room, allowing for cyclic movement of the system. Then, the SMA would be heated once again to return to its austenite shape, and so on.

### *3.4.7 Pulsing a High Electric Current*

Another method that would be used in tandem with those previously mentioned would be the pulsing of a high electric current. SMAs can be heated through the introduction of an electric current, rather than another indirect source of heating. It is well-known that the higher the electric current, the higher the power applied to any system. However, with SMAs, a higher the current supplied to the system, the quicker the SMA is brought above its transition temperature, where it will enter its austenite phase and actuate. Therefore, for this project, a power source with a high-power rating was utilized to bring the SMAs up to a temperature of actuation quickly. Combined with this, it was also found that by pulsing this current (i.e., not having an electric current continuously running through the system), the SMA was allowed the opportunity to return to its martensite phase by cooling slightly in between pulses of an electric current. While this wouldn't allow the SMAs to immediately return to the ambient temperature, it was hypothesized that this pulsing, combined with the bias force introduced to the system, would still allow for movement in the system.

### *3.4.8 Alternating Actuation through Multiple Parallel Wires*

The final design component that was implemented into this system was a combination of multiple wires. The small size of SMAs would ideally allow multiple wires to be embedded at once without any interruption to an origami system. This was conceptualized to allow for the system to undergo more passive cooling by allowing one SMA to cool while the other actuated the system so that the system could continue to move, while still allowing for some cooling to occur. It was hypothesized that alternating of

actuation between multiple parallel wires in the simple fold would allow for the greatest increase in actuation speed of this system, as this would allow the SMAs to get as close to their martensite phase as possible, without a cooling source.

### 3.5 Shape Memory Alloy Samples

As important as a theoretical understanding of the behaviors of shape memory alloys is, it is difficult to ensure that they will behave as anticipated without some level of trial-and-error or knowledge of their chemical makeup. To this extent, twelve samples of SMAs were purchased from Kellogg's Research Labs so that tests could be run to identify the specific material properties of each sample used in this project, to reduce the amount of trial-and-error, and to more closely identify how each would behave within a simple fold.

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| Test Description: ASTM-F2063<br>Batch #: 181105-09<br>Date: Jan 22, 2019 | Chemical Composition (% weight) | Pass/Fail | Details |
|---|---|---|---|
| Ti | Balance | | |
| Ni | 55.8% | Pass | |
| Co | 0.002% | Pass | |
| Cu | 0.003% | Pass | |
| Cr | 0.001% | Pass | |
| Fe | 0.011% | Pass | |
| Nb | 0.005% | Pass | |
| C | 0.035% | Pass | |
| H | <0.001% | Pass | |
| O | 0.032 | Pass | |
| N | 0.001 | Pass | |
| | | | |
| | | | |
| Mechanical Properties: | | | |
| Preparation | Cold Rolled | | |
| Ultimate Tensile Strength | 880 MPa | | |
| Yield Strength | 208 MPa | | |
| | | | |

Figure 3.3: Composition of Shape Memory Alloys from Kellogg's Research Labs

Each sample was purchased as-is from Kellogg's Research Labs, and each sample had the exact same composition as detailed above. The samples were all labeled with a letter of the alphabet, from A to L, to ensure that all tests being performed were being

completed in the exact same way, with no bias or intervention in selecting the best one for the intended application. The process of selecting the best shape memory alloy for the intended purpose consisted of multiple different types of testing, which included DSC testing, static testing, quasi-static testing, and integration into the simple fold to determine the highest achievable actuation speed.

Table 1. Dimensions and Material Properties of Each SMA Sample as Purchased

| | A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mandrel Size (mm)** | 6.300 | 8.000 | 6.100 | 4.750 | 4.750 | 3.200 | 6.300 | 4.750 | 6.300 | 6.300 | 6.100 | 6.300 |
| **Mandrel Size (inches)** | 0.250 | 0.312 | 0.250 | 0.188 | 0.188 | 0.125 | 0.250 | 0.188 | 0.250 | 0.250 | 0.250 | 0.250 |
| **Wire Size (mm)** | 1.000 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.150 | 0.150 | 0.250 | 1.000 | 0.500 | 0.500 |
| **Wire Size (inches)** | 0.039 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.006 | 0.006 | 0.010 | 0.039 | 0.020 | 0.020 |
| **Transition Temperature (°C)** | 45 | 35 | 45 | 45 | 35 | 35 | 35 | 35 | 35 | 45 | 45 | 45 |
| **Transition Temperature (°F)** | 115 | 95 | 115 | 115 | 95 | 95 | 95 | 95 | 95 | 115 | 115 | 115 |

SMA samples were eliminated as possible candidates for the simple fold design based on a multitude of factors that will be discussed in future sections.

## 3.6 DSC Testing

To gather information regarding the mechanical properties of shape memory alloys at different temperatures, extensive testing was conducted on the twelve samples that were established as possible solutions to the research question. As mentioned previously, SMAs have two different phases in which they operate. When taking advantage of one-way shape memory effect, in the low-temperature, or martensite phase, shape memory alloys are flexible and able to be deformed or stretched out for a specific application. In the high-temperature, or austenite phase, shape memory alloys are returned to their original shape or structure, effectively resetting any deformation induced in the low-temperature phase.

Actuation of a specific SMA occurs at the transition between its martensite and austenite phases. This transition is typically denoted by a temperature, which is known as an SMAs transition temperature. It is at this temperature that phase transformations officially occur. While specific transition temperatures were identified and presented with each SMA that was purchased from Kellogg's Research Lab, it was necessary to establish the exact transition temperature associated with each one, as these values are often approximations. Therefore, a thermal analysis was performed.

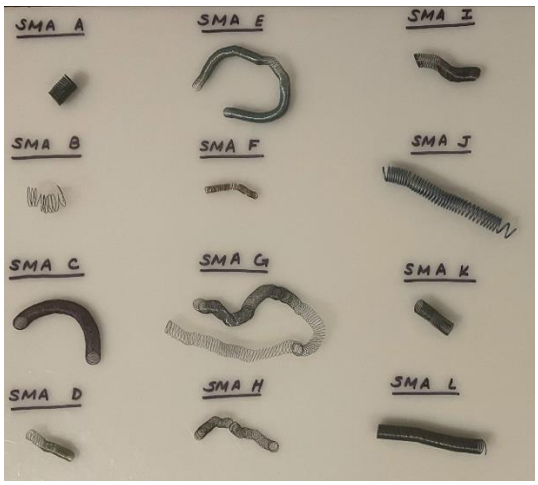


Figure 3.4: Helical SMA Samples

A formal Differential Scanning Calorimetry (DSC) thermal analysis was performed on every sample to accurately identify the exact transition temperature of each SMA. The DSC testing was performed on a TA Instruments Q1000 Model DSC Machine and Controlling Computer. This machine performs a measurement of the rate of heat flow through a sample in relation to an empty reference pan. For the DSC testing completed, the DSC machine heated two pans, a sample pan containing one SMA sample at a time, and an empty reference pan. The machine was then programmed to heat both pans at a specific

rate of 10°C per minute, up to 100°C. This method was consistent with other studies that have previously done this type of testing on SMAs [79, 80, 81]. The DSC pan with the SMA sample in it required more heat to keep its temperature the same as the empty reference pan, because it contained more material. Therefore, the difference in the amount of heat that must be cycled through each pan is what the DSC machine measures to establish the transition temperature of the SMA sample being tested.

Figure 3.5: TA Instruments Q1000 Model DSC Machine

From this testing, it was found that the transition temperature of each SMA sample was slightly different, either higher or lower, but never the same as what was reported by Kellogg's Research Labs. As mentioned previously, it was hypothesized that by quickly heating an SMA slightly over its transition temperature, then turning off the heating source, the rate of cooling would be just slightly faster, therefore speeding up the frequency of actuation. With the accurate transition temperature discovered for each SMA sample, the information could be used to establish the amount of time needed to heat each SMA sample just above its transition temperature, which would be used later on in the project when pulsing and alternating an electric current between two SMA wires.

Table 2. Actual Transition Temperatures of SMA Samples after DSC Testing

| | A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reported Transition Temperature (°C)** | 45.00 | 35.00 | 45.00 | 45.00 | 35.00 | 35.00 | 35.00 | 35.00 | 35.00 | 45.00 | 45.00 | 45.00 |
| **Actual Transition Temperature (°C)** | 42.40 | 34.60 | 37.99 | 41.29 | 31.95 | 36.71 | 36.10 | 31.46 | 40.18 | N/A | 38.55 | 37.28 |
| **Mass of Sample (mg)** | 11.772 | 2.271 | 10.251 | 2.1290 | 10.210 | 10.473 | 5.096 | 8.020 | 2.420 | 6.508 | 8.596 | 7.987 |

The transition temperatures from the martensite to austenite phase were found from tangent lines of the peaks illustrated in the graphs of the heat flow versus temperature, as calculated by the DSC computer. Additional data collected from the DSC controller and computer was put into MATLAB and additional information such as the heat capacity, sample purge flow, and LNCS pressure were recorded. While this information was helpful, it did not prove necessary for determining the actual transition temperature of each SMA sample.

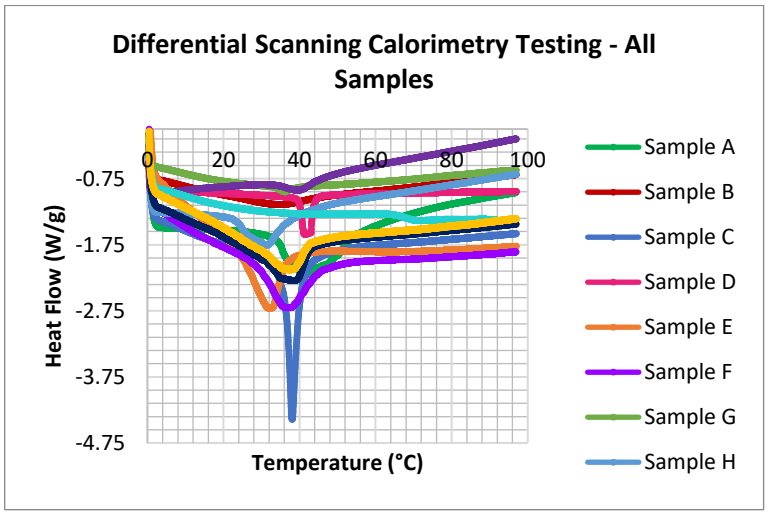


Figure 3.6: Heat Flow Data and Actual Transition Temperature of all Samples

# CHAPTER FOUR

# 4. POWER, ELECTRONICS, AND CONTROLS

## 4.1 Introduction

Actuation of shape memory alloys is reliant on the switch between their martensite and austenite phases. Using one-way shape memory effect, an SMA will be deformed in its martensite phase, but once heated above its transition temperature, will return to a predefined shape in its austenite phase, invoking movement and creating actuation of its system. While there are many methods that could have been useful in heating the SMAs of this system above their transition temperatures to create movement, joule heating served as the method selected to provide heat to the system in a compact manner. In this section, joule heating and its process will be defined as they pertain to the actuation of shape memory alloys. In addition to that, certain issues involving this method will be discussed, and the associated resolutions to those issues will be illustrated. The final solution with regard to the power source for actuating this system will be shown, and decisions made to reach this final solution will be explained for replication in future endeavors.

## 4.2 Joule Heating

One of the ways that shape memory alloys can be actuated is through the cycling of temperature. When using one-way shape memory effect with the intention of switching between the two solid-state phases of an SMA to create actuation, there are two different methods that can be used to heat the system. An SMA can be heated through either internal or external manipulation. Externally, and similarly to raising the temperature of anything, the environment surrounding the shape memory alloy can change by becoming warmer,

therefore allowing the SMA to reach above its transition temperature. Methods of changing the temperature of an SMA through external manipulation include but are not limited to raising the ambient temperature of its surroundings, applying an external heating source, forcing the flow of warm fluids, or placing an SMA in a warm fluid such as water. While the only requirement of an SMA to actuate to its predefined shape through one-way shape memory effect is to be heated above its transition temperature, attempting to change the temperature of an SMA from its martensite to austenite phase by only external manipulation requires a great amount of energy and a larger testing environment, leading to a decrease the overall efficiency and modularity of the system [64, 79].

On the other hand, the efficiency of using an internal method to increase the temperature of an SMA can be much higher. Therefore, it proved useful to investigate the practice further. The main method that can be used to heat an SMA internally is known as joule heating. Joule heating is a process by which heat is created by passing an electric current through a conductor, which in this case would be the SMA. Using an internal heating source to actuate the SMAs in this project was an obvious choice, as the use of joule heating would maintain a compact system while providing a quick source of heating the system. Using joule heating, the heat of the system can be controlled and quickly turned on and off, which became important when attempting to heat the system through pulses that reach just over the transition temperature of the SMAs. With joule heating, the heating quantity of the thin SMA wires, $Q$, can be defined by Joule's heating law, where $d$ represents the diameter of the SMA wire in meters, $V$ is the voltage applied to the SMA wire in volts, $R$ is the total resistance of the SMA wire in ohms, $l$ is the total length of the

SMA wire in meters, and $\rho$ is the electrical resistivity of the wires in ohmmeters. This equation is shown below in (1).

$$Q = \frac{\pi d^2 V^2}{4\rho l} = \frac{V^2}{R} \tag{1}$$

Although there are drawbacks to joule heating, it is one of the quickest and easiest methods to control the temperature of the shape memory alloys in a system. While cooling the SMA from its austenite phase still presented an issue, joule heating was selected as the method of heating to be used for this project because it would increase the frequency related to the heating process, thus increasing the frequency of the system overall, compared to external heating methods.

### 4.3 Associated Issues

While the concept of joule heating is simple to understand, it becomes a lot more difficult to implement with SMAs. The behaviors of shape memory alloys can be very hard to predict, as they are constantly fluctuating with changes in their surroundings. Even with a constant and reliable power source, any change, no matter how slight, in the environment of an SMA can alter its overall temperature and behaviors, which can present an issue in even the most controlled environments. Small changes can include but are not limited to slight changes in the temperature of the surrounding air or any type of wind blowing in the direction of the SMA [80]. Therefore, when working with these shape memory alloys, it is imperative that the testing environment and power source remain consistent in the system. Additionally, thin shape memory alloys typically have a high electrical resistance, which can impact the overall power source by creating low current flow through the system [64]. To confront the negative effects of the high electrical resistance that the SMAs provide to

a system, short heating times and higher current, with no other changes to the surrounding environment, are recommended to adequately control any system involving an SMA for actuation [81, 82].

In addition to being extremely sensitive to their surroundings and providing a high electrical resistance to the circuit they reside in, SMAs are temperamental in that they are prone to overheating and irreversible levels of strain [12]. This proneness to overheating is not limited to either external or internal heating. However, electrical overheating (internal heating) can occur far sooner than any external heating due to the direct nature of the heating method. Overheating an SMA becomes a lot easier on a smaller scale, with a higher current, and when the SMA is stretched in its austenite phase, which are three practices being used in this project. Therefore, this proneness to overheating was an issue that placed a constraint on this research. To combat this issue, the input current of the system was kept as low as possible, and the amount of time in which the SMA was actuated was kept short while remaining long enough to actuate the SMA. The SMA was also not placed under large amounts of stress while in its austenite phase, and the environment it resided in was kept as consistent as possible.

## 4.4 Setup

To perform joule heating, the SMA wires must be connected to a form of electricity. In addition to the requirement of connecting the SMA wires to a power source to initiate joule heating in the system, this project also operated under the constraint that any connection form must be compact and easily embedded into a simple fold. On top of that requirement, the solution also needed to be one that could be easily and consistently

extended to several simple folds that would encompass an entire origami system. While this project only required one simple fold, achieving modularity in this field would require a connection system that could also be modular. While the compact nature of the project provided a challenge, this section details a solution that is compact, modular, and able to reliably supply joule heating to the shape memory alloys in the system.

### *4.4.9 Crimping*

At the beginning of this project, an electric current was supplied to the shape memory alloys using a TENMA 72-2690 Digital Control DC Power Supply (30V, 5A) and a set of alligator clips.


Figure 4.1: TENMA 72-2690 Digital Control DC Power Supply (30V, 5A)

The alligator clips were clamped to either side of the SMA that was being actuated and the power was turned on to heat the SMA. However, this proved to be bulky, making the system a lot bigger than it needed to be. Additionally, securing alligator clips to the ends of the SMAs added weight to the system, which was undesirable, as most origami materials are quite light and unnecessary weight can directly decrease the efficiency of the system. Utilizing alligator clips also increased the level of variability in the electric current

supplied to the system, as the alligator clips couldn't consistently hold onto the SMAs due to their small size, causing an insecure method of flow from the power source to the SMAs.

To solve these issues, this project investigated a method of wiring that would allow the SMAs to be consistently heated using an electric current through crimping. Crimping is a process where two or more pieces of metal are joined together by deforming the metal pieces to hold or be held by one another. To crimp the SMA wires, a process involving female Dupont pin connectors, a Dupont crimping tool, a set of pliers, SMAs, and 1x1 Dupont header connector housing units was required. The steps to crimp SMA wires are outlined below so that the crimping process can be completed by future researchers.

- **Step 1:** Two female Dupont pin connectors are to be unwound and removed for each SMA that needs to be crimped.

Figure 4.2: Illustration of Five Unwound Female Dupont Pin Connectors
Figure 4.3: Individual Female Dupont Pin Connectors

- **Step 2:** A single female Dupont pin connector should be placed in the grip of the Dupont crimping tool that corresponds to the size of the pin connector being used. Ensure that the pin connector is tightly gripped but that it has not completely closed

in on and thus deformed the pin connector. There will still need to be an opening in the pin connector so that an SMA can be inserted and crimped with the connector.

Figure 4.4: Dupont Crimping Tool


Figure 4.5: Front of the Dupont Crimping Tool with Female Pin Connector in Place
Figure 4.6: Back of Dupont Crimping Tool with Female Pin Connector in Place

- **<u>Step 3:</u>** A piece of the SMA being used should be cut to the desired length.

Figure 4.7: Portion of SMA Cut to Desired Length

- **<u>Step 4:</u>** Using a set of pliers, deform the coils on either end of the SMA so that they are in the shape of narrow loops.

Figure 4.8: Deformed SMA Coils to be Crimped

- **<u>Step 5:</u>** The narrow loops created in the previous step will be slid into the front end of the female pin connector that is being held together by the crimping tool.
- **<u>Step 6:</u>** Once the narrow loop is inserted into the female pin connector, the Dupont crimping tool will be squeezed, forcing the SMA wire portion to be forced into the female pin connector.

Figure 4.9: SMA Crimped on Both Ends

- **Step 7:** Any excess SMA wire that hangs out of the crimped portions of the wire should be trimmed.
- **Step 8:** A 1x1 Dupont header connector housing unit should be slid onto each female pin connector. A quiet click will indicate that it is in place.

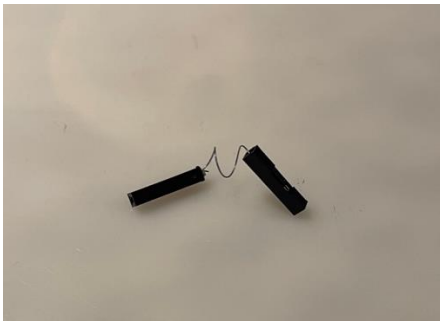

Figure 4.10: SMA Wire Crimped Using Dupont Connectors

In its crimped state, the SMA wire will be significantly smaller in size compared to its original unit comprised of the SMA and alligator clips.

### *4.4.10 Final Power Source Components*

Methods such as pulsing an electric current and using multiple parallel wires to increase the actuation speed of the system were discussed. Although these only include two of the methods discussed to hasten the actuation speed, this stands to illustrate the

importance of the selection of the power source and electrical components of this project. Including the sizing and weight constraints, the configuration of the power source also faced the requirement of being able to pulse an electric current in an alternating fashion between multiple wires. To achieve these goals, multiple components were used.

First and foremost, the power source stood to be altered. While the TENMA DC Power Source was able to supply the power needed by the system, it was lacking the compactness that was demanded of this project. Instead, an Alitov AC-DC Power Supply (Model ALT-1220T) with an output DC voltage of 12 volts, current of 5 amperes, and power rating of 60 watts was used. The size of this power source was significantly smaller than the original power source and allowed for a decrease in the overall size of the system. In addition to providing a solution for the size requirements, this power supply also offered the current required to quickly heat the SMAs, while avoiding possible overheating.


Figure 4.11: Alitov AC-DC Power Supply (Model ALT-1220T)

It was also decided that a combination of a motor driver and an Arduino Uno would be used to send rapid pulses in an alternating fashion to two parallel SMAs. Two SMAs would be used and spread far enough apart to allow for heat dissipation, while also maintaining a compact size. With more than two SMAs in the configuration, the size of the fold would have had to increase, which was undesirable for this project.

The motor driver that was selected was an MDD10A Rev 2.0 Dual Channel 10A DC Motor Driver from Cytron Technologies. This dual channel driver served as the ideal solution to switching the electric current from one wire to the other, as only two SMAs would be used.

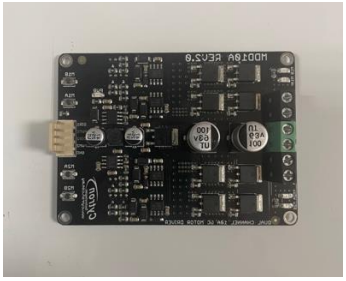

Figure 4.12: MDD10A Rev 2.0 Dual Channel 10A DC Motor Driver

Finally, the last component that served to bring the system together was an Arduino Uno R3 Microcontroller Board. This was a programmable solution that would allow the researcher to send commands to the motor driver, which would use the constant power sent by the power source to actuate two different, parallel SMAs in an alternating fashion. Using the Arduino Uno R3 would allow for any period of actuation (HIGH power) or any period of rest (LOW power) to be defined for the system so that the system could actuate in the most ideal way possible. Once the user defines the system parameters, the Arduino Uno can operate on its own (away from a computer) if it is connected to a source of power. Once connected to any outlet, the power source included in this system will suffice in powering the Arduino, motor driver, and SMA, so the system can operate independently from any sort of computer, ensuring that the final solution for the power source and electronics can be transported and work in any environment, if an electrical outlet is present.


Figure 4.13: Arduino Uno R3 Microcontroller Board

### *4.4.11 Arduino Code*

Although the Arduino Uno R3 offers the ability to control a system without continuous human intervention, it does require initial setup prior to being integrated into a system. For this project, it was imperative that quick pulses were sent to two SMAs in an alternating fashion, allowing for cyclic motion of a high frequency. To do this, code for the Arduino needed to be written to send commands to the motor driver, which was powered by the power source, to send currents of electricity to one SMA at a time.

```
void setup() {
  // Put your setup code here, to run once:
pinMode(3, OUTPUT); // Identifying pin 3 as a pin to send pulses of power to the system
pinMode(6, OUTPUT); // Identifying pin 3 as a pin to send pulses of power to the system
}

void loop() {
  // Put your main code here, to run repeatedly:
digitalWrite(3, HIGH); // Turn the power on for pin 3/SMA 1 (HIGH is the voltage level)
delay(3); // Wait for 0.003 seconds
digitalWrite(3, LOW); // Turn the power off for pin 3/SMA 1 (LOW is the voltage level )
delay(650); // Wait 0.650 seconds for pin 3/SMA 1 to cool down
digitalWrite(6, HIGH); // Turn the power on for pin 6/SMA 2 (HIGH is the voltage level)
delay(3); // Wait for a 0.003 seconds
digitalWrite(6, LOW); //Turn the power off for pin 6/SMA 2 (LOW is the voltage level)
delay(650); // Wait 0.650 seconds for pin 6/SMA 2 to cool down
} // End of loop. Code repeats.
```

Figure 4.14: Sample Arduino Code for Alternating Current

This illustrates an example of the Arduino code that was prepared for one of the possible SMA configurations. Here, “HIGH” represents an electric current being run through one of the SMAs and “LOW” represents it being turned off and switched to the

other wire. The “HIGH” value represents the time (in milliseconds) that was required to bring the SMA sample to its actual transition temperature, as found in the DSC testing performed. The loop outlined in the Arduino code continually repeats, allowing for the system to run without any human intervention, assuming power is supplied to the system. Including a microcontroller in this system proved to be useful in translating a self-sufficient origami fold to an active origami robot. The frequency of this system can be defined by the number of times that the hinge folds in one second. Since the entire hinge configuration folds when only one SMA has been actuated, the frequency of this system can theoretically be calculated from the Arduino code by finding how many times the SMAs would be actuated in a matter of a second. Assuming that the frequency is found at the start of the actuation of one SMA, the theoretical frequency would be about 3.05 Hz, as frequency is found by dividing the cycles performed by the time it took to perform those cycles. In practice, it would be difficult to achieve this frequency. However, this illustrated that a high frequency using this method could be possible.

### 4.5 Integration and Optimization of Actuation Method and Electronics

Integration and optimization of the electronics and the actuation method is an important part of any robotics problem. Throughout the course of designing components or systems of origami robots, taking the time to integrate the components with one another is vital to the success of the project. Rather that implementing the components together at the end of the project, a systematic design method allows a researcher with the opportunity to check their work as they go, so when problems do arise, they are more easily solved.

To optimize the electronics solution required for this project, several components were individually optimized then combined to find the best method of accomplishing the set task. Once a method of supplying power to the system was found, a comparable, yet smaller power source was found and implemented into the system. In addition to that, a motor driver with a power rating able to withstand the constraints outlined by this project was found and used in conjunction with an Arduino microcontroller. Finally, using the Arduino microcontroller, code was run using different delay times, to discover exactly how much time was required to cool the SMAs in between their actuation. Running the code several times to ensure that the delay times were as fast as possible allowed for the greatest optimization to take place.

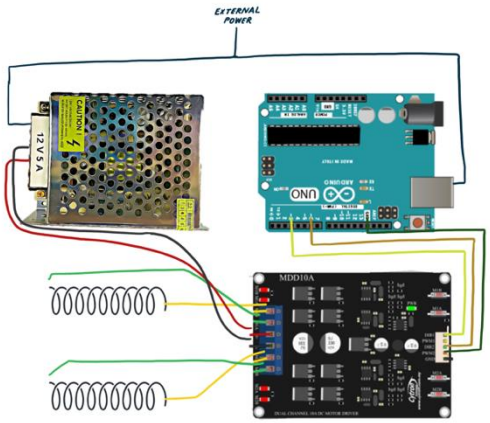


Figure 4.15: Final Solution of Electronics for Actuating the System

In optimizing several different components consequentially, then combining them to create one final solution for the electronics in the system, fewer issues resulted in the design process than likely would have if every component were integrated at the very end of the project.

CHAPTER FIVE

# 5. MECHANICAL TESTING

## 5.1 Introduction

Shape memory alloys are unique materials in that they exhibit solid-to-solid phase changes between two states. At each state, an SMA can behave in different ways, often allowing a single wire to act as two different wires in each of its two states, and these states can be drastically changed from SMA to SMA, depending on the chemical composition, heat treatment, and thermomechanical cycling performed within the specific SMA [84, 85]. Even if only slightly, SMAs will typically reveal different material properties, such as their energy dissipation capacity, yield strength, and fatigue resistance, depending on which solid state they are in [83]. To further understand the specific material properties of the SMAs used in this project, mechanical testing was performed. This mechanical testing included two different types of static testing (performed at a martensite temperature and an austenite temperature) and a single form of quasi-static testing for each of the twelve possible samples that could have been used for the final hinge solution. The following sections will describe the methods, setup, and results of the static and quasi-static testing performed on the SMAs used in this project, along with an explanation of how this testing would prove to be useful in selecting the final SMA that would be used.

## 5.2 Static Testing

To fully understand the material properties and behaviors of the shape memory alloy samples used in this project, and to select the proper SMA sample for use in the final hinge configuration, it was established that mechanical testing would need to be performed.

This mechanical testing would follow typical static axial and quasi-static tension testing to assess the characteristics and behaviors of each SMA sample at different temperatures and under different loads. Prior to testing, it was anticipated that the most crucial bit of information that would be necessary for the successful completion of the final folding hinge configuration would be the stiffness values associated with each of the samples. The final folding hinge for this project would include integrated SMAs which would allow for movement. In their most relaxed state, these SMAs would remain taut between the two surfaces of the fold, so that movement could occur once the SMAs had been actuated. Keeping the SMAs taut between the fold in their martensite phase requires knowledge of the stiffness in their martensite phase, so that the SMAs do not break within the configuration. Additionally, since the SMAs will operate at a temperature higher than their martensite phase during their actual movement, it becomes important to also know their behavior at a higher temperature as well. Therefore, static tension testing at both room temperature (martensite) and a heated temperature (austenite) was required for each of the twelve samples.

In addition to using the stiffness values to ensure that the SMAs would not fail in the active configuration, these stiffness values would also be used to ensure that the selected SMA was strong enough to overcome the bias force introduced by the hinge selected for the configuration. As the project moved forward and integration of all the components occurred, it became a balancing act to ensure that all components were properly compatible. Therefore, knowledge of the stiffnesses of the SMAs being used and

the stiffness of the hinge material used would be important in any theoretical calculations and selections of the correct SMAs for the simple fold setup, prior to integration.

### *5.2.1 Martensite Static Tension Testing*

It was established that static tension testing performed at room temperature would be the most appropriate method to identify the stiffness measurements for each of the twelve SMA samples at their martensite phases. All testing was completed in ambient air conditions, as this testing was measuring the stress of the samples and their associated stiffness values at and before failure, respectively. The testing machine utilized in this mechanical testing was an eXpert 5601 – Admet Electromechanical Tension Testing system. The Admet test rig was fitted with a load cell and position transducer, which allowed for data to be collected in its accompanying microprocessor controller. The machine itself was operated by, and all data was subsequently collected and recorded by, a MTESTQuattro Controller. The Admet test rig was connected to its external data acquisition system through a USB connection to its MTESTQuattro microprocessor controller. The MTESTQuattro device was configured with specific constraints and properties on a desktop computer so that all tests were performed in a consistent manner using this assembly.

To perform this testing, the shape memory alloy samples were cut into lengths no longer than 20mm so that they could be stretched within the constructs of the testing machine. Once the samples were cut to fit the limits of the testing machine, a series of plates were created to fixture the wires to the load cell and plate offered by the machine. Traditionally, samples of a wider diameter are tested, so fastening the wires to the testing

machine became an important part of the process so that they would not slip while they were in tension.

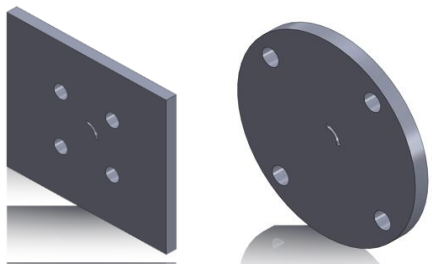

Figure 5.1: Testing Blocks Created to Secure Each SMA to the Testing Machine

Once the testing blocks were made to fix the wires to the top of the load cell and the bottom of the testing plate, the SMA was fit through the slots in the center of the testing blocks. The square-shaped attachment apparatus was then attached to the flat, stationary base of the Admet testing machine with four bolts, and the circular-shaped attachment was secured to the load cell of the testing machine in a similar manner. Once the testing blocks were connected to the testing machine, an SMA of lengths varying from 10mm to 20mm spanned the length of the Admet testing space, where one end of the SMA was attached to the top of the moving motorized load cell, and the other end was connected to the unmoving bottom of the testing device. The SMA vertically occupied the center of the testing space where tensile testing would occur. To calculate the stiffness values, the test method would follow a general axial tension protocol, where the load cell of the Admet testing machine used would pull upwards on the top of the sample while the bottom of the sample remained fixed.

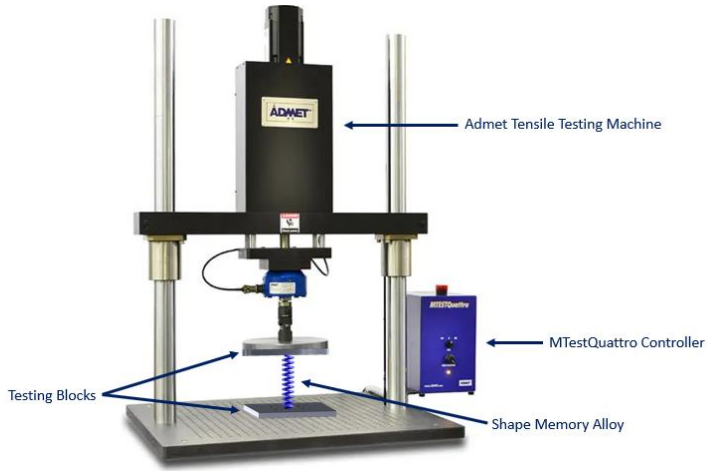


Figure 5.2: Setup for Martensite Static Tensile Testing

The load cell followed a set displacement rate until fracture of the specimen occurred. While the tensile test ran, the controller would collect and record the data values to create a force versus displacement curve, which could be used after testing to identify the stiffness values of each SMA in its martensite phase. The test was run nine separate times, once for each of the SMA samples being investigated after ruling out three unlikely SMA samples in an observational assessment for reasons that will be discussed later.

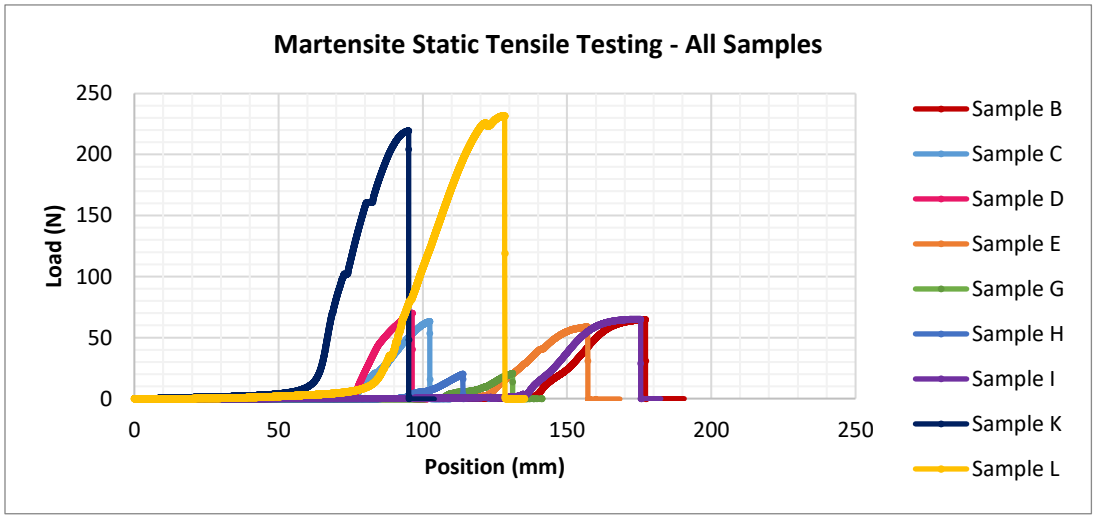


Figure 5.3: Martensite Static Tensile Testing Results for all Samples

Once a specimen had been tested, and therefore had broken, the test specimen was not used in any further experimentation related to this project.

### *5.2.2 Austenite Static Tension Testing*

In a similar way to the room temperature static testing that was performed, it was determined that heated static tensile testing trials would need to be done to find the stiffness values of the shape memory alloy samples in their austenite phases. To complete this testing, the Admet testing unit was set up in the exact same way as it had been in the room temperature static tensile testing. The only difference between this testing and the testing illustrated above, is that the heated static tensile testing trials required the introduction of a power supply and temperature regulation devices.

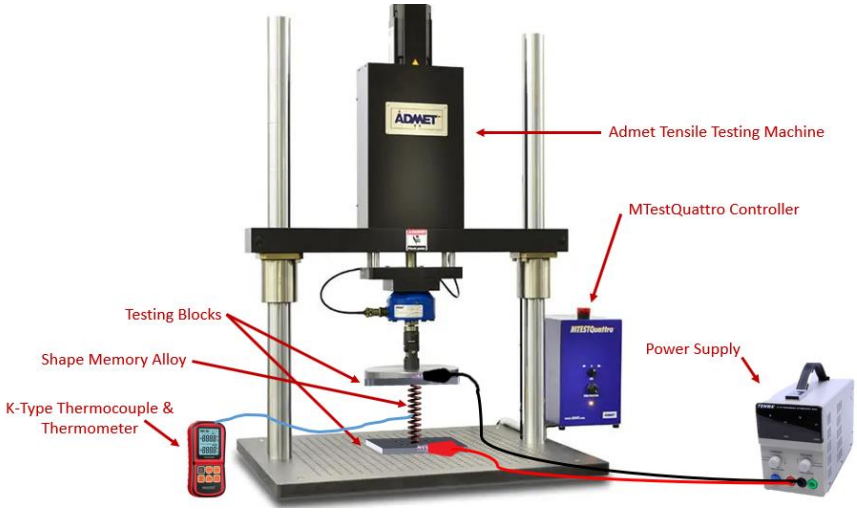


Figure 5.4: Setup for Austenite Static Tensile Testing

For this testing, prior to sliding the SMA through the slots of the attachment apparatuses, a thin, k-type thermocouple was attached to the middle of the SMA wire to gather information of the temperature of the wire during each trial. This was done to ensure that the temperature of the wire was operating at, or slightly above, the austenite transition

temperature for the duration of the testing. Once the k-type thermocouple was attached the middle of the SMA wire, the wire was then connected to the testing blocks and secured to the Admet testing frame. Following the successful fixation of the SMA to the bottom plate and the load cell, alligator clips, which were attached to the power source, were be applied to both ends of the SMA, outside of the testing space. The power source was then turned on and the SMA was heated to its austenite phase prior to the start of the testing protocol.

The testing rig was then be used to measure the load versus displacement of the SMA samples in the exact same way as it had in the martensite static tensile testing trials. The test method again followed a general axial tension protocol, where the load cell of the Admet testing machine used was pulled upwards on the top of the sample while the bottom of the sample remained fixed. The load cell again followed a set displacement rate until fracture of the specimen occurred. While the tensile test ran, the controller collected and recorded the data values to create a force versus displacement curve, which could be used after testing to identify the stiffness values of the SMA in its austenite phase.

Table 3: Comparison of Stiffness Values from Static Tensile Testing

| Martensite Static Tensile Testing – Stiffness Values | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J | K | L |
| Stiffness Value (N/mm) | N/A | 1.624 | 2.724 | 2.856 | 2.024 | N/A | 1.219 | 1.208 | 2.480 | N/A | 8.848 | 6.189 |
| Austenite Static Tensile Testing – Stiffness Values | | | | | | | | | | | | |
| Stiffness Value (N/mm) | N/A | 2.260 | 2.818 | 2.915 | 2.263 | N/A | 1.329 | 2.256 | 3.744 | N/A | 10.930 | 6.552 |

The test was run nine separate times, once for each of the SMA samples being investigated. Once a specimen had been tested, and therefore had broken, the test specimen was not used in any further experimentation related to this project.

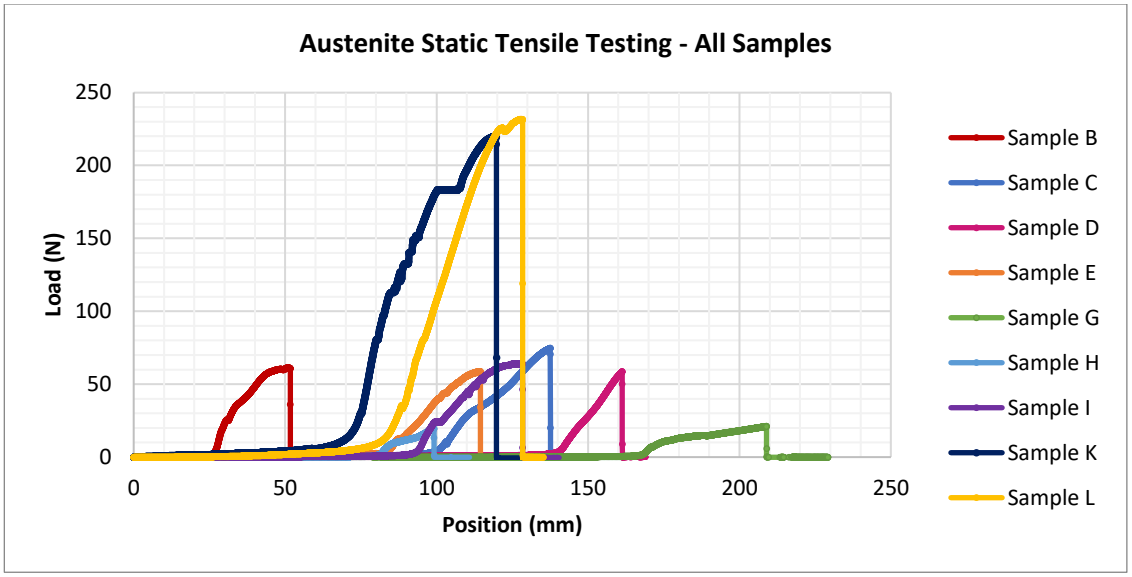


Figure 5.5: Austenite Static Tensile Testing Results for all Samples

## 5.3 SMA Selection

Following the successful completion of the static testing that was performed, a single SMA was selected for use in the remainder of the project. This SMA was selected on the basis of several factors, all of which would provide logical reasons for why it would be the most ideal option for this specific application. By mere observation, it was concluded, almost immediately, that the SMAs of samples A and J were too thick for the small-scale fold that remained the goal of this project; these SMAs would require a lot of energy and would be very slow to return to their martensite temperatures, as they were so thick. Inversely, it was found that sample F was far too thin for any reasonable use in this project; it would not be able to offer any of the force desired in this project. Samples A, J, and F were not mechanically tested for these reasons. In a similar way to those three samples, through static tensile mechanical testing, it was found that samples G and H, and samples K and L were too weak and too strong, respectively, for the intended application

of this project. Those samples were removed, and further analysis of the remaining five samples was performed to select the SMA to be used as the solution for this project.

Since observations and the static tensile mechanical testing were not able to provide any clear distinction between the five remaining samples, additional considerations were made to establish a clear choice for the final SMA to be used. The next factor that was considered in these deliberations was size. For samples B, C, and I, the mandrel size of each helical SMA spring was far larger than those of samples D and E. With the knowledge that this project was to be completed on a small-scale, these SMAs were eliminated from the selection process, leaving just samples D and E to be chosen from. Between these two options, which were the exact same size, and which performed in almost identical manners during the static mechanical testing, the only other method of comparison was to look at their transition temperatures. Using the DSC testing results, it was found that the transition temperature for sample D was slightly higher than that of sample E. Having a higher transition temperature would require a higher temperature to actuate the system. It would also require more time to reset to its lower temperature phase. Therefore, the shape memory alloy selected for use in this application was that of sample E.

Table 4: Sizes and Transition Properties related to SMA Sample E

| **SMA Sample E** | | | | | |
|---|---|---|---|---|---|
| **Mandrel Size (mm)** | **Mandrel Size (inches)** | **Wire Size (mm)** | **Wire Size (inches)** | **Transition Temperature (°C)** | **Transition Temperature (°F)** |
| 4.750 | 0.188 | 0.250 | 0.010 | 35 | 95 |

## 5.4 Quasi-Static Testing

Quasi-static testing is a type of testing that is performed to acquire specific data measurements of a specimen from a universal testing machine at a slow loading rate [84].

While thin shape memory alloys do not provide the perfect test sample to perform such testing, when connected to the testing machine properly, they can be used to establish certain cyclic behaviors that could not otherwise be found in static testing. The specific behavior that was targeted in this quasi-static testing was the long-term stiffness performance provided by each of the shape memory alloy samples. An understanding of the variability in a sample's stiffness over time provides valuable information that would allow for a selection of the best SMA for a specific use. In the case of this project, the SMA would need to illustrate little to no variability in its stiffness values over time, illustrating that it can perform cyclically and consistently, as it would be required in the case of a high-speed origami robot.

To perform the quasi-static testing that was required to determine the cyclic behavior of the stiffness values of each shape memory alloy specimen at its martensite and austenite phases, the Admet testing machine was set up in the same way that it had been for the heated static testing trials.

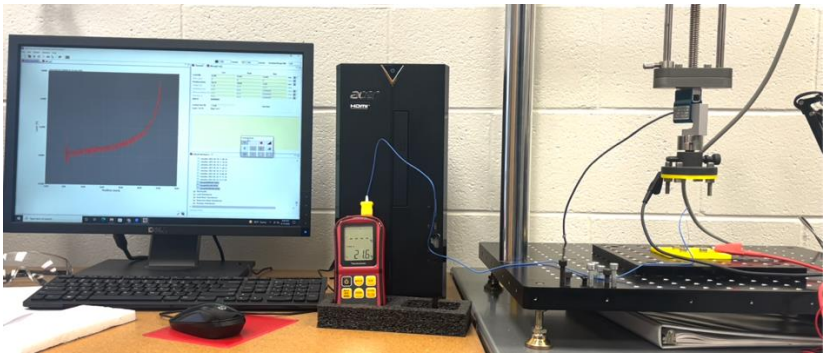

Figure 5.6: Setup for Quasi-Static Mechanical Testing

The only difference between the testing performed in the heated static tensile testing and the quasi-static testing was the test method that was used. Instead of pulling the

SMA sample in tension until fracture, the SMA was to be pulled slowly in tension up until the helical wire was completely taut, with no kinks or remaining coils. The helical SMA was determined to be taut when there was a significant increase (>20% increase in the load of the wire). Once taut, the machine would push downwards on the wire, releasing the load upwards and allowing the wire to be compressed back to its original, flexible length. This cycle was performed a total of 15 times, at both room temperature (while the SMA was in its martensite phase) and at a heated temperature (while the SMA was in its austenite phase). These quasi-static tests were also performed at a short (under 10 mm) and a long length (under 40 mm). Once a sample was used in a test, whether the SMA was short or long, or used in a room temperature or heated trial, the sample was discarded and not used again.

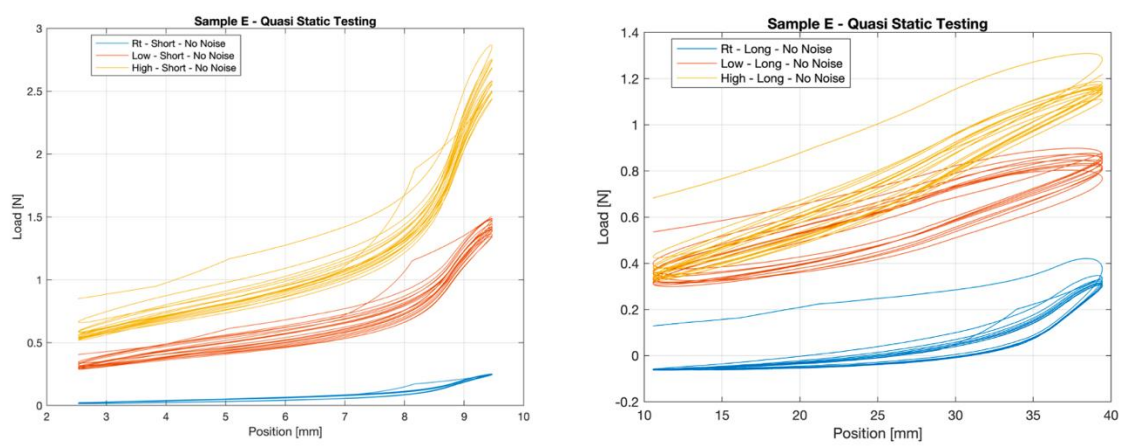


Figure 5.7: Comparison of Quasi-Static Testing Results of the Sample E SMA

From the data that was collected, analysis was performed to reduce any noise established from the Admet testing machine. Once the noise was removed from the data, an average stiffness value for each of the tests performed was established, to adequately

predict the long-term stiffness behaviors of the SMAs in an application such as that of this project. Overall, there was very little variability in the results of this testing, compared to those of the static testing previously performed, which allowed for an average of stiffnesses from the room temperature and heated static testing to be taken and used as an accurate representation of the long-term stiffness value of each of these SMA samples. As there was very little variability, it was predicted that these would have a relatively high ability to perform cyclically, with little to no deterioration in performance, over time.

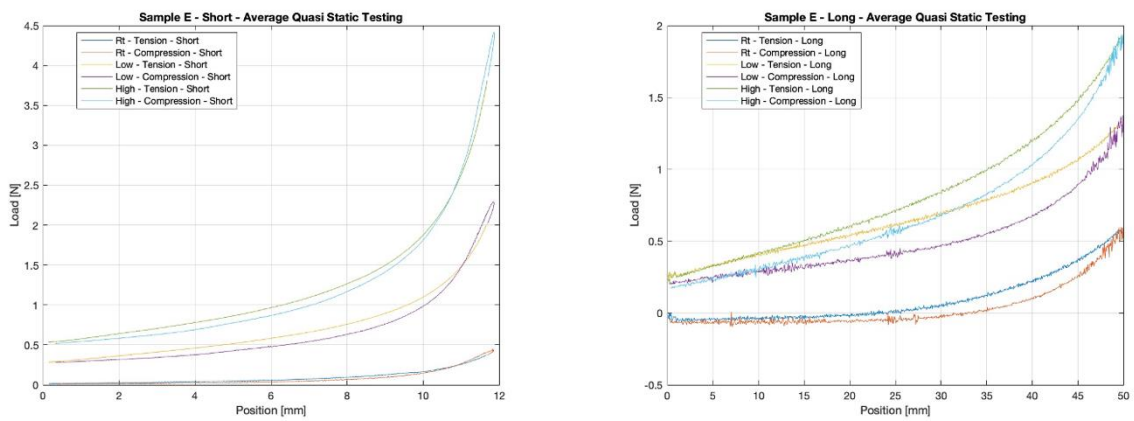


Figure 5.8: Comparison of Average Quasi-Static Results of the Sample E SMA

CHAPTER SIX

# 6. HINGE DESIGN

## 6.1 Introduction

When designing any origami system, one of the most important design decisions is the fold pattern selected. With respect to this project, selecting the right fold became even more important, as a single fold was to be designed to directly translate into a functional origami pattern while also acting as the bias force in this system. This section of this report will detail the design process associated with selecting the final fold used in this project, along with the justification of this choice. The final fold represents a solution that supplies a small-scale, highly manufacturable, and modular concept that can also be used as a bias force for the system. All of these aspects of the fold will be further explained in detail in this section. Additionally, this section will further expound upon the modularity of this hinge and how every decision made with respect to the hinge lends itself to a more modular design. This section will also briefly describe the material used, the material properties of the hinge, and the manufacturability of such a fold, as it relates to the specific material. Finally, this section will end with a detailed account of how the components of this fold were integrated and optimized to secure the most ideal overall design for this specific project.

## 6.2 Compliant Hinge Design

A complaint mechanism can be defined as a creased or folded apparatus that is made from non-paper materials. Compliant mechanisms function in such a way that allows for a localized reduction or expansion of stiffness [90]. Meanwhile, a hinge is defined as a

narrow rectangular region where localized bending of a fold can occur [45]. This project takes advantage of both concepts as it attempts to create a compliant hinge design that is easily manufactured and assembled through folding, offers a built-in bias force to the system through dimensioning of the fold, and represents a viable modular solution for future origami robotics applications.

### *6.2.1 Material Selection*

While the original intent of this project was to use paper to create a simple origami fold that could be integrated into several systems at a low cost, it became evident early in the project that a different material would provide more flexibility as far as the other components of the system were concerned. Although paper would have provided researchers with a small, inexpensive, and compact material that would ensure rapid prototyping, its lightweight and flammable nature provoked several issues with respect to the selected actuation source. With SMAs needing to be directly connected to the material of the fold, using paper became obsolete almost immediately, as joule heating of the SMAs would quickly burn through the paper. In addition to this, because helical SMAs provide a high block force to the system, a heavier duty, or stiffer material was required to promote actuation in general. However, while paper, silicon, and thin flexible sheets were too lightweight and provided little to no spring back force to the system, other materials such as PLA were too stiff and didn't offer the desired flexibility required for the cyclic actuation of a simple fold.

The back and forth of selecting a material that would fit the specific constraints of the shape memory alloy samples that were acting as viable solutions for this project added

a level of trial-and-error that was undesirable for this project. As one of the main goals of this project was to promote the utilization of a systematic method to design an active origami fold, rather than to use traditional trial-and-error methods to do so, it was established that the geometry of a compliant hinge would be designed and selected based on its theoretical material properties, instead of using pure guesswork.

Since it was assumed that no material would perfectly match the properties required from the SMA sample, it was established that the folded hinge would be designed and 3D printed to create specific solutions when required. That, along with the need to remove any guesswork from the design process, required the selection of the material for the fold to be made from only 3D printing capable materials had on hand. The on-hand materials included Nylon, TPU, PLA, and PETG. The selection of the material required research and a basic understanding of the material properties, along with smaller observational amounts of trial-and-error. But the amount of time spent in the material selection process was far less than if several different configurations of the material were selected, assembled, and tested for use.

Ultimately, TPU was selected as the material of choice for the fold that was to be created in this project. Of the materials found on-hand, TPU offered the most flexible and elastic solution. It also offered a material with a high elongation and tensile strength, abrasion resistance, and chemical resistance, for any applications that this fold might be used in. In the past, it has been established that specific folding patterns can lead to specific material properties of a system, including tunable stiffness and multistability [91, 92, 93]. Therefore, when designing the fold, the belief was that design strategies could be made to

make a flexible material stiffer, but it would be more difficult to make a stiffer material more flexible. Therefore, the material eventually used to create the single origami fold for this project was 3D-printed thermoplastic polyurethane, or TPU.

### *6.2.2 Hinge Development*

Several sources in the field of origami robotics have discussed a localized reduction of stiffness in a hinge. It was found that these same methods used to reduce the stiffness value in a hinge could be used inversely to increase the stiffness value of a hinge as well. Since a more flexible material was selected, it was established that increasing the stiffness of the hinge would be the most important factor in creating an active working solution for the problem statement at hand. While folds traditionally offer a system a decrease in stiffness due to the reduction of thickness in the material, it was determined that increasing the thickness of a material in the location of a fold could increase the stiffness value of the system as well.

To design a compliant hinge that would work best within the constraints and parameters of this project, several different folds were considered. These folds included a simple miura-ori fold, a groove joint, and a simple-reduced area fold, amongst others [90].

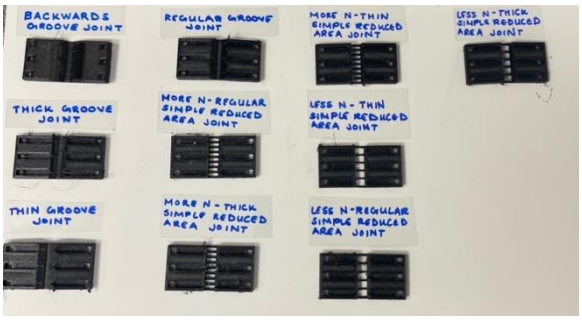


Figure 6.1: Possible Hinge Types

In addition to altering the stiffness of the fold, decisions relating to the ease of manufacturability, integration of sensors, actuation method, and the modularity of the system were considered with respect to the selection of the fold used. While the miura-ori fold allows for the easiest manufacturing method of the three folds presented and has the complete ability to provide multistability to a system then be packed completely flat, it didn't offer as much modularity as the other two folds would. Alternatively, while the simple reduced area fold provided a large variability for any number of systems and stiffnesses, it didn't allow for the opportunity of integrated sensors, if an application required them. Therefore, a simple groove joint was selected for this project.

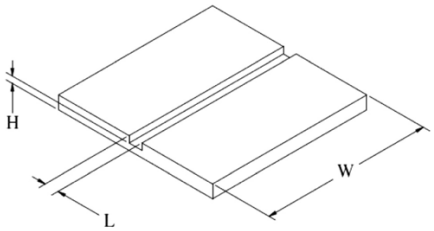


Figure 6.2: A Simple Groove Joint

A simple groove joint would allow for the integration of sensors and actuation methods, it could be translated into several different working origami applications, and its stiffness value could be easily altered based on a simple set of equations. The simplicity of this fold is attractive in that it can truly be integrated into several systems for several different applications while still providing flexibility and variability to the system's designer. For this specific application, the simple groove joint was the perfect solution for the hinge, as it is great for projects with small deflections and rejects almost all torsion,

lateral bending, shear, compression, and tension, allowing for a designer to simplify a system with a large number of other components with several variables [90].

### *6.2.3 Implementing a Bias Force*

Along with the requirement of the hinge to offer a greater stiffness to the flexible material used in this project, there was also a need for the stiffness of the hinge to be great enough to offer a spring-back, or bias force, to the system to enhance its actuation speed. One of the main drawbacks associated with shape memory alloys is that they are relatively slow to actuate. The reason for this is that once an SMA is actuated and in its heated austenite phase, it requires a specific amount of time to return to its lower martensite temperature. Typically, a cooling source or heat sink can be used to hasten this speed. However, when one is not included in a system, like in this project, other methods must be used to hasten the speed mechanically. In certain microscale applications, where cooling sources are hard to implement, bias forces can be used to spring an SMA to its martensite position, even when it remains in its austenite phase [92]. While it isn't common within the field to include a bias force with small-scale applications, a bias force could theoretically be used to provide the same result in this small-scale application that has been seen in previous microscale applications.

Traditional bias forces operate similarly to traditional helical coil springs, which is why a bias force is often described by its ability to offer a spring-back force to a system. For this specific application, the choice of the bias force to be used was a difficult one. In most of the previous projects performed within this field, bias forces were used in microscale applications, and scaling those solutions did not provide viable options in this

project due to the large discrepancies in geometry patterns or robot shape. Additionally, any bias force that would be included would provide additional components that would take up space in the system. Even the smallest torsional springs proved to be bulky and got in the way of the actuation method selected for this project. Even if a bias force could've been chosen that wouldn't have interfered with the helical SMAs selected to actuate the system, it was likely that it would directly interfere with any integrated sensors or the free stroke of the system. Therefore, it was decided that the bias force would have to be provided by the folded hinge itself. While this is not something that has directly been done before, origami offers bistable material properties due to its complex geometries. Folding in general, with respect to origami, has illustrated that different stiffnesses can be harnessed through different types of folds, which provided enough proof-of-concept to proceed with using the hinge as the bias force in the system.

While the proposed systematic design method was utilized for most of this project, small amounts of trial-and-error were required to design the perfect hinge for this application, which was to be expected. Once the final SMA was selected, its stiffness values were used to create a series of hinges that could fit the constraints set by the SMA. This series of hinges allowed for slight variabilities that were to be expected from joule heating, the integration of all materials, and the continuous actuation of the system. With many variables, it is impossible to predict the exact stiffness that might be required by the hinge, despite any previously completed mechanical testing of the SMAs. But reducing the time spent in other aspects of the design process, limiting the design fixation traditionally implemented through most design methods, and using mechanical methods to logically

solve this problem, allowed for more trial-and-error to be performed to select the proper hinge solution for this application.

One of the main advantages of selecting the simple groove fold as the fold for this project was that it provided the least number of variables that could be changed in the hinge design process. This lower number of variables permitted for a more reasonable amount of trial-and-error to be completed, allowing for the hinge design to not be such an overwhelming part of the design process. Following a selection of a single SMA for this application, and this reasonable amount of trial-and-error, a specific hinge design was accepted for the final solution of this project.

## 6.3 Modularity

Another of the main goals of this research project was to introduce and integrate modular design concepts into origami systems. In the past, origami robots have been made individually, on a case-by-case basis, for specific projects. While this has worked for tailoring the design of an origami robot for its explicit application, it becomes difficult to learn and create from them for different projects, as every application is slightly different. The modularity of this mechanism became an important consideration at every step of the design process. While there were other components, such as the power source and actuation method, that could be made smaller or less complex up until this point of the project, introducing modularity to the system was almost fully reliant on the housing unit of the actuation source. Everything about the fold itself, from its material to its size, had to be considered for use in several different applications within the field of origami robotics. In

addition to that, the fold had to be designed so that it could be directly translated from one fold pattern to the next.

Several design characteristics were integrated into the design of the fold to ensure that it could act as a building block in several different applications. One of the main design considerations of this fold was its simplicity. The simplicity involved in selecting a simple groove joint fold would provide support to several origami fold patterns, as the shape of the fold surfaces could change to accommodate for specific patterns, but the properties of the hinge could remain the same. Additionally, even when the fold shape changes, having a consistent hinge would allow for other researchers to easily identify the material properties of the hinge, as it is ruled by relatively simple equations. Another important design decision that was made to ensure the modularity of this fold was the fact that it was made from a flexible material. Having a hinge that is made from flexible materials allows for the fold to be reversible, and theoretically would allow for the fold to work as both a crease and a valley bend, which are the fold types commonly found in origami systems.

One of the most crucial design decisions made, with respect to making this fold modular, was the method of integrating either sensors or the actuation method. Like in other projects, it was decided that the fold would be created from a flexible hinge and two thick panels [93]. While the thickness of the panels had to be kept to a minimum, having thick surfaces on the fold would allow for any required integration of sensors and actuators, so that the inside space of the fold did not include any bulky components, leaving the fold free to actuate with a large stroke, if need be. Using thicker panels for the fold would allow for small cutouts to be made so that the actuation method components could be integrated

seamlessly and without any adhesion methods. The cutouts made in the fold would also allow for different actuation components to be interchanged quickly into the same housing unit. Ultimately, these cutouts would allow for a single fold to be used in many applications, with a large number of SMA components, by way of quick and seamless transitions between components and environments.

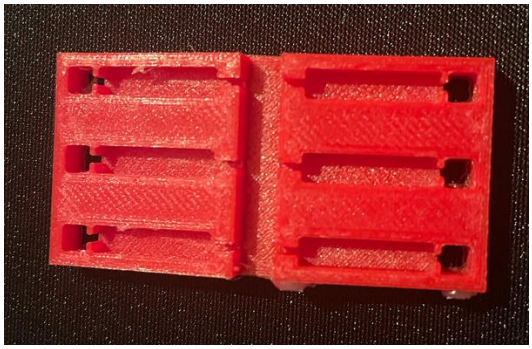

Figure 6.3: Cutouts Designed into Each Fold for Crimped SMAs

Although sensors were not used for this specific application, the same cutout method used for the SMA integration could be used for the sensors, adding to the modularity of the system. In addition to that, the material is lightweight, waterproof, and highly durable, for use in virtually any application requiring SMA actuation in origami systems. While this fold would likely be limited to actuation methods that are more compact, it can be scaled up or down with ease, and the same design could be used with other sources of actuation.

## 6.4 Manufacturability

While a defining characteristic of origami is folding, folding is also known as a well-established and relatively simple manufacturing method which can be used in several different applications to create complex three-dimensional geometries [101, 102]. Folding

traditionally offers advantages such as reduced material consumption and higher strength-to-weight ratios to whichever application they are used. In a similar way to other folding manufacturing methods, origami starts from a two-dimensional layer and is transformed via folding to a three-dimensional structure [34]. It is due to the crossover of folding in manufacturing and folding in origami, along with the ease of fabrication, that origami robotics has gained popularity in several different industries.

When designing any system, manufacturability is a factor that should be considered at each stage of the design process, and the design of origami robots is no different. While following a systematic design method, with each decision made about the final components involved in an origami mechanism, a researcher must keep the logistics of manufacturability of those components in mind. Ideally, each component will be selected, designed, or changed to not only adapt to the system, but also to optimize the integration of all other components at the end of the project. Recently, there has been an increasing demand for the rapid manufacturing and fabrication of complex origami structures for use in several different industries [91]. When fabricating an origami system that can be easily manufactured, the goal is to create a system that can be inexpensive and quickly replicated. To create an easily replicated system, decisions must be made at each step of the design process to ensure that every component, and the entire working system, can fit most cost and time constraints.

Keeping manufacturability in mind, it was important in this project to limit both the money and the time spent to fabricate a compact solution for a high-speed origami fold, as it would increase the modularity of the system. In the case of this project, this origami fold

represented a very inexpensive solution that could be used in many origami systems. The cost of this system would be limited to only the materials used in each fold. Including any electrical components, shape memory alloys, and the 3D printed TPU, it is predicted that the cost of each fold would remain under $10, making this a very simple, yet cost-effective solution for a variety of origami-related projects. In addition to its cost-effective nature, setting up the system is a very seamless process, requiring less than a few minutes total to put all the components in place in the final fold. As far as human involvement required to setup the final hinge, minimal intervention is required.

The only drawbacks associated with the manufacturing of this fold solution would be the requirement of crimping the SMAs, if the project requires specific shape memory alloys to be used, and 3D printing a specifically designed fold. If no specific SMAs are required, pre-crimped SMAs can be purchased to cut down on the time spent in preparing SMAs for this modular fold solution. In addition to the lengthy crimping process required for certain applications, the only other time-consuming part of manufacturing this design would be the 3D printing process, as the time required to print one fold can take up to an hour, if the fold remains at a small-scale. However, printing, in general, can be considered an economical and rapid method of prototyping, compared to other methods [96].

The 3D printer used to fabricate the fold used in this project was an Ultimaker S5 printer. On this printer, each fold took, on average, 54 minutes to print. Once printed, however, assembly of the fold took, on average, 2 minutes to put together. While the crimping process varied in the length of time it required, it can be estimated that a single hinge could be completely manufactured for use in under an hour. While this might take a

little longer than a simple folding process, the modularity of this fold and its assembly time make it an attractive design for future projects involving origami fold patterns.

### 6.5 Design of the Final Hinge

Once sample E was selected as the shape memory alloy for this specific project, several hinges were created and used in conjunction with sample E to establish the most ideal relationship between the actuation source and the bias force offered from the hinge. If the hinge were too thin, it would provide no bias force to the system and the SMA, once actuated, would pull the fold in completely, allowing for no actuation. If the hinge were too thick, the SMA would not provide enough of a force to move the fold at all, restricting actuation. To ensure that some movement was made, the hinge would have to provide just enough of a spring-back force so that it could force the SMA back to its martensite shape once it was done being actuated. While theoretical calculations could have been made to establish the best hinge for this design, ultimately, the behaviors of both the hinge and the SMA would be different once actually integrated with one another. Therefore, a series of tests were performed to find the ideal match between the two. While trial-and-error was meant to be avoided with the use of the systematic design method proposed for projects such as these, it was established that a certain level of trial-and-error is necessary when it comes to integration and optimization of origami systems.

Fortunately, the previous selection of the SMA removed certain variables from the trial-and-error process and required that the only changing variables be the dimensions of the hinges for this compatibility testing. Several configurations were tested before the final

hinge configuration was selected. To test the compatibility of the different hinges, SMAs were integrated and powered in each hinge.

Figure 6.4: Testing Setup to Determine Hinge Stiffness

The response of the system was then observed by the researcher. If the hinge was too strong or too weak, it was discarded and the following test was performed with a weaker or stronger hinge, respectively. The compatibility testing was performed until two final hinges were selected as possible solutions for this project.

| | 40 Degrees | | 55 Degrees | | 65 Degrees | | 90 Degrees | | 105 Degrees | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Height | Width | Height | Width | Height | Width | Height | Width | Height | Width |
| TPU | 0.55 | 2 | 0.55 | 2 | 0.55 | 2 | 0.55 | 2 | 0.55 | 2 |
| TPU | | 3 | | 3 | | 3 | | 3 | | 3 |
| TPU | | 4 | | 4 | | 4 | | 4 | | 4 |
| TPU | | 5 | | 5 | | 5 | | 5 | | 5 |
| TPU | | 6 | | 6 | | 6 | | 6 | | 6 |
| TPU | 0.65 | 2 | 0.65 | 2 | 0.65 | 2 | 0.65 | 2 | 0.65 | 2 |
| TPU | | 3 | | 3 | | 3 | | 3 | | 3 |
| TPU | | 4 | | 4 | | 4 | | 4 | | 4 |
| TPU | | 5 | | 5 | | 5 | | 5 | | 5 |
| TPU | | 6 | | 6 | | 6 | | 6 | | 6 |
| TPU | 0.75 | 2 | 0.75 | 2 | 0.75 | 2 | 0.75 | 2 | 0.75 | 2 |
| TPU | | 3 | | 3 | | 3 | | 3 | | 3 |
| TPU | | 4 | | 4 | | 4 | | 4 | | 4 |
| TPU | | 5 | | 5 | | 5 | | 5 | | 5 |
| TPU | | 6 | | 6 | | 6 | | 6 | | 6 |
| TPU | 0.85 | 2 | 0.85 | 2 | 0.85 | 2 | 0.85 | 2 | 0.85 | 2 |
| TPU | | 3 | | 3 | | 3 | | 3 | | 3 |
| TPU | | 4 | | 4 | | 4 | | 4 | | 4 |
| TPU | | 5 | | 5 | | 5 | | 5 | | 5 |
| TPU | | 6 | | 6 | | 6 | | 6 | | 6 |

| | |
|---|---|
| | Too weak |
| | Too strong |
| | Possible |
| | Would Work |
| | Not Tested |

Figure 6.5: Hinge Configurations Tested for a Final Solution

Once two hinges (TPU groove joints with lengths of 25 mm, heights of 0.85 mm, widths of 4 mm and 5 mm, and angles of 55 degrees) were found that would work well with the SMA chosen, the same testing was performed using image processing software, to further analyze the response of each system.

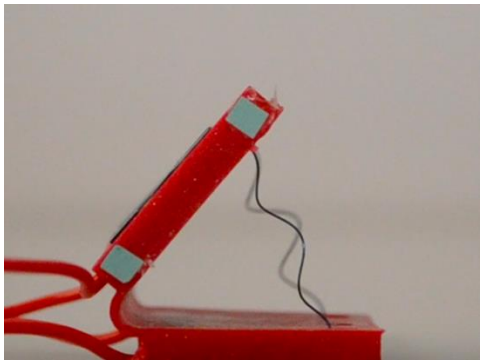

Figure 6.6: Hinge Testing Setup for Image Processing

The response of the system was measured by the speed of actuation, the free stroke angle measures, and the cyclical behavior of the SMA within the configuration. Once the data was further analyzed for the most ideal selection of the two hinges, the final hinge (simple groove joint with a length of 25 mm, width of 5 mm, and height of 0.85 mm) was selected and paired with sample E to create a high-speed, compact, modular origami fold solution.

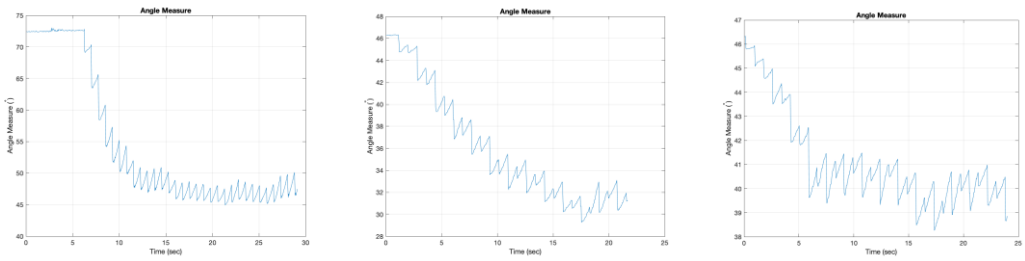


Figure 6.7: Response Curves of the SMA-Hinge Configuration found through Image Processing

CHAPTER SEVEN

# 7. CONCLUSION

## 7.1 Introduction

To conclude this project, each of the several different components (i.e., the power source, actuation method, and hinge) were combined into one simple fold to present a single modular solution to the problem statements set at the very beginning of the project. This section of the report will detail the process of integrating all the components of this design into one final fold. It will also briefly examine the final solution, expand upon any optimization that occurred, and elaborate on any issues that ensued upon integration of all components. An argument made for the proposed systematic design method will be made. Any results specific to the final solution will be presented, and a discussion of these results will follow. To conclude this paper, intended future work and recommendations will be made to establish a clear trajectory for both systematic design and modular components within the field of origami robotics.

## 7.2 Integration and Optimization

At each step of the design process, components were selected, modified, and optimized so that they could present the fastest, smallest, or most powerful solutions to the specific problem they were trying to address. However, the optimization performed on the components at each step of the design process doesn't completely transfer over to the final solution. Oftentimes, singular components tend to perform differently on their own than they do in the overall system. Typically, constraints that come from integrating different components to form one final solution might require a designer to go back and either

change the components or change different factors of the overall apparatus. While optimization is imperative for each of the components, to present the best solution to each smaller part at the end of the project, optimization is often required again after the components are all integrated with one another.

### *7.2.1 Integration*

This project included several different components that would eventually come together and create a high-speed, compact, and modular fold for applications in the field of origami robotics. Namely, the main components utilized in this project were the actuation method, the power source, and the hinge. For the actuation method of this project, thin, helical shape memory alloys were selected as the means of stimulating movement in the system. These were selected because they provided a compact, lightweight, and inexpensive solution for the goals of this project. The shape memory alloy selected from the group of samples presented at the beginning of the project was found to be the one that fit the project's constraints of size, material properties, and strength in the best way compared to the other available samples. Similarly, the power source selected had power ratings that would provide and surpass the power necessary to actuate the system. In addition to having a power rating that would provide enough power to actuate the shape memory alloys by joule heating, the power source itself was compact, lightweight, and capable of being connected to the selected controller. The last main component that was selected for this project was the hinge. The material of the hinge was selected because it was lightweight, flexible, and easily manufacturable and configurable for any number of applications. The hinge itself also had great material properties and provided a bias force

to the system. On their own, each of the components solved the specific problems that they needed to solve. The actuation method was compact and easily used in a small modular system, the power source was able to supply the necessary current and voltage to the actuation method, and the folding hinge was able to effectively house the system's components while providing a bias force to the actuation method.

Due to the systematic design method used, integration and assembly of each component with one another required only a few steps. Once the fold itself was printed and the SMAs were crimped, assembly of all the components, once they were prepped and ready to be integrated into the final fold, took less than two minutes total. To begin, two SMAs were taken by their crimped portions (the portions with the Dupont female connector pins) and placed into both sides of both surfaces of the fold (either the right or the left), with the SMA spanning the diagonal of the fold. Once the SMAs were inserted into the hinge, breadboard connector wires were inserted into the Dupont connector pins and then connected to the power supply assembly. Once everything was properly assembled, actuation could begin as soon as power was supplied to the system. Overall, assembly and integration of the components to the system required very little interruption of the flow of the project, as design decisions were made early on to ensure the successful integration of all the components in the system.

### *7.2.2 Optimization*

As mentioned previously, once integration occurs, additional optimization is typically required to ensure that the best solution is selected for the intended application. This project was no different. Although the components were optimized at each step of the

systematic design method, once the components were put together, certain constraints become more stringent and certain components begin to behave differently once put under and unexpected load or an unforeseen environment. For this project, it was decided that multiple SMA wires would be used at once to increase the speed of actuation within this system. However, once integrated, the selected hinge was too weak for two SMAs, as it was only tested using one. Therefore, a new hinge had to be selected for use in the final system so that it was strong enough to provide enough spring-back force for two SMAs, rather than one. The selection of a new hinge, however, required a different actuation speed of the two SMA wires, as the hinge was now strong enough for the alternating current speed to be hastened just slightly. Once it was established that the hinge could provide more of a bias force to the system, the entire Arduino code had to change to ensure that the SMAs were moving at the proper speed for the components in the system. Following these small adjustments, the system was ready to operate fully and without much further intervention.

Although optimization was necessary once the components were integrated with one another, changes were slight, and optimization of the system was relatively simple, due to the optimization performed in all other previous steps. This served to illustrate that the proposed systematic method was useful in eliminating the large amounts of trial-and-error that are normally seen in typical design methods within this field.

### 7.3 Results and Discussion

At the start of this research project, several motivations were outlined. These motivations included embedding compact actuators into origami, introducing modular

design to origami robots, and improving upon currently used design methods in the field. Once the project had begun, additional motivations such as understanding the material properties of SMAs and implementing them without a cooling source were investigated. Throughout the project, these motivations were considered to use systematic design and SMAs to enhance actuation of modular, high-frequency origami robots.

### *7.3.1 Embedding Compact Actuators into Origami*

The method involved in embedding compact actuators into origami was simple. Research was performed to understand different advantages, disadvantages, and methods of actuation that would present the greatest number of solutions to the constraints outlined for this project. For this specific project, the two largest constraints regarding the actuation method were its compactness and its speed. First and foremost, the actuation method needed to be compact and easily embedded into a small origami fold. Secondly, the actuation method needed to be as fast as possible, to promote high-frequency folding in origami robots. To satisfy the first of these constraints, shape memory alloys were selected out of several different methods to be the actuation source used in this project. SMAs provided a compact solution that were not only easily embedded into the system, but also promoted a high force, stroke, and variability to the system. While it was more difficult to satisfy the high-frequency constraint, most other actuation methods considered did not have the ability to remain compact, making SMAs a valid choice, despite their lower actuation speed.

To embed the SMAs into the overall system, each SMA was cut and crimped according to the size requirements set forth by the folding hinge configuration necessary

for this project. These requirements were defined by the overall size of the fold and what the angle measure of the hinge was to be for a particular application. To accommodate for the embedding of the SMA, this folding hinge was equipped with cutouts specific to the crimping method used, with tolerances that would allow for easy assembly without the use of an adhesive to connect the pieces together. Altogether, the selection of a compact actuation method, the crimping method, and the design of the hinge itself all contributed to the ability of embedding these compact SMAs into the origami fold of this project.

### *7.3.2 Introducing Modular Design to Origami Robotics*

As a continuation of embedding the SMAs into the origami fold, the motivation of introducing modular design to origami robots was furthered through optimization of every component of this system. Within this system, every active component was optimized with the intention of providing proof-of-concept that the general components could be altered for use in several different applications in the future. By optimizing each of these general components for this specific use, it was illustrated that the same could be done for any project that uses this folding hinge for an origami robot. The idea behind creating a simple origami fold was that it could be used in the future as a building block for different origami systems and that the components illustrated in this project could be used or slightly modified for use in other applications.

Methods of increasing the modularity of this folding hinge that were previously discussed included crimping the SMAs to ensure that they were more easily powered and embedded into the system and designing the hinge so that crimped SMAs could easily be interchanged and locked into place from application to application, depending on the

requirements for each project in which it is used. Aside from those methods of making this a more modular design, other components such as the power source and wiring used to actuate the SMAs were made smaller in size, once a solution was found, so that these components could be easily transferred from one application to the next, without compromising their capabilities. In addition to that, the material for the hinge was specifically selected to act as a built-in bias force of the system, so future projects only need to change the dimensions of the hinge to achieve the stiffness values that they require, rather than implementing entirely new system parameters associated with an external bias force. Finally, the hinge was created in such a way that sensors could easily be integrated into the system with the same method used in this project for the crimped SMA wires. Through design and 3D printing methods, the shape of the sensor can easily be designed into the hinge, in the same way the cutouts were used for the crimped SMAs. This would keep the system small and could easily represent a valid solution for integrating sensors in any project, depending on the sensor systems required.

Within this field of origami robotics, in the past, there have been no attempts to increase the abilities and use of modular designs. Typically, projects done in this field have been completed from start to finish, with each component and system created taking a new shape, style, and performing differently than any other project made before. However, these start-to-finish projects can take a very long time and often result in a lot of failure through trial-and-error. Instead, the implementation of modularly designed components, at least in certain aspects of this field, could provide a more timely and cost-effective solution to allow for further investigation to be done in this field with respect to actuation methods

and the bistability of origami patterns, rather than the fabrication of an application-specific robot. Within this field, origami robots have been created as application-specific solutions. To date, no author has reported an attempt to create a modular fold, or "building block" for origami robots.

### *7.3.3 Improving Upon Current Design Methods*

Typically, the research done within this field has been done through small adjustments made to previous solutions or through extensive trial-and-error processes that result from the lack of a consistent design method. Within this field, two different methods of design have traditionally been used: direct and inverse design. Direct design is defined as a process that includes designing and integrating components into a previously established origami pattern, where inverse design includes creating an origami pattern from a set of components. While both have worked in the past, new discoveries in this field are limited to small adjustments or time-consuming trial-and-error processes. This study aimed to find a new method of creating origami robots, one that could work for a vast array of origami patterns, components, and actuation methods.

Through extensive research into current methods used to fabricate origami robots, a new, systematic design method was created to assist with easily fabricating origami robots in future projects. Rather than highlighting the importance of the components or the origami pattern, as is done in inverse and direct design, respectively, this systematic design method emphasizes the importance of the actuation method. This design method can be used with several actuation methods, origami patterns, and components, and allows for a researcher to keep each piece of a system in mind as the other parts are being created,

optimized, and assembled. This systematic design process encourages less trial-and-error and allows for a deeper understanding of each component and how they contribute to the overall system. To date, this is one of the only proposed systematic design methods within this field. It is also the only systematic design method in this field that highlights the importance of the actuation method, rather than the origami pattern or the other individual components of an origami robot.

### *7.3.4 Implementing Shape Memory Alloys Without a Cooling Source*

The goal of implementing SMAs as a high frequency actuation method without a cooling source became a motivation of this project after the actuation method was selected. Once SMAs were selected, it was realized that they are rarely used in small-scale applications. Typically, SMAs are either used in microscale applications without a cooling source, or large-scale applications with a cooling source [97]. The main drawback of using SMAs as an actuation source is that they are an incredibly slow method of actuation, compared to other sources. SMAs require heating to a specific transition temperature to actuate, but then must return to their original temperature before a full actuation cycle can be completed. Unfortunately, due to this, any application requiring SMA actuation is completely limited by the time it takes to allow an SMA to return to its original temperature after heating.

However, adequately predicting and modeling a system based on the time required to return an SMA to its original temperature, combined with the unpredictability that comes with possibly overheating an SMA is difficult to manage. Typically, any use of an SMA at anything larger than a microscale is combined with a cooling source or heat sink. In

previous projects, the addition of a cooling source has increased the response time of the SMA significantly. But, while the implementation of a cooling source would have ensured actuation of high frequency in this project, it also would have significantly decreased the system's modularity by increasing the size of the assembly. Increasing the size of the system and requiring a cooling source would effectively limit the number of applications that this modular fold could be implemented in. Rather, designing a system that can address the problem of speed from a design standpoint presented a more modular solution.

Therefore, design was done at a small-scale, so that specific design parameters could be changed and scaled for any system. Once an understanding of the material properties of shape memory alloys was established, it became evident that the design of the system would contribute the most to hastening the actuation speed of the shape memory alloys in this system. First, the system was designed with small, thin, helical wires, which would allow for a large free stroke and block force with a greater surface area that could allow for faster heat dissipation. In addition to this, SMAs with a lesser transition temperature were selected for use in this project. A lower transition temperature would require a lower amount of energy to actuate the system, but also a decreased amount of time to return the SMA to its ambient temperature, compared to a higher transition temperature.

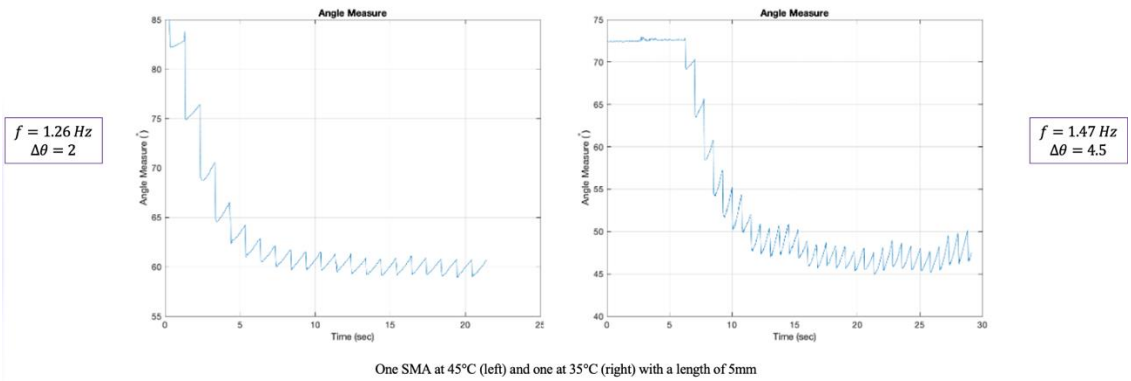


Figure 7.1: Comparative Results of SMA-Hinge Configurations Due to SMA Temperature Changes

In addition to selections made with respect to the actuation source, once a specific shape memory alloy was selected for use in this project, it was discovered that pulsing high electric currents and alternating actuation through multiple SMA wires could increase the overall actuation speed of the project. By quickly pulsing a current through the SMA wires in the configuration, to allow them to briefly meet just above their transition temperature, the SMA wires would actuate for just long enough to provide movement to the system. Then, the current flow would stop and the SMA would be allowed to return to its lower temperature state. Pulsing the current by quickly turning it on and off proved to prevent overheating in the wire and proved to be faster than maintaining a higher temperature for longer than allowing the SMA to return to its temperature. Once it was discovered that pulsing an electric current would be useful in decreasing the time it took to fully actuate the system, it was found that alternating actuation between multiple wires would allow for continuous actuation of the system and more down time for each SMA to return to its lower temperature state. This worked in such a way that when one SMA was being heated, the other could decrease its temperature, and vice versa.

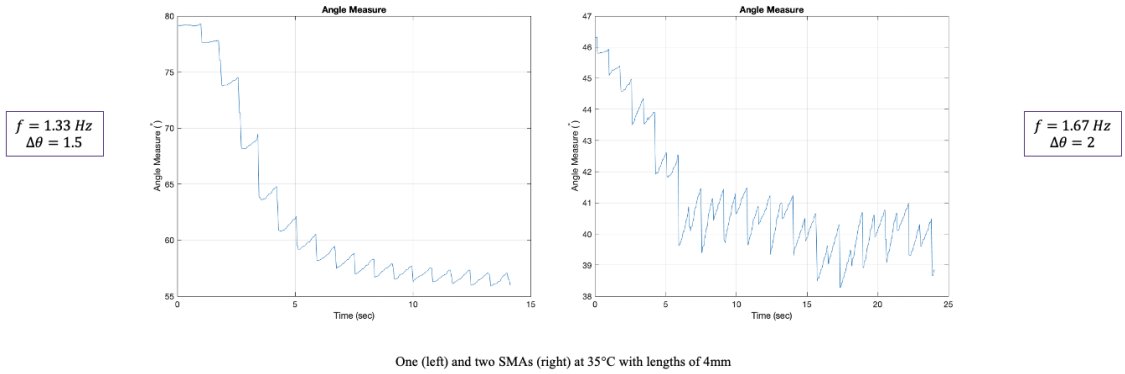


Figure 7.2: Comparative Results of SMA-Hinge Configurations Due to Changes in SMA Quantity

Finally, the last method used to increase the speed of actuation of this system was to implement a built-in bias force. This bias force would effectively act as a coil-type spring, which would spring the hinge back to its starting position, even if the SMAs were still heated and trying to compress the space between the surfaces of the fold. The bias force was made to be just stiff enough that it would allow for the SMAs to return to the shape characteristic of their lower temperature phase, even while they were in their high temperature phase. This promoted movement even when the SMAs had not returned to their original temperatures.

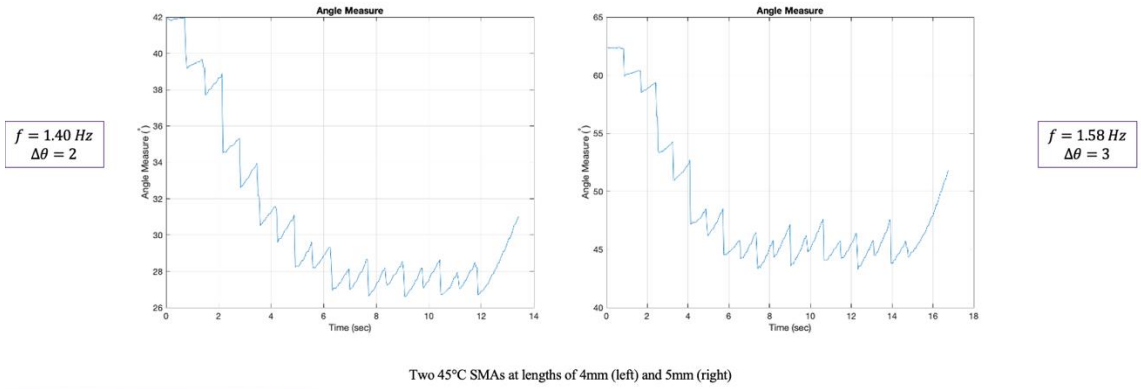


Figure 7.3: Comparative Results of SMA-Hinge Configurations Due to Changes in Hinge Size

Overall, these factors did effectively hasten the actuation speed of the final hinge configuration, compared to the same setup with none of these design considerations implemented. To date, a combination of design considerations has rarely been used to hasten the actuation speed of an origami robot. Typically, heat sinks, cooling sources, and one method of design is used to make the actuation of these systems faster. This project presents the first known opportunity that combines several considerations on a small-scale to improve the actuation frequency of the system, without an active cooling agent.

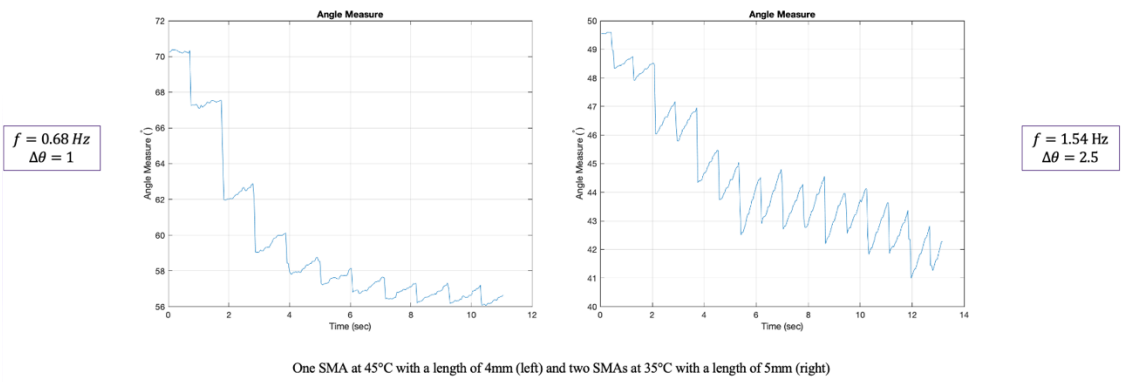


Figure 7.4: Comparative Results of SMA-Hinge Configurations With No Design Changes and All Design Changes

Altogether, it was found that these methods did increase the actuation speed of SMAs within a simple fold, compared to SMAs in a configuration with no mechanical design parameters used to assist in increasing actuation speed. While it was believed that the actuation frequency would be around 3 Hz, the actual actuation frequency of the final hinges remained around 1.5 to 2.3 Hz, illustrating a limitation in the frequency able to be achieved by SMAs without a cooling source in general. While this limit has rarely been discussed, this project provides proof-of-concept that SMAs are limited by the time required for them to reach their martensite temperature. While mechanical design did help

with increasing the frequency of these systems slightly, SMAs require a specific amount of time to cool, especially in applications larger than those of a microscale. When tested under the same conditions with a cooling source, the actuation frequency and free stroke effectively doubled in almost every assembly tested.

For this project, a true balance between free stroke and actuation frequency was managed in the final solution. To achieve a high stroke (around 11 degrees), the actuation frequency would remain lower (around 0.9 Hz) at a small-scale. However, to achieve a higher actuation frequency (around 2.5 Hz), the free stroke would become lower (<1 degree). The final solution selected was chosen because it represented a middle-ground regarding both free stroke and actuation speed. The final solution selected achieved a frequency of 1.67 Hz and a free stroke of around 3 degrees.

## 7.4 Future Work and Recommendations

While this project opened the door to systematic, modular, and high-frequency design considerations that could assist in creating an origami robot, there are still several stones left to be unturned. Although this project presented a solution that could implement modular design within the field, this did not provide an all-encompassing solution that could be immediately integrated into any origami pattern to create an origami robot. Future work within this field might consider integrating a sensor into this design so that the responses of a particular fold within an origami pattern can be recorded and observed. In the future, work done with shape memory alloys within this field might consider other possible design considerations, such as embedding additional SMAs into each fold and alternating a high current between even more SMAs. Another project might take the form

of combining several of these folds to create a single origami system and integrating SMAs into specific folds to move the entire system at once with a minimal amount of power and assembly with SMAs. There is still a lot to be explored within this field, specifically in relation to compact, modular, and high-frequency design constraints.

It is the recommendation of this work that future projects implement several design characteristics to hasten the speed of their actuation methods, regardless of the selected actuation method. It is also recommended that a systematic design approach be used to assist in the design process of any type of origami system, with components such as the actuation method, sensor components, application, and origami pattern kept in mind at every major design decision. Finally, it is recommended that future origami projects implement factors of modular design to their solutions for the direct spread of information to others within the field. Ideally, this direct spread of information will allow for greater contributions, resulting in more diverse discoveries and novel applications in which origami robotics can be used to change the way the world operates.

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