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Ph.D. Dissertation of Engineering

Deployable Soft Composite Structures with Morphing and Shape Retention

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Abstract

Deployable Soft Composite Structures with Morphing and Shape Retention

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In this dissertation, the possibilities of systematically designing and constructing deployable soft composite structures utilizing smart soft actuators composed of shape memory alloy (SMA) based smart soft composites (SSCs) as the basic elements are proposed and explored.

The first part of the dissertation describes the working principles of SMA based SSC actuators and presents new basic actuators that are suitable for implementation in deployable structures. The base SSC actuator design is extended from simple bending actuators to hinge actuators and linear actuators. A brief mathematical model is described to predict the deformation of the proposed SSC actuators. These actuators with diverse and large deformation
are simple to fabricate, inexpensive, lightweight and simple to actuate. Based on these advantages, soft robots such as crawling robots and compliant gripper are designed and evaluated.

In the second part, a structure based on the variable stiffness principle is integrated into the SSC actuator which can enable the proposed composite actuator to both produce a soft morphing motion and to have shape retention capability. This is accomplished by embedding low-melting-point material with heating components in a SSC actuator structure. The stiffness variation of the actuator is accomplished by melting the embedded low-melting-point material using heating components embedded in the structure. The actuator can then retain its deformed configuration with the variable stiffness structure in the high stiffness state after the low-melting-point material structure is solidified.

In the third part, deployable structures are proposed using the proposed actuators with stiffness reversible property as the basic element of the assembly. This basic actuator can be used to form modules capable of different types of deformations, and these modules can then be assembled into deployable structures. The design of deployable structures is based on three principles: design of basic actuators, assembly of modules and assembly of modules into large scale deployable structures. Various deployable structures such as a segmented triangular mast, a planar structure comprised of single-loop hexagonal modules and a ring structure comprised of single-loop quadrilateral modules are designed and fabricated to verify this approach.

The final part of the dissertation is a study of tiling techniques for use as a reference for the construction of planar deployable networks based on the
proposed SSC hinge and linear actuators. A general approach to construct planar deployable networks has been proposed which can be divided into three steps: selection or design of suitable tiling, design and validation of joint connections, and construction of networks. Several possible configurations have been discussed and verified using the assembled structures.

**Keywords:** Deployable structure, smart soft composite, shape memory alloy, reversible/variable stiffness, bending actuator, tiling

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Preface

The work presented in this dissertation was carried out at the Department of Mechanical and Aerospace Engineering at Seoul National University during the period from September 2012 to February 2016.

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“You crown the year with your bounty,
and your carts overflow with abundance”.

Seoul, February 2016
Wang Joshua Wei (王伟)
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Chapter 1. Introduction

1.1 Deployable structures

Deployable structures are a unique type of engineering structures which can alter their geometry to meet practical requirements, accompanied with the advantages for storage, transportation, remote controllability and reutilization. Deployable structures are also known by other names such as expandable and extendible structures. Common examples of deployable structures are umbrella and its similar structures, bi-stable structures, some tensegrity structures, some origami shapes, inflatable structures and scissor-like structures. Most conventional deployable structures are generally composed of linkages where the elements are connected to each other using mechanical joints and, through the strategic positioning of these elements and connections, can accomplish a stable deploying process and maintain its configuration either in the folded or unfolded state. This generally leads to large-sized mechanisms and complex assembly processes that make them heavy, complex and high-cost.

However, there is currently significant interest in low-cost, lightweight, and compactly packable deployable structures for various types of missions, especially when the structure needs to be compact during a certain phase of the mission and easily deployable during another, such as space missions. Recent advances in functional materials and structures that are easy to control, inexpensive, and capable of continuous deformations have opened new doors for engineers to design deployable structures with compact systems. These advances have not only been driven by the aerospace industry, but also by industries in diverse fields such as rescue robots, architecture, and many more.
because this kind of structure enables the integration of multiple functions into a single design to make it interact more effectively with its environments.

To succeed in a truly integrated environment, deployable structures need to reconcile the inherently conflicting requirements of low mass, good shape adaptability, and high load-bearing capability although the available design solutions invariably carry intrinsic limitations. Therefore, to meet these requirements, deployable soft composite structure (DSCS) made of a type of adaptive composites with capabilities of both morphing and shape retention is proposed and developed in this research. Morphing structures with reversible or variable stiffness are an effective method to realize shape adaptation since they can realize large deformations at low stiffness and can maintain their shape at high stiffness. Therefore, structures with variable stiffness capabilities represent a promising solution for tackling the conflicting requirements of deployable structures.

1.2 Scope and aim

The aim of this dissertation is to develop basic soft actuators made of adaptive composites, and then, to explore the possibility of assembling and constructing DSCSs using the proposed basic actuators.

In this process, we first examine the existing SMA based soft actuators and extend the actuators to soft hinge actuators and soft linear actuators. Then we proposed the method to enable the actuators have reversible stiffness to be able to perform capabilities of both morphing and shape retention for the same actuator structure. After that, we concentrate on the possible ways to assemble
them to larger scale DSCSs. Finally, tiling technique is applied in construction of planar deployable soft composite networks.

1.3 Outline of dissertation

Chapter 2 presents a brief review of existing work related to this research, including classification of existed deployable structures, comparison of soft actuators, principles for structure with variable or reversible stiffness, and the mathematical tiling technique. The reason for including tiling is because it is used later in producing planar deployable soft composite networks.

Chapter 3 describes the design and working principle of the proposed shape memory alloy (SMA) based smart soft composite (SSC) actuators, including the existed SSC bending actuators, extended SSC hinge actuators and SSC linear actuators. The performance of the actuators are also evaluated as well as applications for related actuators are illustrated.

Chapter 4 focuses on the method to enable the actuators have shape retention capability with reversible stiffness because this property is useful and effective for deployable structures under both stored state and deployed state. This chapter is ended with further discussion and conclusions.

Chapter 5 is devoted to the construction of DSCSs using the proposed SSC hinge and linear actuators with shape retention. Different basic SSC actuators can be used to construct DSCSs based on three principles: design of actuators, assembly of modules and assembly of modules into large scale deployable structures. This study focuses on two types of structures often used in aerospace
applications: structures of deployable mast and structures of deployable reflector. Finally, an in-depth discussion ends this chapter.

Chapter 6 deals with the tiling technique and its application in construction of planar deployable soft composite networks (PDSCNs). Several prototype of the networks of SSC hinge actuator and linear actuator have been discussed and verified by the assembled structures.

The main contributions of the research are summarized in Chapter 7, together with suggestions for future work to conclude this dissertation.
Chapter 2. Review of Previous Work

2.1 Deployable space structures

Deployable structures are structures capable of large configuration changes that they can normally transform from a compactly stowed state to a large deployed state in an autonomous way. With many potential applications in space, a significant amount of research has been conducted in the field of deployable space structures over the past five decades. There are main two types of structures in aerospace industry being of linear deployable structures such as masts and booms, and planar deployable structures such as reflector antennas. Masts are a type of linear deployable structure typically used for separating electronic devices to reduce interference or supporting other structures such as solar arrays. Tensegrity masts is one type of such structure that they use cables instead of conventional struts where only the traction forces are applied [1]. The folding articulated square truss (FAST) was developed by using revolute hinges along the longerons with axes parallel to the sides of the square bays and two pairs of diagonal bracing cables on each face of the bays [2]. The able deployable articulated mast (ADAM) are developed that the spherical hinges positioned at the ends of the longitudinal members and the rigid lateral square rotates almost 90° during deployment by the same institute for applications requiring very long and stiff masts [3]. A large number of other ingenious truss concepts have also been invented such as the variable geometry truss [4] and the cable-stiffened pantographic mast [5]. Antennas are used not only for communication but also for ground-based observation and astronomical studies. The most common type of deployable antennas is the mesh antenna being available in many configurations with a reflective surface composed of a knitted
lightweight metallic mesh supported by different methods. The rigid-rib antenna (RRA) and the wrap-rib antenna (WRA) were developed in an umbrella-type concept with a central hub and parabolic ribs [6-8]. The AstroMesh antenna and the cable-stiffened pantographic deployable antenna (CSPDA) are developed by attaching paraboloidal networks to deployable frameworks [9,10].

Traditional deployable structures constructed by mechanical components such as linkages and joints show many obvious disadvantages such as massive mechanisms and complex assembling process. To solve these problems, deployable structures made of smart materials have been developing during past decades. Shape memory polymers (SMPs) and shape memory composites (SMCs) are of great interest for low-cost self-deployable structures. Potential applications for SMPs in space include deployable truss, solar arrays and reflector antennas [11-13]. Different SMC booms are already available, but their application has only been envisaged for non-astrophysics missions due to the facts of failing to deploy heavy structures, low deployable accuracy and post-deployment stability [14]. To avoid these problems, structures based on cold-hibernated elastic memory technology have been investigated that the original structure can be warmed and deformed into the temporary shape upon cooling; and it can be recovered by reheating and be rigidized by subsequent cooling [15]. By using this technology, the overall end-to-end process for designing, fabricating, deploying and rigidizing gossamer structures can be greatly simplified. Compared with SMPs, SMAs are still preferred for applications that require higher actuation forces and faster response. However, there are very few conceptual designs on SMA based deployable structures for aerospace applications.
2.2 Comparison of smart actuators

2.2.1 SMA based actuators
SMAs are metal alloys capable of thermo-mechanical characteristics due to martensite phase and austenite phase transition in the material which can be separated into two major mechanical behaviors as shape memory effect (SME) that the specimen exhibits a large residual strain, generally up to 7%, after mechanical loading and unloading that can be fully recovered as the temperature rises; the pseudo-elastic effect that a specimen reach a large strain after loading that is then fully recovered in a hysteresis loop after unloading [16]. SMAs exhibit characteristics such as large force-weight ratio, large life cycles, sensing capability, and negligible volume which can reduce the size, weight and complexity of mechanisms. On the other hand, SMAs usually show low energy efficiency and they are difficult to be precisely controlled due to the hysteresis associated to the material activation [17]. A relative small actuation strain of the SMAs hindering their further applications, therefore SMA springs with large stroke have been used for many biomimetic robots [18-22]. However, SMA springs are not easy to be integrated for applications with compact structure. Then, it is still possible to transfer SMAs’ limited deformation to the matrix’s large complex and continuous deformations by attaching SMA wires to a flexible structure externally or by embedding SMA wires in a soft matrix.

Through this method, SMA based soft actuators have been being developed with bending, twisting and bending-twisting coupled deformations. Brinson et al. proposed and built one of the most popular constitutive model for the behavior of SMAs [16] and then applied it to the bending of a beam through an externally positioned SMA wire [23]. A mold with theoretical results for SMA
reinforced composite beam with small bending deformation was developed [24]. A large bending actuator is early proposed by using a SMA wire placed inside a plastic tube embedded in a flexible beam and its related mathematical model was also developed [25]. The actuator with a large deformation using a pre-strained SMA wire embedded directly within the matrix was proposed and the Brinson model was applied to verify the results [26,27]. After that, multiple SMA wires had been embedded in a soft matrix for achieving bending in multiple directions [28,29]. Through embedding a thin incompressible plate in the matrix, the actuator structure can be designed with a small thickness for large bending deformation and a faster shape recovery [30-32]. Smart soft composites (SSCs) consisting of smart materials, an anisotropic material and a matrix is systematically proposed and developed with large and diverse continuous deformations [33]. Woven type SSC actuator with very thin thickness to generate large bending deformation was developed and applied for a small scale spoiler and winglet [34,35]. SSC twisting actuators were developed by embedding a pair of SMA wires in a polymeric matrix at constant and opposite eccentricity across the cross section in opposite directions [36-38]. Actuating different embedded SMA wires of the same actuator results in multiple types of deformation [39]. SSC twisting actuator embedded with a single torsionally prestrained SMA wire at the center of its matrix is also developed [40]. SSC actuator with coupled bending-twisting deformation with embedded angled fibers in the matrix inducing anisotropic properties and its application to a underwater robot is developed [41,42]. The properties and performances of the SSC actuators show that this kind of actuators have the potential possibility for the deployable structures of aerospace applications.
2.2.2 Other types of actuator

Shape memory polymers (SMPs) are chemically or physically crosslinked networks which are able to memorize a permanent shape and that a trigger such as heat and light will lead to a transformation from the deformed and fixed temporary shapes to the memorized permanent shape [43]. SMPs offer deformation to a much higher degree compared with SMAs due to a higher transduction efficiency with the cost of an increased response time. SMPs also show their inherent advantages of being cheap, lightweight, easy processability and being of biocompatible and biodegradable [44,45]. SMPs are capable of large deformations which make them as possible solutions for morphing aircrafts and deployable structures in aerospace applications [46,47]. There exists a lot of research using SMPs to design origami-inspired deployable structures. SMPs has been used to design a type of self-folding hinges to achieve localized and individually addressable folding to transfer a flat sheet into a functional three-dimensional shape [48-52].

Ionic polymer-metal composites (IPMCs) is ionic polymers in a composite form with a conductive medium such as a metal can exhibit large dynamic bending deformation under stimulation by a time-varying electric field [53,54]. IPMC actuators can be fabricated in curved shape with thermal treatment for the applications of biomimetic robots such as jellyfish robot [55]. By patterning the electrodes in multiple segments along the length, it is possible to enable the actuators with multiple degree-of-freedom (DOF) bending motions [56,57]. IPMC actuators with multiple electrodes fabricated by selective growth technique can achieve both bending motion and twisting motion [58-60]. IPMC actuators with a regular cross section having multiple insulated electrodes on surface can generate a biaxial bending motion induced by applying different
voltages to these four electrodes [61,62]. IPMC actuators is most comparable to SMA based soft actuators because that both of them are capable of large deformation with multiple DOFs and with multiple actuation modes.

Soft pneumatic actuators based on flexible elastomers with ballooning deformations by inflating eccentrically placed pneumatic networks are capable of large deformations with different types of motions such as bending motion [63,64], twisting motion [65] and contractile motion [66]. An alternative is to embed stiff but flexible structures in the elastomers to achieve a wide range of anisotropic motions under pneumatic inflation [67]. Flexible elastomers with distributed micro-pneumatic networks at the interface of two different elastomers can achieve complex 3D motions for robotic applications [68,69]. Other pneumatic actuator based robots such as gripper, hand and arm are also developed [70-72]. However, the pump used to provide the air pressure in the actuator limits their mobility and mainstream usage. Several soft pneumatic robots are developed with on-board pressure generation [73,74], but they are limited by the size or actuation speed.

2.2.3 Comparison
Since the mentioned actuators possess different working principles with different actuating characteristics, therefore, a qualitative comparison of their performance is shown in a radar graph of Figure 2.1, accompanied with the general requirements of deployable structures. From this figure, it can be seen that the SSC actuators with suitable designs for specific environments are able to fulfill the general requirements of deployable structures.
Morphing structures with variable stiffness are an effective method to realize shape adaptation since they can realize large deformations at low stiffness and can maintain their work configuration at high stiffness [75]. Therefore, structures with variable stiffness capabilities represent a promising solution for tackling the conflicting requirements of deployable structures. Fluidic flexible matrix composites (FFMCs) or inflatable structures that work by opening and closing their inlet valves and granule jamming (GJ) that can change from a flexible to a solid state after vacuuming can also achieve a wide range of stiffness [76-78]. Nevertheless, these kinds of structure are inseparably connected with mass appendants, which increase their integration requirements. Multi-stable structures (MSSs) with the advantages of large deflection capability without substantial actuation have a large potential for variable stiffness morphing applications, however, no in-depth applications are developed and their stability with controlled bucking has received very limited
Conductive elastomer which can rapidly and reversibly changes its mechanical rigidity when powered with electrical power has been embedded in a flexible matrix to create a composite structure with changeable module [80]. Nonetheless, the applied high voltage make this principle is not available for low-power applications. Various studies demonstrate variable stiffness structures by embedding phase changeable materials (PCMs) in a flexible matrix which can undergo a significant stiffness reduction by applying a temperature higher than its phase transition temperature to the embedded material and can be easily integrated with other types of structures [81-83]. However, this solution requires a relatively long transition time for both stiffness reduction and stiffness recovery because of the required heating and cooling times, which confines this type of structure to applications without strict time requirements. Although there are limitations, a number of applications such as deployable structures do not have strict time limits such that this type of structure presents significant potential for these applications. Since the mentioned principles for variable or reversible stiffness with different characteristics, therefore, a qualitative comparison of their performance is shown in a radar graph of Figure 2.2, accompanied with the general requirements of deployable structures. From this figure, it can be seen that the principle of PCM is able to fulfill the general requirements of deployable structures.

2.4 Tiling and patterns

2.4.1 General tiling and patterns
A plane tiling is a family of closed sets called tiles that cover the plane without gaps or overlaps. Tiling has other names such as tessellation, mosaics and
paving [84,85]. A pattern is a discernible regularity in a design that the elements repeat in a knowable manner. Tiling and patterns perhaps can be traced back the very early history of civilization that man began to select the shapes and colors of stones for constructions or decorations. The tiles could be either regular geometric shapes or irregular shapes such as shaped like animals and other natural objects. The art of designing the tiling and patterns is very early and well developed. On the contrary, the study for mathematic properties of tiling and patterns is comparatively recent and many research areas have yet to be explored in depth. A most systematic study of tiling and patterns can be found in Grünbaum and Shephard’s book [86].

2.4.2 Tiling by regular polygons
Tiling is usually represented by the number of edges of the regular polygons around any cross point in a clockwise or anti-clockwise order and its representing method is systematically described [87,88]. For instant, \((3^6)\) represents a tiling that each point is surrounded by six triangles, 3 is the number
of the edges of a triangle and superscript 6 is the number of triangles. In a similar way, \((3^4.6)\) means a cross point is surrounded by four triangles and one hexagon. \((3^6;3^4.6)\) means a 2-uniform tiling where there are two types of cross points of \((3^6)\) and \((3^4.6)\). Tiling composed of regular convex polygons can be classified into four types: regular and uniform tiling, \(k\)-uniform tiling, homogeneous and edge-transitive tiling, and tiling that is not edge-to-edge [87].

2.4.2.1 Regular and uniform tiling

There are three kinds of edge-to-edge tiling by unitary equilateral triangles, squares, and regular hexagons. Meanwhile, there exist eight different edge-to-edge tiling, also known as semi-regular tessellations, with more than one kind of regular polygon, but still having the same arrangement of polygons at every corner. In all, there exist eleven distinct edge-to-edge tiling where all the vertices are of the same types. They are \((3^6)\), \((4^4)\), \((6^3)\), \((3^4.6)\), \((3^3.4^2)\), \((3^2.4.3.4)\), \((3.4.6.4)\), \((3.6.3.6)\), \((3.12^2)\), \((4.6.12)\) and \((4.8^2)\), and some of these tiling as shown in Figure 2.3.

2.4.2.2 \(k\)-uniform tiling

A \(k\)-uniform tiling is an edge-to-edge tiling that its vertices form precisely \(k\) transitivity classes with respect to the group of all symmetries of the tiling. It is observed that uniform tiling coincide with 1-uniform tiling. There exist 20 different types of 2-uniform edge-to-edge tiling by regular polygons such as \((3^6;3^4.6)\), \((3^6;3^4.6)_2\) and \((3^6;3^2.4.12)\) where \((\_1)\) and \((\_2)\) denote two different arrangement of 2-uniform edge-to-edge tiling. These tiling are shown in Figure 2.4. Denoting \(K(k)\) as the number of distinct \(k\)-uniform tiling, \(K(1)=11\), \(K(2)=20\), \(K(3)=39\), \(K(4)=33\), \(K(5)=15\), \(K(6)=10\), \(K(7)=7\), and \(K(k)=0\) for each \(k \geq 8\).
Figure 2.3 The edge-to-edge monohedral tiling by regular polygons

Figure 2.4 Three different types of 2-uniform tiling
2.4.2.3 Homogeneous and edge-transitive tiling

A tiling by regular polygons is homogeneous if each set of mutually congruent tiles forms one transitivity class. Shown in Figure 2.5 are three such tiling where the first one is also 2-uniform, the second one is 3-uniform and the third one is 4-uniform. One vertex of each transitivity class is marked.

![Figure 2.5 Three examples of homogeneous tiling](image1)

2.4.2.4 Tiling that are not edge-to-edge

Some tiling by regular polygons without the requirement that the tiling is edge-to-edge are shown in Figure 2.6.

![Figure 2.6 Three examples of tiling that are not edge-to-edge](image2)
2.4.3 **Tiling by other geometries**

Irregular tiling can also be made from other shapes such as pentagons, polyominoes and in fact almost any kind of geometric shape such as with irregular interlocking tiles, shaped like animals and other natural objects. The *Hirschhorn tiling* proposed in 1985 is a pentagon tiling using irregular pentagons, because regular pentagons cannot tile the Euclidean plane as the internal angle of a regular pentagon is not a divisor of $2\pi$. No general rule has been found for determining if a given shape can tile the plane or not, which means there are many unsolved problems concerning tessellations [66]. Shown in Figure 2.7 are tiling by non-regular polygons.

![Figure 2.7 Three examples of tiling by non-regular polygons.](image)

2.4.4 **Summary**

According to the study of tiling and patterns, there are different ways to cover the plane with an identical units or combined units. However, not all the tiling and patterns are suitable for constructing planar soft deployable networks. It is worth noting that all the tiling and patterns can be considered as a unit tessellation in a repeated way. Meanwhile, the tessellated unit can be constructed by using the basic soft actuator in a feasible manner. The suitable
tiling and patterns for assembling planar soft deployable networks and the method for constructing tessellated units will be further discussed in Chapter 6.
Chapter 3. Basic Actuator Design

3.1 Overview

In this chapter, different types of soft actuator are investigated by embedding the SMA wires in polymeric matrixes with different configurations to achieve different modes of actuation deformations. The layout of this chapter is as follows. Section 3.2 presents the basic principles for a SMA based soft actuator with pure bending deformation. Subsequently, the proposed soft hinge actuator, and its performance and application are described in Section 3.3. The proposed soft linear actuator and its performance are illustrated in Section 3.4.

3.2 SSC bending actuator

3.2.1 Actuator description

SMA itself has limitation in the range of actuation by its strain with a maximum value of around 7%. To enhance the range of actuation, SMA wire as the smart material can be embedded in the soft polymeric matrix eccentrically with a distance of $d$ to the actuator structure’s geometrical neutral plane, as shown in Figure 3.1 (a). While actuating, the small contraction of the pre-strained SMA wire results in a large and continuous bending deformation of the actuator structure as shown in Figure 3.1 (b). That is, applying an electric current to the pre-strained SMA wire causes its temperature to go up through Joule heating and, when it reaches its austenite phase transition temperature, the SMA wire will start to contract. By contracting, the SMA wire produces a local contraction of the matrix at an eccentric plane within the actuator which produces a large
bending deformation of the actuator. After the SMA wire cools down below the austenite phase transition temperature, the actuator structure begins to recover to its original shape due to the elastic recovery force of the bended structure. The structural variation in SMA during the deformation process is shown in Figure 3.2.

Figure 3.1 Schematic of SMA based bending actuator

Figure 3.2 Phase transformation of SMA
3.2.2 Materials and manufacturing

Smart materials can be placed eccentrically from the neutral surface of the matrix structure with either smart material being placed towards one side or two sides to make the actuator capable of either unidirectional or bidirectional bending deformations. In this research, SMA wires are used as the smart material, polydimethylsiloxane (PDMS) elastomer as the flexible matrix, and acrylonitrile butadiene styrene (ABS) for fabricating the embedded rigid structure and actuator molds throughout all actuators, and all materials used are commercially available. The SMA wires used throughout this research are nickel-titanium alloy (Ni: 55 wt%, Ti: 45 wt%, Dynalloy) wires which have a good strain recovery capacity, stable transformation temperatures with a relatively high electrical resistance compared with other types of SMA wire [89, 90], its actuation temperature is above room temperature, but easily attainable through joule heating, and its range of actuation temperature is within the useful temperature range of the chosen polymer. PDMS (Sylgard 184, Dow Corning) is a translucent and flexible elastomer with low thermal conductivity and high thermal stability that can withstand the strain of the embedded SMA [91-93], but a number of other polymers, fabrics, composites and other flexible and elastomeric materials could also be used for the matrix. The main properties of the SMA and PDMS are shown in Table 1 and Table 2, respectively.

The fabrication of all the soft actuators in this research follows a general process as below, shown in Figure 3.3. In order to assemble and build the structure, an ABS mold is built using a 3D printer (Dimension 768 SST, Stratasys, USA) that positions the components within the matrix during curing of the PDMS. First, the pre-strained SMA wires and other to be embedded components are positioned within the mold. What is worth mentioning is that the previous
research has shown a micrograph of SMA wire embedded composites and it indicates that the actuation of SMA wire will cause different scale of local distortion to the composite hosts [89]. Because of the distortion and the large contraction stress of the SMA wire, both ends of SMA wire were clamped using copper connectors that are also embedded in the matrix to prevent sliding between the SMA wire and the matrix. Second, the PDMS solution with a weight ratio of 10:1 monomer and hardener is mixed, degassed in a vacuum casting pump and poured into the mold. The assembly is then placed in an oven at a temperature of 58 °C for 10 hours to cure the PDMS. This temperature was chosen because it is below the actuation temperature of the SMA wires. After the curing process, the specimen is taken out of the oven and the ABS mold is removed.

Figure 3.3 General fabrication process of SSC actuator

Table 1 Material properties and modeling parameters of SMA wires

<table>
<thead>
<tr>
<th>Description (parameter)</th>
<th>Value (Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martensite start temperature ((M_s))</td>
<td>42 °C</td>
</tr>
<tr>
<td>Martensite finish temperature ((M_f))</td>
<td>52 °C</td>
</tr>
<tr>
<td>Austenite start temperature ((A_s))</td>
<td>68 °C</td>
</tr>
</tbody>
</table>
Austenite finish temperature \( (A_f) \) & 78 °C \\
Martensite Young’s modulus \( (E_M) \) & 28 GPa \\
Austenite Young’s modulus \( (E_A) \) & 75 GPa \\
Martensite shear modulus \( (G_M) \) & 10.56 GPa \\
Austenite shear modulus \( (G_A) \) & 28.20 GPa \\
Poisson ratio \( (\nu_{sMA}) \) & 0.33 \\
Effect of stress on austenite temperature \( (C_A) \) & 10.3 (MPa°C⁻¹) \\
Effect of stress on martensite temperature \( (C_M) \) & 10.3 (MPa°C⁻¹)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDMS Young modulus</td>
<td>1.8 MPa (25°C)</td>
</tr>
<tr>
<td>PDMS Specific gravity</td>
<td>1.03 (25°C)</td>
</tr>
<tr>
<td>Useful temperature range</td>
<td>-45 °C to 200 °C</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Table 2 Material properties of PDMS

The minimum atmospheric temperature for proper functioning of the actuator is determined by the lower bound of the useful temperature range of the polymeric matrix, which is -45 to 200°C for the PDMS matrix used in this work. However, the maximum atmospheric temperature for proper functioning of the actuator is the temperature below which none of the embedded materials begin their respective transformation. These are the melting point temperature of the FA, 62 °C for Field’s metal, and the Austenite start temperature at which the SMA wires begin recovery, 62 °C for the SMA material used. Thus, using the proposed materials, the range of atmospheric temperature in which the actuator can be used is -45 to 70°C. What is worth mentioning is that the matrix material used in this research is polymeric elastomer, but a number of other polymers, fabrics, composites and other flexible and elastomeric materials could also be used. The SMA materials used in this research also can be changed by the one
with the required phase-transition temperature. Thus, the range of atmospheric temperature in which the actuator can be used could be changed to adapt for the actual external environment.

3.2.3 Mathematical modeling

The mathematical modeling is used to predict the bending deformation of the soft actuators by using Brinson modeling and Euler beam theory. From figure 3.1, the actuation force from the SMA wire deviating from the middle surface can be decomposed into a contracting force \( F_{SMA} \) applied on the middle plane to generate a contracting deformation, and a bending moment \( M = F_{SMA}d \) applied on the actuator structure to generate a bending deformation. In order to develop the model, the geometric shape of the bending section was approximated by a circular arc during actuation, which is assumed to behave as an Euler beam, and the distance \( d \) between the SMA wire and the geometrical neutral plane is assumed to remain constant throughout the bending deformation. Second, the strain of along the SMA wire was assumed to be equal throughout the actuator structure under stable states. Before pouring the PDMS during the fabrication process, the SMA wire is pulled by hanging a certain weight at the free end to obtain an approximate initial strain of 5%.

The first step in the model is to express the stress and the strain of the SMA wires as a function of the bending angle of the actuator. First, the longitudinal stress \( \sigma_{L,act} \) in the actuator can be expressed as a function of the force generated by sum of all SMA wires as follows:

\[
\sigma_{L,act} = \frac{F_{SMA}}{A_{act}} \tag{3.1}
\]
where \( F_{SMA} \) is the force generated by SMA wires and \( A_{act} \) is the area of the cross-section of the actuator. The longitudinal strain of the actuator is then expressed in terms of the longitudinal deformation of the actuator (\( \Delta L \)) and of \( F_{SMA} \), and the bending deformation of the actuator (\( \theta \)) as a function of \( M \) and the flexible length of the actuator (\( L_t \)):

\[
\varepsilon_{L,act} = \frac{\Delta L}{L} = \frac{\sigma_{L,act}}{E_{act}}
\]

\[
R\theta - (R - d)\theta = \theta d = (\varepsilon_0 - \varepsilon_{cur} - \varepsilon_{L,act})L_{act}
\]

\[
\frac{\theta}{L_t} = \frac{M}{E_{act}I} = \frac{F_{SMA}d}{E_{act}I}
\]

where \( \varepsilon_0 \) and \( \varepsilon_{cur} \) are the initial strain and current strain of the SMA wire, \( d \) is the distance between the SMA wires and the middle place of the actuator structure, \( E_{act} \) is the Young’s Modules of the actuator and \( I \) is the moment of inertia of the cross-section of the actuator structure, \( L_{act} \) is the total length of the embedded SMA wire. The stress in the SMA wire (\( \sigma_{SMA} \)) in terms of \( F_{SMA} \) is calculated as follows:

\[
F_{SMA} = n_{SMA} \sigma_{SMA} A_{SMA}
\]

where \( n_{SMA} \) is the number of the SMA wires embedded in the matrix and \( A_{SMA} \) is the cross-sectional area of each SMA wire.

The stress that the SMA wires are capable of producing depending on the strain
is calculated using an SMA constitutive model, which describe the relationship between the stress, strain, temperature and the crystallographic phase of the material. In this research, the one-dimensional Brinson model is used to model the behavior of the SMA wire [16,94]:

$$\sigma - \sigma_0 = E(\varepsilon - \varepsilon_0) + \Omega(\xi - \xi_0) + \Theta(T - T_0)$$  \hspace{1cm} (3.5)

where $\sigma$ and $\sigma_0$ are the current and initial stresses, $E = \xi E_m + (1 - \xi) E_a$ is the Young’s modulus of the SMA materials, $\varepsilon$ and $\varepsilon_0$ are the current and initial strains, $\Omega = -E \varepsilon_L$ is the phase transformation contribution and $\varepsilon_L$ is the maximum recoverable strain, $\xi$ and $\xi_0$ are the current and initial martensite fractions, $\Theta$ is the thermal expansion factor, and $T$ and $T_0$ are the current and initial temperatures. Assuming the initial stress to be zero, a negligible thermoelastic term and an initially fully martensite phase, we obtain:

$$\varepsilon = \frac{\sigma}{E} + \varepsilon_L (\xi - 1) + \varepsilon_0$$ \hspace{1cm} (3.6)

when the initial strain of the SMA wire is assumed to be equal to the maximum recoverable strain, equation (6) can be rewritten in:

$$\varepsilon = \frac{\sigma}{E} + \varepsilon_L \xi$$ \hspace{1cm} (3.7)

During the strain recovery of the SMA wire for the martensite to austenite phase transformation, its martensite fraction can be calculated as follows:
\[
\xi = \frac{\xi_0}{2} \left\{ \cos \left[ a_A(T - A_r) - \frac{a_A \sigma}{C_A} \right] + 1 \right\},
\]
(3.8)

for \( C_A(T - A_r) < \sigma < C_A(T - A_s) \) when \( T > A_r \). \( a_A = \pi / (A_s - A_r) \) is a curve-fitting parameter of material constant. The relevant modeling parameters and their values are shown in Table 1. The Modeling results of the SMA wire is shown in Figure 3.4, accompanied with experimentally obtained data at 100°C using an Instron 3343 universal testing machine with an environmental chamber to maintain the temperature. It is noticed that only the modeling of the SMA wire for the martensite to austenite phase transformation is described, because all the actuators’ actuation deformation is based on this phase transformation.

3.2.4 Application to soft crawling robots

To describe the performance of the SSC bending actuator further, the crawling robots were built using a biomimetic SMA-based SSC bending actuator capable of mimicking the looping gaits of the inchworm.

3.2.4.1 Inchworm-inspired robot

First, based on the biological analysis of the inchworm, the robot structure was designed and its locomotion was divided into two stages: an anchor-pull
Figure 3.4 Experimental data and model for stress-strain curve of SMA

locomotion and an anchor-push locomotion was proposed. The schematic of an inchworm is shown in Figure 3.5 along with a real inchworm with its longitudinal muscles contracted on the top left and a cross-section of the abdomen showing its main muscle structure on the top-right. The contraction of the longitudinal muscle fibers leads to a bending deformation of the body of the inchworm, which results in a shortening of its overall length. Then, by immobilizing the true legs and prolegs alternately, it uses a looping gait for locomotion. If the longitudinal muscle fibers are actuated symmetrically then the inchworm will undergo a linear locomotion, but if it contracts its longitudinal muscle fibers asymmetrically then the body will undergo a non-symmetric deformation which results in a turning locomotion using one of the feet as an anchor.

The robot structure was designed as a thin rectangular shape with a structure size of 196 × 140 × 4 mm (length × width × thickness). Figure 3.6 shows the
detailed design of the overall structure. In this figure, the 8 SMA wires are grouped in 4 different groups: SMA-front (SMA-front-1 and SMA-back-2), SMA-back (SMA-back-1 and SMA-front-2), SMA-left (SMA-left-1 and SMA-left-2) and SMA-right (SMA-right-1 and SMA-right-2), and the actuation of a group refers to actuating both corresponding SMA wires simultaneously. The SMA wires in each group are to be connected in series such that they are simultaneously actuated. The robot foot was segmented in sections with different friction coefficients with both ends being covered by PI film to reduce the coefficient of friction (COF).

Figure 3.5 Biological analysis of the inchworm

The robot structure was designed as a thin rectangular shape with a structure size of 196 × 140 × 4 mm (length × width × thickness). Figure 3.6 shows the detailed design of the overall structure. In this figure, the 8 SMA wires are grouped in 4 different groups: SMA-front (SMA-front-1 and SMA-back-2), SMA-back (SMA-back-1 and SMA-front-2), SMA-left (SMA-left-1 and SMA-left-2) and SMA-right (SMA-right-1 and SMA-right-2), and the actuation of a
group refers to actuating both corresponding SMA wires simultaneously. The SMA wires in each group are to be connected in series such that they are simultaneously actuated. The robot foot was segmented in sections with different friction coefficients with both ends being covered by PI film to reduce the coefficient of friction (COF).

![Inchworm robot structure](image)

**Figure 3.6** Inchworm robot structure

The experiences were conducted on a flat horizontal rubber mat at room temperature. For the linear locomotion of robot, all four SMA wires in the body were actuated simultaneously. **Figure 3.7** (middle) shows the robot at different steps of the locomotion with the shape of each feet shown on the left and right. The robot was actuated to move forward and then backward for five strides.
totaling 75 seconds each. The results showed that the effective average stride length was 54 mm during ten periods with a total distance of 540 mm in 150 seconds and a corresponding average speed of 3.6 mm/s with a linear locomotion efficiency of 96.4%. For the turning locomotion, the SMA wires were actuated on only one side of the body. Forty strides with a left turning locomotion were done by actuating only SMA-left to obtain a total turn of 90 degree equaling 2.3 degree per stride. The resulting locomotion of the forty combined strides is shown in Figure 3.8. In order to improve the turning locomotion efficiency of the robot, the experiments were repeated with the same robot where the low and high friction segment of the feet were interchanged by removing the PI film from the two sides of the foot and attaching a single PI film to the middle section of the feet. Using the same method, a left-turning motion was tested and took 21 strides to complete a 90 degree turn, so the average turning angle of the robot was determined to be 4.3 degree per stride with a turning linear locomotion efficiency of 39.7%.

3.2.4.2 Smart phone robot
Recently smart electronics taking many shapes and fulfilling diverse functions have been commercialized such as wearable electronics. Based on the inchworm-inspired robot, a soft morphing smart phone robot was designed and fabricated that is both lightweight and thin [95]. In order to design and build a smart phone robot capable of a high-level of interaction with humans are capable of being used in surveillance and communication, a smart phone (Samsung Galaxy SHW-M110S) was integrated with the crawling robot introduced previously. The smart phone is comprised of three main functional parts including the screen, main board and battery. The batteries’ voltage required to actuate the SMA wires and to run the smart phone is 7.4 V and 3.7 V respectively. Therefore, two batteries with a voltage of 3.7 V were used. The
Figure 3.7 Linear locomotion for one period

Figure 3.8 Turning for forty periods for a turning angle of 90 degree

position of the components within the structure is shown in Figure 3.9. The
electronics placed in the middle of the body are rigid and prevent deformation in this section. A custom PCB installed with an ATmega8 microcontroller and Bluetooth module was used to realize communication between the smartphone’s interface and the SMA wire controller. To realize the communication between the cell phone and the robot controller, an application built by App Inventor using a graphical interface was developed. The communication was established between the Bluetooth modules of the cell phone and the robot controller. The application is capable of sending commands for moving forward, backward, turning left, right and to stop either by pressing buttons on the screen or through voice command. The interface of this application is shown in Figure 3.10.

Figure 3.9 Integration of smart phone robot (a) All components and CAD model (b) Fabricated robot
The locomotion of smartphone robot was evaluated for five strides totaling 125 seconds with a total displacement of nearly 75 mm. The results show that the average stride length is 15 mm and the corresponding average speed is 0.6
mm/s. The linear motion for one stride is shown in Figure 3.11.

3.3 SSC hinge actuator

This section introduces the design of a SSC hinge actuator capable of a pure bending motion concentrated on specific sections of the actuator. This actuator makes use of a SMA wire in a PDMS matrix embedded with segmented rigid components. The bending deformation was accomplished by actuating the SMA wire embedded along the length of the matrix eccentrically from neutral surface.

3.3.1 Design and manufacturing

Since some segments of the actuator are flexible and others rigid, the bending deformation of the actuator is concentrated on the flexible segments of the actuator. The bending deformation of the proposed actuator is shown in Figure 3.12. In this figure, an actuator with a single hinge and two rigid segments is shown and, similarly, an actuator with multiple hinges can be manufactured by embedding multiple rigid components throughout the structure. Throughout this research, the length of the actuator will be referred as being the dimension parallel to x-axis, the thickness being parallel to y-axis, and the width being parallel to z-axis, where the deformation of the actuator occurs in the x-y plane. The manufacturing of the soft hinge actuators is mainly follows the general manufacturing process, the only different is that the rigid components are also built using the same FDM machine and are placed in the bottom of the ABS mold before pouring PDMS into the mold.
3.3.2 Actuator performance

3.3.2.1 Experimental setup

Experiments were conducted to understand the effect of different design parameters on the bending performance of the actuator. To do so, the dimension of the cross section of all actuators was fixed at 15×3 mm (width × thickness) and the distance between the SMA wire and the neutral plane of the actuator was fixed at 1 mm during the fabrication process. The bending angle \( \theta \) of the actuator is measured by placing the actuator vertically along the x-axis direction and clamping one end of the actuator. Then, the actuator was fully actuated by applying a fixed electric current for one minute such that no further motion can be detected. Then, the bending angle between the neighboring rigid segments of the flexible hinge is measured visually.

3.3.2.2 Effect of length of rigid segment

In the first experiment, the effect of the length of the rigid segment of the actuator on the bending capability is analyzed by keeping constant the length of the flexible segment at 20 mm and by varying the length of the rigid segments.
Three samples were fabricated for each configuration with total rigid segment lengths ranging from 0 mm to 160 mm in increments of 20 mm. Meanwhile, in order to determine the suitable current to actuate the hinge actuator, currents of 0.5 A, 0.6 A, 0.7 A and 0.8 A were applied to each configuration to determine the effect of the applied electric current on the maximum bending curvature. The results are shown in Figure 3.13 for the maximum bending curvature with different applied currents. For a current of 0.5 A, the maximum bending curvature of the actuators are much lower than other currents due to insufficient heating of the SMA wire to generate a maximum contraction force. For currents of 0.7 A or higher, it can be seen that the maximum bending curvatures is nearly constant which shows that the SMA wire is completely actuated. In addition, to prevent overheating of the SMA wire, a current of 0.7 A was used for subsequent experiments. Results also show that the bending curvature goes up along with an increase in the length of the rigid segments and that the corresponding bending angles goes up from 20.5° when there are no rigid segments to 121.2° when the length of the rigid segments is 160 mm with the applied current of 0.7 A.

Figure 3.13 Effect of length of rigid segment with different currents
3.3.2.3 Effect of length of flexible segment

The second experiment is conducted with the length of the rigid segment being kept constant and by varying the length of the flexible segment. The length of each rigid segment is fixed at 40 mm with a total length of 80 mm for the rigid segments. Three samples were built for each actuator with a flexible segment length ranging from 10 mm to 70 mm in increments of 10 mm. The results are shown in Figure 3.14 for the maximum bending curvature and its corresponding bending angle. The results show that a longer flexible segment length leads to a smaller bending curvature, but larger bending angle.

![Figure 3.14 Effect of length of flexible segment](image)

3.3.2.4 Effect of having multiple hinges

In the third experiment, actuators with a fixed length but with a varying number of hinges were tested. The total length of the actuator was fixed at 100 mm and three samples were built for each actuator with one to five hinges uniformly distributed along the length. The length of each hinge was fixed at 10 mm. As shown in Figure 3.15, the bending angle of the actuator can be calculated based
on the total bending angle of the actuator, or based on the individual bending angle of each hinge of which the average bending angle is used for comparison. The results for the total and average bending angles as well as the bending curvature are shown in Figure 3.16. According to the results, it can be seen that with an increase in the number of hinges, the bending curvature for each hinge decreases, but the total bending angle increases for number of hinges up to three and then remain constants for actuators with three to five hinges.

![Figure 3.15 Configuration of the two-hinge actuator](image)

3.3.2.5 Multiple hinges with same total length

The fourth experiment is similar to the preceding experiment with the total length of the actuator being fixed at 100 mm, but the sum of the length of all hinges is kept constant at 50 mm for any number of hinges. Therefore, the length of each hinge was 50 mm for the actuator with a single hinge, 25 mm for the actuator with two hinges, and 10 mm for the actuator with five hinges. The results for the total and average bending angles as well as the curvature are shown in Figure 3.17. According to the results, it can be seen that actuator containing more hinges have the same total bending angle, but that the bending angle of each individual hinge decreases. In this experiment, the bending
curvature of each hinge and the total deformation of the actuator are nearly constant regardless of the number of hinges.

Figure 3.16 Effect of number of hinges with same length

Figure 3.17 Effect of number of hinges with fixed total hinge length

3.3.3 Result comparison

The mechanical model was described to predict the bending capability of the
hinge actuator in Section 3.2.3. To assess the validity of the model and to compare the performance of the different configurations of the actuator, the performance for each group of actuation is compared against the values obtained from the developed model. The results for the maximum bending curvature are shown in Figure 3.18 (a) for the actuators with same length of flexible segment but increased length of rigid segments, in Figure 3.18 (b) for the actuators with the same length of the rigid segment but increased length of the flexible segment, in Figure 3.18 (c) for the actuators with a total length of 100 mm with different numbers of 10 mm-flexible-segment, and in Figure 3.18 (d) for the actuators with a total length of 100 mm with by different number of hinges whose total length is 50 mm.

From the test results shown in Figure 3.18 (a) and (b), it can be seen that the proposed model is able to predict that a smaller flexible length ratio of the hinge actuator will lead to a larger maximum bending curvature. As shown in Figure 3.18 (c) and (d), the model also predicts well that the number of hinges doesn’t have a significant effect on the maximum bending curvature of the actuator, and that it is the total lengths of all hinges which affects the bending curvature of the actuator. It can also be seen from the overall results shown in figure 6 that the experimental data and the modeling data are very well correlated. However, there are still some differences between the experimental data and modeling data, mainly when the total length of the flexible segments is small. This could be due to the deformed shape of the hinge actuator’s flexible segment caused by the contraction of the SMA wire. That is, the SMA wire will not follow the change of arc of curvature of the matrix to follow a more direct path.
Figure 3.18 Comparison of experimental and modeling results

3.3.4 Application to compliant gripper
The proposed SMA-based hinge actuator allows for significantly reduction in the weight, size and complexity of certain applications. In this section, a simple finger mechanism based on the hinge actuator with passively adaptive capability when grasping object was proposed and designed.

3.3.4.1 Gripper configuration
Passively adaptive capability of fingers is useful not only for obtaining a good fingertip grasping performance, but also allows for power grasping of the object using a single actuation mechanism [96]. From the previous experiments, it can
be seen that a small flexible length ratio will lead to a larger maximum bending curvature. Simultaneously, the flexible length should be not too short in order to obtain a larger maximum bending angle. In this design, the total length of each finger was fixed at 115 mm with the length of the embedded SMA wire fixed at 100 mm. Each finger actually contains two flexible segments with an equal length of 15 mm. The top view of the fabricated finger structure in the unactuated state is shown in Figure 3.19 (a). The gripper was designed to have three fingers in order to be able to grip a wide variety of objects, and an ABS finger nail with length of 7 mm was glued to the fingertip with a protruding length of 2 mm which allows for securing of small objects between the nail and the finger that could be hard to grasp using a normal fingertip grasp. The three fingers are mounted in a triangular pattern to a metacarpal plate with a fixed length of 25 mm for each finger, so that a pair of fingers sits in opposition to a third finger at an angle of 60° shown in Figure 3.19 (b). The three fingers were connected in series and were actuated using an electrical current of 0.6 A regardless of the target object to grasp in order to demonstrate its passively adaptive capability.

3.3.4.2 Task performance evaluation

To evaluate the passively adaptive capability of the gripper, fingertip grasping tests were first performed to grab hollow cylindrical objects with a large range of diameters of 1 mm, 3 mm, 5 mm, 20 mm, 40 mm, 60 mm and 80 mm. The manufactured objects are hollow and have a low weight in order to focus on the deformation shape of the fingers. The object with diameter of 1 mm is a copper tubule and other objects were built from ABS using the FDM machine used to manufacture the rigid segments. In order to maximize the chance of successfully grabbing the object, the fingers remain straight until positioned in
front of the object. Then, the gripper is actuated such that the position corresponds to the intended grasp. Based on the size and shape of the objects, the finger hinge will adjust its shape to complete the grasp. The fingertip grasping results for the different sized objects are shown in Figure 3.20. From the results, it can be see that the gripper can grab objects with a large range of dimensions by adjusting the bending angles of both hinges of each finger.

It can be seen in Figure 3.20 that the smaller diameter objects with diameters ranging from 1 mm to 5 mm can be only grabbed and secured by the gripper with the help of the fingernail, in particular in the case of the objects with diameters of 1 mm and 3 mm show in Figure 3.20 (a) and (b). However, objects with a diameter of 20 mm and above can easily be secured using a fingertip grasp and do not require the use of the fingernails. However, large diameter objects can be also grabbed by the gripper using power grasping. The second test was conducted to test power grasping of the cylindrical object with a diameter of 80 mm. Figure 3.21 (a) and (b) shows the fingertip grasping and
Figure 3.20 Grasping task for cylindrical objects with different diameters

Figure 3.21 Fingertip grasping and power grasping for the same object

power grasping results respectively. The contact zones were highlighted in orange on both sides of the object. From Figure 3.21 (b), it can be seen that
once the fingers have contacted the objects, the distal finger segment will cage around the object to complete the grasp.

### 3.3.4.3 Grasping force test

In order to compare the grasping capability between power grasping and fingertip grasping, an experiment was conducted where the gripper is installed to the previously used universal testing machine in order to measure the force generated by the gripper on a fixed object during an upward motion. The test begins by placing the gripper to execute a power grasp on a fixed cylindrical object with a diameter of 80 mm, as shown in the upper-right section of Figure 3.22. Then, the gripper is moved upwards using the universal testing machine while the gripper passively adapts its grasp from a power grasp to a fingertip grasp under uninterrupted actuation. During this process, the vertical displacement of the gripper is around 25 mm and the vertical pulling force generated by the gripper is shown in Figure 3.18, which shows that the gripper is capable of passively changing from one grasp to another depending on the situation and that the pulling force from power grasping is much bigger than that from fingertip grasping. From this figure, it can be also seen that the decrease in pulling force undergoes three stages according to the type of grasp. In the first stage, for displacements smaller than 5 mm, the pulling force is high due to having a complete power grasp on the object. In the second stage, for displacements between 5 mm and 10 mm, the pulling force decreases as the displacement increased. This shows that during this stage the grasp is passively changing from a power grasp to a fingertip grasp. For displacements larger than 10 mm, it can be seen that that gripper is fully in a fingertip grasp and that the pulling force gradually decreases due to the contact point of the fingertip grasp going up along the cylinder.
3.4 SSC linear actuator

This section introduces the design of a SSC linear actuator consisting multiple stages of bending actuators sharing a single embedded SMA wire. The bending deformation was accomplished by actuating the SMA wire embedded along the length of the matrix with opposite eccentricity for every two adjacent segments.

3.4.1 Design and manufacturing

Since every two adjacent segments of the actuator are interlaced, the actuator presents an undulating deformation after actuation. The configurations of a three-segment actuator before and after actuating are shown in Figure 3.23. In this figure, an actuator with three segments sharing one embedded SMA wire is described and, in a similar way, an actuator with more segments can be designed and fabricated. Throughout this research, the length of the actuator will be referred as being the dimension parallel to x-axis, the thickness being
parallel to y-axis, and the width being parallel to z-axis, where the deformation of the actuator occurs in the x-y plane. The manufacturing of the soft linear actuators is mainly follows the general manufacturing process, the only different is that the rigid scaffolds with small holes for placing the SMA wire are also built using the same FDM machine and are placed in the ABS mold before pouring PDMS into the mold.

Figure 3.23 Schematics of a three-segment actuator

3.4.2 Actuator performance
Experiments were conducted to understand the effect of different design parameters on the contracting performance of the actuator. To do so, the dimension of the cross section of all actuators was fixed at 10×2.5 mm (width × thickness) and the distance between the SMA wire and the neutral plane of the actuator was fixed at 0.7 mm during the fabrication process. The linear contracted length and the transverse expanded width are measured by placing the actuator vertically along the x-axis direction and clamping one end of the protruded SMA wire.
During the experiment, the effect of the number of segments of the actuator on the dimension variation is analyzed by keeping constant the total length of the actuator at 120 mm and by varying the segment number. Three samples were fabricated for each configuration with number of the segments ranging from 2 to 6. An experimental electric current of 0.65 A was applied to actuate all the actuator samples. The results of the dimension of the final configurations for different actuators are shown in Figure 3.24. From the results, after actuation, it can be seen that the actuator with 2-segment has a shortest length of 92.4 mm with a contraction ratio of 23% and a largest expanded width of 22.1 mm with a expansion ratio of 7.4 times.

![Figure 3.24 Dimension variation of linear actuator with multiple-segment](image)

The repeatability of the actuator with 2-segment was also evaluated with an actuating time of 5 s and a cooling time of 10 s. The actuator was hung vertically by fixing one end and a weight of 10 gram was suspended to its free end to obtain a faster length recovery. Forty cycles of the actuation is recorded and
shown in Figure 3.25. From the result, it can be seen that after around 15 cycles the actuator achieves a stable length contraction of approximate 15%.

![Graph showing length contraction over actuation cycles](image.png)

Figure 3.25 Repeatability test of the linear actuator with 2-segment

### 3.5 Summary

This chapter has presented different types of SMA based SSC actuator with different types of deformation, but with similar working principles and fabrication process.

The chapter started with a description of the basic bending actuators including working principle, general manufacturing method, mathematical modeling. The applications of the bending actuator to inchworm-inspired robots were presented. The second part of this chapter was devoted to the study of the SSC hinge actuator. First, the design and working principle was described. Then the performance of the SSC hinge actuators with different geometric parameters or
under different actuation conditions was evaluated. The experimental results were verified by the modeling results. An application to a compliant gripper was presented to end this part. In the third section, an SSC linear actuator consisting multiple stages of bending actuators sharing a single embedded SMA wire was described and its performances such as deformation and repeatability were also evaluated.

The work presented in this chapter has shown that it is possible to design different types of actuator with different types of morphing. The developed actuators are lightweight, with little implementation requirements, and capable of large deformation and passively adaptability, such that it has potential applications in a wide range of field. This mechanism can be also embedded with other mechanisms to generate a larger range of motion.
Chapter 4. Actuator with Shape Retention

4.1 Overview

This chapter describe a method to enable the soft actuator to be able to retain its shape in multiple configurations without continuous energy consumption by changing locally between a high-stiffness and a low-stiffness state. This was accomplished by embedding low-melting-point materials such as fusible alloy (FA), Ni-chrome (Ni-Cr) wires and SMA wires in a SSC structure. The soft morphing capability of SMA based smart soft structures allows the actuator to produce a smooth continuous deformation. The stiffness variation of the actuator was accomplished by melting the embedded FA structures using Ni-Cr wires embedded in the FA structure.

The layout of the chapter is as follows. Section 4.2 describes the design and manufacturing method to enable the soft actuator structure have the property of reversible stiffness. Section 4.3 investigates the actuators’ performance such as stiffness variation, shape retention capability of one and two segmented actuator. Section 4.4 applies the stiffness reversible principle to the soft hinge actuator. Finally, a conclusion is given in Section 4.5.

4.2 Materials and design

4.2.1 Materials

There are many materials with low melting point including thermoplastics, such as polycaprolactone (PCL), and fusible alloys (FA), such as Field’s metal,
Lipowitz’s alloy or Wood’s metal. In this work, Field’s metal (RotoMetals, Inc) with a melting point of 62°C was selected. This kind of FA is an eutectic alloy of bismuth, indium, and tin (32.5 wt% Bi, 51 wt% In, 16.5 wt% Sn) and was selected due to its high thermal conductivity, low viscosity in the melted state, high-stiffness in the solid state, its non-toxicity, its melting point falls within the temperature range of the PDMS matrix and is lower than the SMA’s Austenite starting temperature. In order to melt the FA structure, Joule heating of a Ni-Cr (80 wt% Ni, 20 wt% Cr) wire is used [97]. The Ni-Cr wire has a diameter of 0.15 mm and is covered with a polyimide (PI) tube (D. Soar Green, China), which has a good thermal conductivity and are electrically non-conductive, to prevent the current from going through the fusible alloy. The dimensions and material properties of the PI tubes are listed in Table 3.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>0.18 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.015 mm</td>
</tr>
<tr>
<td>Density</td>
<td>1.41×10^3 kg/m^3</td>
</tr>
<tr>
<td>Temperature limit</td>
<td>380 °C</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td>&gt;1.18×10^10 KV/m</td>
</tr>
</tbody>
</table>
| Heat conductivity coefficient | 35.0×10^-5 °C/cm |}

4.2.2 Design

The proposed actuator has a rectangular shape where two SMA wires, referred to as SMA-1 and SMA-2, are embedded in the PDMS matrix along the y-axis close to the upper and lower surfaces, as shown in Figure 4.1. Two symmetrical FA structures are placed in parallel to the SMA wires in the middle of the matrix. The relative position of all the components is shown in the schematic of cross-section A-A of the actuator in Figure 4.1. The actuation process to change from
one fixed shape to another is shown in Figure 4.2 with the actuation sequence for the Ni-Cr wires and the SMA wires shown in Figure 4.2 (a). During this process, the embedded FA structures are melted by applying current to the Ni-Cr wires from time \( t_0 \) until time \( t_1 \). Then, the current to the Ni-Cr wires is switched off and actuating either SMA-1 or SMA-2 from time \( t_1 \) to time \( t_2 \) will result in either an upward or downward bending deformation depending on which SMA wire is actuated. Then, current continues to be applied to the actuated SMA wire until time \( t_3 \) to allow the melted FA structures to solidify again. Figure 4.2 (b) to (e) shows the state of the actuator from time \( t_0 \) to time \( t_3 \).

![Figure 4.1 The actuator configuration and its components](image)

4.2.3 Fabrication

The SMA wires were clamped with connectors to connect with the conductive wire and to prevent relative sliding between the SMA wires and the matrix. The FA structure was built by casting using a three dimensional printed mold made from ABS. The ABS mold is manufactured by the same FDM machine. The
Ni-Cr wire covered with a PI tube is positioned in the mold and fixed mechanically using screws located on an external jig. The FA is pre-melted in a beaker at temperature of $90 \, ^\circ \text{C}$ in an environmental chamber, drawn into a syringe and injected into the mold as shown in Figure 4.3 (a). After injecting the FA into the mold and allowing the assembly to cool for 20 s, the FA structure is then removed from the mold and the structure shown in Figure 4.3 (c) is obtained. An enlarged view of the tip of the actuator is shown in Figure 4.3 (d) showing the positions of the Ni-Cr wire and of the PI tube within the FA structure. The Ni-Cr wires can be heated segmentally by removing a portion of the Polyimide tube around the Ni-Cr wire and by connecting the current to one end of the Ni-Cr wire and the other end to the FA structure. The schematics of the FA structure with a single segment and with two segments are shown in Figure 4.3 (b) where a current passing from A to C in the structure with two segments will melt the left segment of FA structure and an electric current passing from B to C will melt the right segment of the structure. By using the FA structure with two segments with a connector positioned at the halfway point of the SMA wire, it is possible to actuate only a portion of the actuator.

Figure 4.2 The proposed shape retention process
A second ABS mold made by the same FDM machine as the FA structure’s mold is used to manufacture the actuator. First, the two FA structures are positioned in the mold and mechanically fastened using bolts located on an external jig. Second, the two SMA wires with connectors are positioned in the mold with a certain pre-strain and mechanically fastened using bolts located on the same jig. Third, PDMS is poured into the mold. After the curing process, the specimen is taken out of the oven and the ABS mold is removed. The complete structure of the actuators with one SMA wire segment (upper) and two SMA wire segments (below) with overall actuator dimensions of 100 20 3 mm (length width thickness) are shown in Figure 4.3 (e).

![Figure 4.3 Fabrication process of FA structure and actuators](image)

### 4.3 Performance evaluation

#### 4.3.1 Structural variable stiffness characteristics

The variable stiffness property of the actuator stems from the difference in stiffness between the solidified and the melted FA structure. In order to quantify this difference in stiffness, the flexural property of the actuator was measured.
using a three-point loading test according to the ASTM D 790-03 standard test method. The test was done using a span-to-depth ratio of 16:1 on a tensile testing machine (5948 MicroTester, Instron) with a 3-point flexure fixture (2810-400, Instron).

4.3.1.1 Stiffness reduction: effect of electric current

To change the overall stiffness of the actuator, a series of electrical current of 0.2 A, 0.4 A, 0.5 A, 0.6 A, 0.8 A and 1.0 A were applied to the Ni-Cr wire to heat the embedded FA structures for a fixed time period of 90 s. By applying current to the Ni-Cr wire, the FA structure within the actuator heats up gradually and turns into the liquid phase. The stiffness of the structure decreases in parallel with this change in phase of the FA structure. It was determined through experiments that the structure neither yields nor breaks before the 5% strain limit of the testing method, therefore the flexural stress ($\sigma_f$) which can be calculated as in (4.1) is taken at the 5% strain limit.

$$\sigma_f = \frac{3PL}{2bd^{3/2}}$$  \hspace{1cm} (4.1)

where $P$ is the load applied to middle point of the specimen, $L$ is the supporting span of the three point bending test, and $b$ and $d$ are the width and thickness of the tested actuator specimen.

The results are shown in Figure 4.4, from which it can be seen that the decrease in flexural stress undergoes three distinct stages depending on the magnitude of the applied current. In the first stage, for a current smaller than 0.2 A, the flexural stress decreases very little due to insufficient heating of the FA structures to begin the melting process. In the second stage, for currents
between 0.2 A and 0.8 A, the flexural stress decreases when the current is increased, which shows that the FA structures change from an incompletely melted state to a completely melted state between these currents. For currents of 0.8 A or higher, it can be seen that the flexural stress is constant, which shows that the FA structure is completely melted.

Figure 4.4 Flexural stress of the actuator based on the applied current

In order to melt the FA structure faster, a higher current can be used to accelerate the increase in temperature of the structure. However, at both ends of the matrix, the Ni-Cr wire and the PI tube are in direct contact with the PDMS matrix, which has an upper temperature limit of 200 °C and the upper temperature limit of the PI tube itself is 380 °C. The temperature of the Ni-Cr wires should remain within the temperature limit of the PDMS and of the PI tube. In addition, a higher current will generate more redundant heat. To avoid these problems while still having rapid heating of the FA structures, a current of 1.0 A was selected for the Ni-Cr wires.
### 4.3.1.2 Stiffness reduction: effect of heating periods

Next, an experiment was conducted for different heating periods of the FA structure with an applied current to the Ni-Cr wires of 1.0 A. Tests were conducted for heating times ranging from 0 s to 60 s with time increments of 10 s to determine how long the Ni-Cr wire should be heated before actuating the SMA wires. A cooling time of 10 minutes was given between each test. The results are shown in Figure 4.5, from which it can be seen that the flexural stress becomes nearly constant for heating times greater than 40 s. This indicates that the embedded FA structures are completely in the melted phase. From the first two experiments, it can be seen that the flexural stress of the non-heated sample (3.34 MPa) is eight times that of the sample (0.41 MPa) after complete melting of the FA structures.

![Figure 4.5 Flexural stress of the actuator based on the heating time](image)

Figure 4.5 Flexural stress of the actuator based on the heating time
4.3.1.3 Stiffness recovery
The third set of experiments were conducted to test the cooling time of the actuator at a room temperature of 23 °C after continuous heating of the FA structures for 50 s at a current of 1.0 A, which was shown to fully melt the FA structure in the previous experiment. Experiments were conducted in increments of 30 s up to 300 s and in increments of 100 s from 300 s to 600 s. It can be seen from the experimental results shown in Figure 4.6 that the flexural stress of the actuator increases significantly with the cooling time until 240 s and is nearly constant afterwards. This indicates that it takes approximately 240 s for the structure to cool down completely.

![Figure 4.6 Flexural stress of the actuator with different cooling times](image)

4.3.2 Structural shape retention characteristics

4.3.2.1 Shape retention sequence
The actuating current for the SMA wires and the required current for heating of the Ni-Cr wires embedded in the matrix with diameters of 0.152 mm were
determined to be 0.55 A and 1.0 A, respectively. The time \( t_1 \) was determined to be 50 s in previous experiments and the time \( t_2 \) corresponds to the heating time plus the cooling time, which corresponds to 290 s based on the results of the previous experiments. Figure 4.7 (a) describes the time sequence of the actuator, and Figure 4.7 (b) to (d) shows the position of the actuator for bending in the left direction with different cooling times of \( t_0 = 0 \) s, \( t_1 = 50 \) s, \( t_2 = 290 \) s and \( t_3 = 1800 \) s. In Figure 4.7 (e), the positions of the actuator at times \( t_2 \) and \( t_3 \) are juxtaposed for comparison. From this comparison, it can be seen that there is a slight recovery after stopping the actuation of the SMA wire, which is mainly due to removing the bending force from the actuated SMA wire and from the recovery force from the unactuated SMA wire.

![Figure 4.7 Experimental results of shape retention sequence diagram](image)

### 4.3.2.2 Shape retention of two-segmented actuator

Section 4.2.1 described the shape retention sequence of a shape retention actuator with a single segment, which is capable of maintaining three configurations: straight, left-bending and right-bending shapes. By building a segmented actuator, it is possible to obtain an actuator capable of deforming into a greater amount of shapes of increased complexity and of retaining those shapes. Each segment is capable of having three configurations: straight, left-
bending and right-bending. Thus, depending on which segments of the FA structures is melted and which portion of the SMA wires is actuated, this actuator is capable of achieving $3^n$ final configurations where $n$ corresponds to the number of segments. In this section, an actuator with two segments as described in Section 4.2 was tested. The configuration of this actuator was shown in Figure 4.3 (e) (bottom). The nine configurations of an actuator with two segments were obtained experimentally using a heating time of 50 s with a current of 1.0 A and a cooling time of 240 s and are shown in Figure 4.8 where the two segments of the structures are shown in yellow and red.

Figure 4.8 Nine configurations of the two-segmented actuator

4.3.2.3 Reduction of energy consumption
In comparison with an actuator without shape retention capability, one of the main advantages of an actuator with shape retention capability is energy savings for long-term deformation of a structure since it does not continuously need an
applied current to maintain its deformed shape. To attain its deformed shape, the actuator must first melt the embedded FA structure, then deform itself and maintain its shape until the FA structure solidifies again. After this, no energy input is required. A similar actuator without shape retention capability would need a constant and continuous energy input. The energy consumption of SSC actuators with and without the proposed shape retention mechanism are calculated and shown in Figure 4.9. From these results, it can be seen that until approximate 425 s the energy consumption of the actuator with shape retention capability is bigger than that of the actuator without shape retention capability due to the energy required for heating the Ni-Cr wire being higher than the energy required for heating the SMA wire during the same period of time. After 290 s, the actuator with shape retention capabilities stops consuming energy and at 425 s the total consumption of both actuators is equal. After 425 s, the actuator without shape retention capability will continue consuming approximate 1.66 J/s while the actuator with shape retention capability will not consume any energy, it thus becomes beneficial to use an actuator with shape retention capabilities if the predicted time in the deformed shape is greater than 425 s.

4.3.3 Shape retained multiple configurations
The position of the end point is used in order to quantitatively describe the final retained shape of the actuator after cooling of the actuator for the different configurations. The final retained bending angle of the actuator can be determined theoretically and depends on the configuration of the actuator.

For an actuator with a single segment, the position of the actuator’s end point
Figure 4.9 Energy comparison of two different actuators

Figure 4.10 Schematics of one-segment actuator

$O_1$ with respect to the fixed point $O$ before actuation, as shown in Figure 4.10 (a), can be expressed using the homogeneous transformation matrix as in (4.2).

\[
H_{oo_1} = \begin{bmatrix}
1 & 0 & L_1 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(4.2)

In this matrix, the first two numbers of the last column are the coordinates of
the end point \((L_1,0)\) in the inertial frame. After actuation, as shown in Figure 4.10 (b), the coordinate of the end-point and the direction axes and fixed on the endpoint have a translation and rotation motion with a counterclockwise bending angle of with respect to the fixed coordinate of the fixed base point \(O\) and of its direction axes and . The distance \(L_2\) between the deformation tip of the actuator and the fixed base point of the actuator \(O\) can be calculated as in (4.3):

\[
L_2 = \frac{2L_1}{\theta} \sin \left(\frac{\pm \theta}{2}\right)
\]

(4.3)

where corresponds to the clockwise and anti-clockwise bending angle of the retained deformation shape for one segment. Then, the position of the actuator end point with respect to the fixed point \(O\) can be expressed using the homogeneous transformation matrix as in (4.4):

\[
H_{oO_2,\pm \theta} = \begin{bmatrix}
\cos(\pm \theta) & -\sin(\pm \theta) & L_2\cos(\pm \theta/2) \\
\sin(\pm \theta) & \cos(\pm \theta) & L_2\sin(\pm \theta/2) \\
0 & 0 & 1
\end{bmatrix}
\]

(4.4)

(4.2) and (4.4) are basic transformation matrixes. Therefore, for an \(n\)-segmented actuator, the end point position with respect to the fixed base point can be expressed as in (4.5) and the first two numbers of the last column of this matrix are the coordinates of the end point with respect to the inertial frame.

\[
H_{oO_n} = \prod_{i=1}^{n} H_{o_{i-1}O_i,\pm \theta}
\]

(4.5)
For the two-segmented actuator presented in this study, the nine configurations of the shape retention actuator were recorded using a camera and the coordinates of the middle points and of the end points were measured visually. The experimentally measured data and the predicted values obtained through the model are shown in Figure 4.11. In this figure, the nine configurations of the actuator obtained from the modeling are juxtaposed and shown with gray lines. In this experiment, only the in-plane shape retention capability of the actuator was tested. There are some errors between the experimental and numerical results which could be due to imprecisions in the properties of the actuator and the experimental measurement method, but the developed model corresponded well with the experimental data. The PDMS matrix material is much softer than the SMA material, so when actuating SMA-1 to achieve the maximum deformation, the distance from SMA-1 to the actuator’s neutral surface should be a little larger than d due to the SMA wire being able to deform slightly the matrix, and the distance from SMA-2 to the actuator neutral surface should be a little smaller than d. However, in the model, the distances were assumed be constant. In addition, the experimental data was obtained using a camera positioned manually, which could lead to some visual measurement errors.

4.4 Application to hinge actuator

The properties described in this chapter can also be applied on a hinge actuator, a linear actuator, and a large range of soft actuators with soft matrix to enable them possess both soft morphing and shape retention capabilities.
4.4.1 **Structural configuration**

The hinge actuator with shape retention capability is described as an example which also will be used in the following chapters [98]. A similar fabrication method is shown in **Figure 4.12**. The first step in the fabrication process of the actuator is to use 3D printing to fabricate the mold structure as well as the embedded rigid structure. The rigid structure itself also contains a sub-mold which, when assembled with a cover, allows for casting of the FA structure directly at its intended position on the rigid structure. This sub-mold has holes on both sides to allow for positioning of the Ni-Cr wire covered with the PI tube into the FA structure, as shown in Figure 4.12 (a). The FA is pre-melted in a beaker at temperature of 90 °C in an environmental chamber, and then the liquid FA is drew by a plastic syringe and injected into the mold. After 30s at room temperature, the ABS surrounding the FA structure is cut and removed using a knife, as shown in Figure 4.12 (b). Afterwards, the rigid structure containing the FA structure along with the SMA wires are placed in a second mold with small holes for positioning of the SMA wire. Both ends of the SMA

Figure 4.11 Modeling and measured coordinates of middle and end points
wires are clamped using copper connectors to prevent sliding between the SMA wires and the PDMS matrix. The PDMS solution with a weight ratio of 10:1 monomer to hardener is mixed, degassed and poured into the actuator mold containing all components, as shown in Figure 4.12 (c). The assembly is then thermally cured at a temperature of $55 \, ^\circ C$ for 10 h. The mold of the actuator is then removed to obtain the actuator and electric wires are connected to each end of the SMA wires, as shown in Figure 4.12 (d).

![Figure 4.12 Schematic diagram outlining fabrication of the basic actuator](image)

### 4.4.2 Structural performance

A hinge actuator with overall dimensions of $100 \times 15 \times 3 \, \text{mm}$ (length $\times$ width $\times$ thickness) is fabricated where the length of the hinge segment is $20 \, \text{mm}$. The dimensions of each FA structure are $40 \times 2 \times 2 \, \text{mm}$ (length $\times$ width $\times$ thickness) such that it has a $10 \, \text{mm}$ overlap with the rigid structure on each side to ensure a smooth bending deformation and a good stability under high stiffness and the configuration of the fabricated actuator is illustrated in **Figure 4.13** (a).
The actuator is capable of varying its stiffness by changing the phase of the embedded FA structures. An electric current of 1.0 A was applied to the Ni-Cr wire for 40 s to change the phase of FA structure from the solid state to the liquid state, resulting in the actuator switching from a high stiffness state to a low stiffness state. With a low stiffness, the configuration of the actuator can be changed easily through an external load, in Figure 4.13 (b). The actuator turns back to the high stiffness state after waiting for cooling of the FA structure through heat dissipation, and in the high stiffness state the actuator is capable of sustaining external loads, in Figure 4.13 (c). The bending modulus of the actuator structure was also tested under the two different stiffness states and result shows that the higher one has a bending modulus of 137.08 MPa and the lower one of 3.47 MPa, which corresponds to a ratio of approximately 39.5 times, in Figure 4.13 (d). If the actuator is folded in the direction where the
SMA wire is near the external surface of the actuator, applying a current of 0.6 A to the SMA wire and of 1.0 A to the Ni-Cr wire will result in recovery of the deformed shape to the original shape by making use of the elastic potential energy from the structure and the actuation force of the embedded SMA wire, in Figure 4.13 (e).

### 4.5 Summary

This chapter first described an SMA-based SSC actuator with variable stiffness properties which relies on FA structures embedded in a SSC actuator capable of both soft morphing and of retaining multiple shape configurations. By designing an actuator with multiple segments, this actuator can obtain and retain complex shapes. This is achieved by both changing its local structural stiffness and deforming the corresponding segments to deform locally the structure. The time for changing from highest stiffness to lowest stiffness of the actuator was determined as 50 s and that for the inverse process was determined as 240 s. Therefore, this method is suitable when there is no strict time requirements for changing the stiffness of structures. Later on, this principle was applied to soft hinge actuators. The advantage of this composite structure is that the properties of this structure can be tailored to its application by modifying the volume, position, geometry and composition of the embedded low-melting-point material structures. Applications for this type of actuator range from medicine science to transformable or dynamic mechanical structures.
Chapter 5. Assembly for Deployable Structures

5.1 Overview

This basic actuator can be used to form modules capable of different types of deformations, which can then be assembled into deployable structures. The design of deployable structures is based on three principles: design of basic hinge actuators, assembly of modules and assembly of modules into large-scale deployable structures.

Various deployable structures such as a segmented triangular mast, a planar structure comprised of single-loop hexagonal modules and a ring structure comprised of single-loop quadrilateral modules were designed and fabricated, as shown in Section 5.2, Section 5.3 and Section 5.4, respectively. Finally, a prototype for a deployable mirror was developed by attaching a foldable reflective membrane to the designed ring structure and its functionality was tested by using it to reflect sunlight onto a small-scale solar panel, as shown in Section 5.5.

5.2 Deployable triangular mast

5.2.1 Structural assembly

The basic hinge actuator presented in the last section can be used as a type of self-deployable linkage element with a hinge point that can be assembled as a module. These modules can then be assembled to form large scale deployable structures. To illustrate this concept, a module is first built by connecting two
triangular platforms through three hinge actuators using passive mechanical revolving joints, as shown in Figure 5.1. Folded state of the mast structure is shown in Figure 5.1 (a) and the components of the mechanical revolving joints are shown in Figure 5.1 (b). Fully deployed configuration of the structure where the motion range of the mechanical hinge is 90° is shown in Figure 5.1 (c).

Figure 5.1 Assembly of the triangular mast structure

5.2.2 Performance evaluation

The loading capability of the module is tested by using a universal test machine applying a load to the center of the upper platform when the hinge actuators are in a high stiffness state, as shown in Figure 5.2 (a) to (c). The stiffness of the module with the hinge actuators in the low stiffness state is not tested since the module cannot keep its deployed shape when the hinge actuators are in the low stiffness state and no current input is given to the SMA wires.

The capabilities of the module to self-deploy was then tested from the folded state to the deployed state. The initial condition of the module is when all hinge
actuators are fully folded at 180° and in the low stiffness state. If the three hinge actuators are deployed asynchronously, the upper platform will have three degrees-of-freedom (DOF) including two rotary DOF and one linear DOF with respect to the fixed bottom platform. Thus, the three hinge actuators should be actuators synchronously to ensure that the module deploys only in the linear direction. Therefore, the FA structures of the three hinge actuators were connected in series to melt the FA structure synchronously, and the SMA wires of the three hinge actuators were also connected in series to obtain a smooth linear deployment, as shown in Figure 5.2 (d). The height of the folded and deployed module are 30 mm and 130 mm respectively. Three such modules were then assembled in series to form a deployable mast, containing a total of nine hinge actuators, in order to test the potential for such modules to be assembled as a larger scale deployable structure. The mast was then deployed in the horizontal position from an initial state were all modules are in the folded state. It could be observed that the three modules of the mast deployed smoothly and synchronously, as shown in Figure 5.2 (e). The length of the folded and deployed mast are 82 mm and 379 mm, respectively, which shows that its deployable ratio is approximately 4.6.

5.3 Planar deployable structure

5.3.1 Hexagonal single-loop module
The simple hinge actuator and structures mentioned above can only change from the folded state to the deployed state while the full inverse transformation is not possible. This is due to the required length of the actuator to obtain a full range of actuation from the deployed state to the folded state combined with the limited length of the actuator. Based on our previous studies of hinge
actuators in Section 3.3, both the length of the flexible hinge and the length of the rigid segments should also be long, which is not possible with a limited length. To solve this problem, single loop modules composed of multiple hinged structures are presented that are capable of both deploying and folding transformations. The hinged structures are connected together at each ends using passive mechanical revolute joints to form a single loop module that can switch between the folded and unfolded states with a smaller available range of motion from the hinge structures.

Figure 5.2 Triangular masts and their deploying process
The hexagonal module consists of a six-bar mechanism with six revolving joints and three DOFs where two actuators with two hinges each form an hexagonal structures in the deployed state and a small structure in the folded state, as shown in Figure 5.3 (a). Although the structure has redundant actuation such that the number of hinge with actuation is more than the DOFs of the structure, since the structure is symmetric it can be smoothly and symmetrically deployed and folded when both actuators are simultaneously deformed, as shown in Figure 5.3 (b).

![Figure 5.3 Schematic of hexagonal single-loop module](image)

**5.3.2 Assembly for planar structure**

A hexagonal module based on the previously introduced design is created and tested to show its deploying and folding motion. The actuators used the module have a length of 190 mm and two uniformly distributed bendable sections spaced 80 mm apart with the length of each bendable section being 15 mm. When the hinge is in the low stiffness state, actuating SMA-1 or SMA-2 will
result in a deploying process or a folding process, with the folded, intermediate and deployed states shown in Figure 5.4 (a). The capability of these hexagonal modules to be used as tiles to form an extended planar deployable structure with a large area is investigated. Tiling is usually expressed by the number of polygons around any cross point in a fixed direction order. There are two possible shapes for edge-to-edge tiling of a hexagonal module, as shown in Figure 5.4 (b). Here, the first tiling configuration is chosen to demonstrate the capability of the proposed design due to the configuration of the single loop structure. Four hexagonal structures are assembled together to show the possibility for this structure to be expended as a large network in two planar directions. In the x-direction, the two adjacent hexagon structures are connected using scissor-like joints with a limited revolving angle of 120°, as shown in Figure 5.4 (c). Because of the scissor-like joints, the adjacent hexagon structures can be deployed interdependently and synchronously. In the y-direction, the two adjacent hexagon structures are bonded together through the rigid segment. Therefore, during the deploying process as shown in Figure 5.4 (d), the entire structure will expand in the y-direction coupled with a corresponding contraction in the x-direction. To further understand the motion of the assembly, the specific mechanical connections including two different kinds of joints of the structure are shown in Figure 5.5. The height of the structure expands from 45 mm to 224 mm and the ratio in height between the deployed and folded structure is approximately 5.
Figure 5.4 Deploying processes of hexagonal module and its assembly

Figure 5.5 Detail design of two different kinds of mechanical joints
5.3.3 **Deploying characteristics**

5.3.3.1 **Deploying force**

To estimate the deploying ability, the deploying force of the hexagon-looping module was measured. The experimental setup and its schematic are shown in **Figure 5.6**. The structure is fixed on the platform, and then, the actuator of the testing machine (Instron 5948) goes down from the deployed highest point progressively with 5 mm. After each adjustment, the hexagon-looping module will be actuated and deploy automatically until stopped by the testing machine. After each adjustment, a specific bending angle $\theta$ can be measured and then applied to the modeling. The, the vertical upward force $N$ will be measured and record. To model the vertical force, the force analysis of link 1 is also shown in figure 5.6 (b), then, it can be approximately obtained as:

$$ N = \frac{2M}{L \cos \theta} \quad (5.1) $$

![Figure 5.6 Experimental setup and force analysis.](image)

In fact, the torque $M$ is different from the bending moment at Section 3.2.2. The torque $M$ in this section is generated by the remaining stress that the stress from the SMA wire subtract the stress required for a bending deformation of $\theta$, as described in **Figure 5.7**. From the figure, it can be seen that a smaller $\theta$ results
in a larger stress difference causing a larger deploying force and a corresponding larger torque $M$. The experimental and modeling results of the upward deploying force of the hexagon-looping module is shown in Figure 5.8. Seen from the results, the experimental and modeling results fit well, however, with the reduction of bending angle $\theta$, the measured force starts to be levelled off which could be due to the low stiffness of the matrix of the actuator. With a small $\theta$, the stress generated from the SMA wire is quite large which will deform the matrix to generate a buckling zoom between the experimental and modeling results as shown in the enlargement of figure 5.8. This phenomenon gives the SMA wire a shortcut for contraction and because of this reason the deploying force is reduced. It also can be proved from the observed experiments that a smaller $\theta$ will result in a larger deformation of the flexible matrix.

![Figure 5.7 Schematic of generation of deploying force or torque.](image)
5.3.3.2 Passive precise deployment

One challenge of self-folding structures is achieving precise deformation without human observation and intervention [99]. It is possible to control the accurate and repeatable bending angles of the hinge actuator through the actuator design alone. However, it would require more excessive efforts for precise fabrication and material design with tighter tolerances. To achieve a precise deployment, one proposed method is using the mechanical joints with mechanical stop for a limited rotation angle $\theta_h$ as shown in Figure 5.9. The mechanical stop will physically limit the bending angle of the hinge actuator to achieve a final desired configuration of the assemble structure after deploying. The schematic of the deploying process of a hexagonal module accompanied with the configurations of the mechanical joint is shown in Figure 5.10. To verify this method, the assemblies of hexagonal-looping modules using mechanical joints with limited rotational angle $\theta_h = 60^\circ$ and $90^\circ$ are evaluated and the results are shown in Figure 5.11.
Figure 5.9 Folded and deployed mechanical joint

Figure 5.10 Folded and deployed mechanical joint

Figure 5.11 Assembly using different mechanical joints
5.3.3.3 Active precise deployment

The other proposed method is using the PID controller to obtain different bending angles using the same hinge actuator. The resistance of the SMA wire can be used as a type of self-sensing sensor within the actuator since the phase change process of the SMA wire corresponds to a change in resistance. As such, a determined resistance corresponds to a determined martensite fraction, and then to a determined strain, finally to a determined bending angle. Therefore, to control the resistance of the embedded SMA wire, a PID controller is implemented in Labview with NI CompactRIO platform. This method is accomplished with the reference of [100]. The schematic of the experimental setup is shown in Figure 5.12. The NI 9264 module together with a custom current control board is used to control the amount of current sent to the actuator and the NI 9234 module is used to read the voltage within the actuator. From these two variables, the resistance of the embedded SMA wire can be calculated using Ohm’s law.

![Figure 5.12 Setup for the PID controller](image)

In this section, the PID controller is used with the process variable (PV) being the resistance of the embedded SMA wire and the controller output being the current output to the SMA wire. This setup is used to reach and maintain a
specific resistance within the actuator in order to determine the response of a hinge actuator to the change in resistance of the embedded SMA wires. Three actuators with 0.152 mm SMA wires, and matrix dimensions of 120 mm in length including a flexible segment length of 20 mm, 15 mm in width and 3 mm in thickness were built and tested using a camera to record the bending angle of the actuator. The actuator with a length of 120 mm was used so that the range of voltage values during tested correspond with the range of values allowable by the voltage input module, which is from -5 V to +5 V. The PID settings used for the different gains are $P = 0.003$, $I = 0.001$ and $D = 0.001$ for these experiments. The initial resistance of the actuators were first measured by applying a current of 0.05 A and then lowering the set-point for the resistance gradually while measuring the bending angle of the actuator at different resistances. The results for the three samples are shown in Figure 5.13. The results shown in this figure show that the bending angle of the actuator almost linearly depends on the change of the resistance of the embedded SMA wires.

![Figure 5.13 Bending angle versus resistance for the hinge actuators](image)

Figure 5.13 Bending angle versus resistance for the hinge actuators

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5.3.3.4 Forward kinematics of the assembled structure

To determine the position and orientation of the connecting points of the assembly, the forward kinematics is applied to describe the motion without consideration of the forces and torques causing the motion. The study object is the assembly described in Section 5.3.2 which is a planar structure with all joints can be considered as single DOF revolute joints. The assembly is constructed using four hexagon-looping module where each module can be considered as a six-bar mechanism with 3 DOF. Therefore, four identical actuations are provided to obtain a symmetrical deformation of the module as described in Section 5.3.2. Then, the deformation of the whole assembly can be determined. As shown in Figure 5.14, to know the motion trajectories of endpoint $O_4$ and $O_6$, the links are numbered from 0 to 6. Link 0 is fixed and does not move when the joints are actuated. To perform the kinematic analysis, a coordinate frame $o_i x_i y_i$ is rigidly attached to link $i$. The frame $o_0 x_0 y_0$ is attached to link 0 referred to as the inertial frame. The DH convention [101] is applied to establish the coordinates as shown in Figure 5.14. Then, the DH parameters from $O_6$ to $O_0$ are shown in Table 4.

Table 4 DH parameters for assembly of hexagon-looping modules

<table>
<thead>
<tr>
<th>Link</th>
<th>$a_i$</th>
<th>$\alpha_i$</th>
<th>$d_i$</th>
<th>$\theta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$a_1$</td>
<td>-180</td>
<td>0</td>
<td>$\theta$</td>
</tr>
<tr>
<td>2</td>
<td>$a_1$</td>
<td>180</td>
<td>0</td>
<td>$2\theta$</td>
</tr>
<tr>
<td>3</td>
<td>$a_2$</td>
<td>0</td>
<td>0</td>
<td>$\theta$</td>
</tr>
<tr>
<td>4</td>
<td>$a_1$</td>
<td>-180</td>
<td>0</td>
<td>$\theta$</td>
</tr>
<tr>
<td>5</td>
<td>$a_1$</td>
<td>180</td>
<td>0</td>
<td>$2\theta$-180</td>
</tr>
<tr>
<td>6</td>
<td>$a_1$</td>
<td>-180</td>
<td>0</td>
<td>$2\theta$-180</td>
</tr>
</tbody>
</table>
Figure 5.14 Coordinate frames attached to the assembly

In DH convention, each homogeneous transformation $A_i$ is represented as a product of four basic transformations showing the position and orientation of the $i$-th frame coordinate expressed in the $(i-1)$-th frame and the result is shown in (5.2):

$$
A_i = \begin{bmatrix}
c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\
s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\
0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(5.2)

Based on Table 4, the homogeneous transformation matrices $A_1$ to $A_6$ can be calculated, then the $T$-matrices can be given by (5.3). It is worth mentioning that the first three entries of the last column of $T_i^0$ are the $x$, $y$ and $z$ components of the end-point in the base frame. The coordinates of the end-points can be adjusted by the initial condition of the structure before
actuation. The rotational part of the matrix gives the orientation of the frame of end-point relative to the base frame.

$$ T_i^0 = \prod_{i=1}^{i} A_i $$ (5.3)

A group of experimental and modeling results are shown in Figure 5.15. These results were obtained by using the given rotated angles $\theta$ are 0°, 10°, 20°, 30° to 40°, and $a_1= 60$ mm, $a_2=75$ mm. It can be observed from the results, the experimental data and the modeling data have a small difference which can be due to the improperly deformed shape of the whole structure. This could be caused by the neglected gravity of the whole structure and the friction between the structure and the supporting desktop.

Figure 5.15 Experimental and modeling results of motion trajectory

5.4 Ring deployable structure
5.4.1 **Quadrilateral single-loop modules**

A four-bar mechanism with four revolving joints has a single DOF, so a quadrilateral module built using two compliant hinge structures similarly provides a single DOF resulting in a simpler single-loop module. However, the deformation is asymmetrical unlike the hexagonal single loop module. The developed quadrilateral module has one compliant hinge structure without SMA wires embedded in the matrix and one with two embedded SMA wires to generate the deploying and folding bending deformations, as shown in **Figure 5.16** (a). Then, the two hinge structures are connected using passive mechanical revolute joints to form a single-loop module. When the hinges are in the low stiffness state, actuating SMA-1 will result in the module being deployed and actuating SMA-2 will result in folding of the module, and both the deployed and folded configurations can be kept without energy consumption when the hinges are in the high stiffness state, as shown in Figure 5.16 (b).

![Figure 5.16 Schematic of quadrilateral single-loop module](image)
5.4.2 Assembly for ring structure

Then, a quadrilateral module based on the previously introduced design is created to verify the capability of this actuator to form a 1-DOF single-loop module. The actuators used the module have a length of 160 mm and their bendable length is 20 mm. When the hinge is in the low stiffness state, actuating SMA-1 or SMA-2 will result in a deploying process or a folding process, with the folded, intermediate and deployed states shown in Figure 5.17 (a). Assembling multiple such 1-DOF single loop modules using passive mechanical joints, it is possible to form large-scale deployable structures. A ring deployable structure with a high extensible area ratio is proposed using multiple quadrilateral modules where each module corresponds to one edge of a flat two-dimensional structure, as shown in Figure 5.17 (b). To illustrate this concept, six basic quadrangular modules are assembled into a six-edge ring shape configuration. This assembled structure can be folded and fixed in a compact state with the active hinges in the high stiffness state. Under a low stiffness state, the whole structure can transfer from a compact folded state to a fully deployed state by actuating the corresponding SMA wires, as shown in Figure 5.17 (c) and (d), and can then transform back from the deployed state to the folded state by actuating the antagonistic SMA wires. To further understand the motion of the assembly, the specific mechanical connections including only one kind of joint are shown in Figure 5.18. The assembled structure can be folded into a cylinder volume where the diameter of the cross-section is 9.4 mm, and it can be deployed in a cylindrical volume whose cross-section has a diameter of 26 mm. Thus, the extensible area ratio is approximately equal to 8 and could be much increased using a larger amount of modules to form a ring deployable structure with more edges or using actuators with a longer length.
Figure 5.17 Deploying processes of quadrilateral module and its assembly

Figure 5.18 Design of the mechanical joints for ring structure

5.5 Deployable reflective mechanism
One area of interest for this kind of deployable structure is for aerospace applications. To show its functionality, a reflective mechanism is designed for rovers making use of solar-based power systems even when entering caves where direct access to sunlight is not available. When executing space missions, a rover has two options for power: radioisotope thermoelectric generator (RTG) or a solar-based power system. RTGs are expensive and quite bulky, while solar-based power systems are cheap and reliable. However, solar-based power systems should be always exposed to sunlight to generate power, and will not work without direct access to sunlight such as when the rover enters caves and other areas that are permanently shadowed. One method to solve this problem is to use strategically placed deployable mirrors to bring light into these environments. Furthermore, due to the restrictions of aerospace applications these deployable structures should be compact and lightweight.

A deployable mirror based on the ring-shape deployable structure is demonstrated that is low cost and has a simple deploying mechanism to accomplish repeatable deploying and folding deformations in order to be usable throughout multiple missions. Based on the previously presented six-edge ring deployable structure, a reflective membrane is cut into a hexagonal shape with an edge length 100 mm and is fixed to the deployable structure by using a cable-based tensegrity structure, as shown in Figure 5.19 (a). In this figure, the cables in blue are used to create tension to unfold the reflective structure during deployments and the cables in orange are used to pull down and fold the center of the reflective surface during folding. The deployable mirror structure is fabricated and its deploying process is tested, as shown in Figure 5.19 (b) and (c). To verify the effect of the light reflection, the deployable mirror is used to reflect the sunlight onto a small-scale solar panel (50×60 mm) located in a shelter without direct access to sunlight, as shown in Figure 5.19 (d). A light-

90
emitting diode (LED) in a sealed aluminum tube was connected to the small-scale solar panel for verification of the viability of the proposed structure. When the sunlight is reflected to the solar panel, the intensity of the LED is increased significantly, as shown in Figure 5.19 (e). The experimental setup in real is shown in Figure 5.20, without the sunlight being reflected onto the solar panel, the voltage and current outputted to the LED were measured to be 1.90 V and 2.24 mA, and the small-scale solar panel generated a power of 4.26 mW. With reflected sunlight to the solar panel, the working voltage and working current for the LED measured to be 2.05 V and 8.31 mA, and the small-scale solar panel generated a power of 17 mW with an increased power ratio of 4.

Figure 5.19 Deployable mirror and evaluation of its performance
5.6 Summary

The described hinge actuators are capable of variable stiffness and continuous morphing, and can be used to construct deployable structures based on three principles: design of basic hinge actuators, assembly of modules and assembly of modules into large-scale deployable structures. This study focuses on two types of structures often used in aerospace applications: deployable masts and deployable reflectors. The design of a triangular mast was first proposed through using three basic hinge actuators to form a module and using three superposed modules to build the deployable mast structure capable of deploying at a height of 4.6 times its folded height. Then, single-loop modules were built using two basic hinge actuators in order to reduce the required range of actuation of the actuator and enable the fabrication of modules capable of both unfolding and folding deformations. Then, the single-loop modules were used to build a planar deployable structure for large one-dimensional deployable applications and a ring deployable structure for large two-dimensional deployable applications. The planar deployable structure is capable of an expansion ratio of 5 in height and the ring deployable structure
of an expansion ratio of 8 in area. It is worth mentioning that the proposed modules are not limited to the suggested deployable structures and could be used to form different types of deployable structures. Moreover, it should be pointed out that deployable modules and structures are not limited to using a single type of actuator or module and can be made by using different combinations of actuators, modules and structures.
Chapter 6. Tessellation for Deployable Networks

6.1 Overview

In the previous works, we presented the construction of certain deployable soft composite structures (DSCSs) with the proposed basic actuators. However, it was lack to give any reasons, especially for the planar DSCSs, why a particular network pattern was chosen. Neither did we show the existence of other network patterns. In this chapter, we will show how we arrive at possible network patterns for planar DSCSs.

In general, a network could be constructed by infinite elemental components in a certain way. Therefore, it is also possible to assemble the simple soft actuators repetitively to form large planar deployable soft composite networks (PDSCNs) referring to the different tiling patterns. As such, the PDSCNs should have two transferrable states: fully folded state and fully deployed state. A fully folded state is defined as the situation that all the constituted soft actuators before actuation are mutual parallel. That is, the comprised soft actuators are mutual contacted side by side that the whole structure cannot be compressed any more. With a fully actuation of the constituted soft actuators, all the actuators achieve maximum deformations which results in a fully deployed state of the PDSCNs. By virtue of diverse types and actuated deformations of the basic soft actuators, the PDSCNs could be built with tiling patterns comprised by both polygons and other motifs formed with smooth lines. The basic soft actuators or modules as basic tiles are considered to build PDSCNs with the guidance of tiling technique. Hence, the key issues are what kind of tiling patterns can be suitable for the construction of PDSCNs and how to assemble.
The layout of this chapter is as follows. Section 6.2 present some satisfied conditions for the tiling patterns for the PDSCNs. Section 6.3 and 6.4 present application of tiling to the networks of SSC hinge actuators and SSC linear actuators, respectively. Some conclusions and discussion follow in section 6.5.

6.2 Tiling analysis

6.2.1 Types of joints
To assemble a network structure, basic actuators need to be connected according to certain way by different types of joint to accomplish the function of deployment. In this chapter, there are total two different types of revolute joint are considered: one is SSC active joints (AJs) serving as SSC hinge actuators denoted in solid dot, the other one is passive joints (PJs) denoted in hollow dot including SSC passive joints serving as soft hinges without actuation and mechanical joints with passive motion. The schematic of the two types of joint are described in Figure 6.1. It is worth noting that the PJs can be fabricated not only for connecting two rigid parts but also for connecting two AJs, two PJs, or one AJ and one PJ.

6.2.2 Tiling patterns for PDSCNs
In fact, the PDSCNs cannot be assembled with any tiling patterns. Therefore, the tiling patterns need to fulfill some specific conditions for accomplishing the function of PDSCNs being capable of transferring between a fully folded state and a fully deployed state. One example of the schematic of the PDSCN configuration with a fully deployed state is shown in Figure 6.2. The tiling pattern is shown in solid lines and each edge can be taken as a basic SSC actuator or one segment of the actuator. The direction of the folding lines in $x$-
direction is parallel to the actuator’s length direction when the PDSCN is in a fully folded state. The deploying direction in $y$-direction is perpendicular to the direction of the folding line.

![Diagram](image)

Figure 6.1 Two types of joint and their schematics. (a) AJ: SSC active joint, (b) PJ: SSC and mechanical passive joint

To construct a PDSCN with tiling pattern of polygons, it is convenient to assemble polygonal module as tile by using the SSC hinge actuators through mechanical PJs. To enable the polygonal modules have a fully folding and deploying motion, only looping modules composed of two hinge actuators with the same configuration are considered in this chapter. The schematics of quadrilateral, hexagonal and octagonal looping modules are shown in Figure 6.3. As described in Section 3.3, it is difficult for an AJ to achieve a bending angle of $180^\circ$, therefore, it is effective to local the PJs on the folding line shown in dotted line to achieve a complete folded form. Based on this design, from a complete folded state to a deployed state of the polygonal module, the rotational angle for AJs is $\theta_d$ which has no limitation of the minimum angle. By virtues
of continuous deformation of SSC bending actuators, it is still possible to construct PDSCNs with tiles with no-polygon shape constructed directly using SSC bending actuators.

![Figure 6.2 Schematic of a PDSCN with a fully deployed form](image)

Figure 6.2 Schematic of a PDSCN with a fully deployed form

![Figure 6.3 Looping structures with edge number of four, six and eight](image)

Figure 6.3 Looping structures with edge number of four, six and eight

From the discussion and referring to Figure 6.3, the satisfied condition for the tiling patterns of the PDSCNs can be summarized as following. First, each tile should have even edges and it should be symmetrical about the folding line. Second, there should exist a group of parallel folding lines going through all the tiles. Third, the folding lines should go through tiling vertices and have no
intersections with the edges. Fourth, the vertices located on the folding lines should be PJs to obtain a fully folding state with edge length in any size.

6.3 Networks of SSC hinge actuators

The basic SSC hinge actuators can be used to constitute closed looping modules in polygonal shapes which can be used to construct the possible PDSCNs with certain tiling patterns.

6.3.1 Case A: tiling with unitary polygons

6.2.2.1 Side-by-side assembly

There are two kind of assemblies for edge-to-edge monohedral tiling with unitary polygons of squares and hexagons as tiles, respectively. One type is shown in Figure 6.4 where each tile denotes a module composed of two hinge actuators with the same configuration. Based on the tiling pattern, there is only one kind of equivalent nodes representing the sole connection of the modules.

![Figure 6.4](image)

Figure 6.4 Edge-to-edge assembly with squares and hexagons as units

The connection pattern of the hinges for tiling with quadrangle unit is shown in
Figure 6.4. To examine whether such a group of hinge connections can produce continuous deployable deformation, the freedom of the connection node is first examined, and then, the geometrical parameter will be verified. The connection node could be considered as a 1-DOF four-bar linkage with two AJs and two mechanical PJs where the involved two AJs provide two same actuation. The schematic of connection node design is shown in Figure 6.5 and it is up-and-down symmetrical. With feasible freedom, the geometrical parameters of the connection group also need to satisfy the Equation (5.1) and (5.2) to avoid the interference between the two AJs when deployed. However, the connection node for tiling with hexagonal units shown in Figure 6.4 (b) could be considered as a three-bar linkage with two AJs and one PJ. For a three-bar linkage has no DOF, the connection group cannot generate any motions and the assembly cannot be constructed.

\[ R_d (\pi - \theta_d) = L_{d,h} \]  \hspace{1cm} (5.1)

\[ (R_d + t_{d,2} + \frac{t_{d,1}}{2}) \cos (\frac{\pi - \theta_d}{2}) \geq R_d + \frac{t_{d,1}}{2} \]  \hspace{1cm} (5.2)

Figure 6.5 Connection for edge-to-edge assembly with square units
6.2.2.2 Wrap-around assembly

The other type of assemblies for edge-to-edge monohedral tiling is shown in Figure 6.6 where the modules are connected in a wrap-around manner. Based on the tiling pattern, there are two type of equivalent nodes representing two different connection groups of the modules.

![Figure 6.6 Wrap-around assemblies with equilateral square and hexagon](image)

The connection patterns of the hinges for tiling with quadrangle unit is shown in Figure 6.6 (a). There are two types of joint connection which have no constraint conditions of DOF and geometrical dimension. The schematic of the design of the connection nodes are shown in Figure 6.7 and Figure 6.8 and they are also up-and-down symmetrical.

The connection patterns of the hinges for tiling with hexagonal unit is shown in Figure 6.6 (b). There are also two types of joint connection which has no constraint conditions of DOF and geometrical dimension. The schematic of the design of the connection nodes are shown in Figure 6.9 and Figure 6.10.
Figure 6.7 PJ composed connection schematic for wrap-around assembly with quadrangle units

Figure 6.8 AJ composed connection schematic for wrap-around assembly with quadrangle units

Figure 6.9 AJ composed connection schematic for wrap-around assembly with hexagonal unit

Figure 6.10 AJ and PJ combined connection schematic for wrap-around assembly with hexagonal unit
6.3.2 Case B: tiling with hybrid polygons

According to the tiling patterns for constructing PDSCNs, it can be observed that it is not necessary for the tiles having the shape of regular polygon. In this section, one PDSCN with tiles of non-regular hybrid polygons is proposed. An example of this kind PDSCN and its connection group are shown in Figure 6.11. There are also two types of joint connection which has no constraint conditions of DOF and geometrical dimension. The schematic of the design of the connection nodes is shown in Figure 6.7 and Figure 6.8.

![Figure 6.11 PSDNs with tiles of non-regular hybrid polygons](image)

6.4 Networks of SSC linear actuators

6.4.1 Tiling with non-polygons

As mentioned previous, it is still possible to construct PDSCNs with tiling patterns of the shapes formed by smooth circular arcs. Considering a portion of the network in Figure 6.12, each continuous curve can be considered segments of SSC linear actuator and every two adjacent actuators can be connected using PJs.
6.4.2 Network construction

6.4.2.1 Fabrication of passive joints

As described in previous section, the linear actuators can be connected by using PJs to form a network. The mechanical PJs need to be attached to the connection point on the surface of the actuator and assemble them together subsequently. The PJs can be accomplished in a similar way using wires or tapes to bond the actuator together. This kind of method increases the follow-up effort. In order to avoid this, a kind of method for fabricating PJs is proposed that the PJs can be fabricated along with the fabrication of the actuator. An overall ABS mold can be designed and fabricated that several linear actuator molds are interconnected in parallel and the interconnecting part will be PJs automatically after PDMS curing. By using this method, two linear actuators coupled with PJs are manufactured at the same time. The fabricated structure is shown in Figure 6.13. In this figure, the configurations of the structure before and after actuation, along with the status of the PJs at different positions are described.
6.4.2 Assembly with different configuration

To show the feasibility of constructing networks with the tiling pattern described in Section 6.4.1, eight linear actuators connected with PJs are constructed and its deploying and folding process are shown in Figure 6.14. For each actuator, the total length is 190 mm where the length of the longer segment is 50 mm, and that of the shorter segment is 26 mm, and every two adjacent segment has an overlap length of 3 mm. The function of the overlap part is to ensure the configuration of each actuator have a smooth waving deformation after actuating. The assembled structure can be totally compressed with a height of 30 mm, and it can be deployed with a height of 165 mm. Thus, the extensible height ratio of the whole structure is approximately equal to 5.5 and it can be much increased using linear actuators with length of each segment is longer.

By using mechanical PJs in wedge block shape, the linear actuator can be assembled in a closed cylindrical shape structure. As show in Figure 6.15, eight same linear actuators are assembled in a cylindrical shape structure with PJs in
wedge block shape with wedge angle of 45°. This cylindrical shape structure is a kind of expandable structures and its outer diameter can be changed between 40 mm and 65 mm along with the actuation, and the expanding process is shown in Figure 6.16.

Figure 6.14 Configurations of the structure composed of eight linear actuators and its deploying and folding process

Figure 6.15 Cylindrical structure assembled using in wedge-block PJs
6.5 Summary

This chapter has presented a method to build PDSCNs using deployable units or modules as tiling. The detailed overall procedure is described in Figure 6.17. It mainly involves three steps: selection or design of suitable tiling, design and validation of joint connections, and construction of networks. This work has been applied to PDSCNs comprised of SSC hinge actuator based units and segmented SSC linear actuators, respectively.

It is worth mentioning that there are many ways of constructing deploying units including the units made from a combination of more than one type of actuators. Based on the diverse units, an abundant of PDSCNs can be constructed with suitable connections. In this chapter, not all the possibilities were attempted, however, a few simple examples have been studied to verify that the approach is feasible and valid.
Figure 6.17 Flow chart of overall procedure of designing PDSCNs
Chapter 7. Conclusion

The aim of this dissertation was to explore ways of constructing deployable soft composite structures (DSCSs) using adaptive composites with capabilities of both soft morphing and shape retention. The main work can be divided into two parts: one to determine how the basic actuators can be designed and fabricated, and one to determine how the DSCSs can be assembled using the proposed actuators. In this chapter, the main contributions are summarized and the needed future work is highlighted.

7.1 Main contributions

7.1.1 SSC actuators
The first effort of this dissertation was to design the basic SSC actuators with different types of deformation. For the first time, the SMA based SSC hinge actuator and linear actuator were successively proposed based on the basic SSC bending actuator and their performance were also evaluated. One primary application of the soft actuators is soft robotics showing the merits of permitting adaptive and flexible interactions with unpredictable environments. Based on SSC actuators, an inchworm-inspired soft robot was designed and fabricated with large bending deformation and large stride length, and a soft compliant gripper was proposed and manufactured which can grab objects with a large range of dimensions.

One disadvantage of SSC actuators is its low stiffness which limit their applications for load-bearing. To surmount this problem, a variable stiffness
principle was applied to the SSC actuator for the first time. This method enables
the actuator structure have the property of variable or reversible stiffness which
endows the SSC actuator the capabilities of both soft morphing and shape
retention.

7.1.2 Deployable soft composite structures
The SSC actuators with shape retention capability can be well used for
deployable soft composite structures which represent a promising solution for
reconciling the inherently conflicting requirements for deployable structures of
low mass, good shape adaptability, and high load-bearing capability. In this
work, for the first time, DSCSs being composed of the proposed actuators with
capabilities of both morphing and shape retention are proposed and developed.
The design of DSCSs is based on three main principles: design of basic
actuators, assembly of modules and assembly of modules into large-scale
deployable structures. Various deployable structures such as a segmented
triangular mast, a planar structure comprised of single-loop hexagonal modules
and a ring structure comprised of single-loop quadrilateral modules were
designed and fabricated to verify this approach.

Tiling techniques are applied as a reference for the construction of planar
deployable soft composite networks based on the proposed SSC hinge and
linear actuators for the first time. A general approach to construct planar
deployable networks has been proposed which can be divided into three steps:
selection or design of suitable tiling, design and validation of joint connections,
and construction of networks. Several possible configurations have been
discussed and verified using the assembled structures.
7.2 Future works

The research reported in this dissertation opens up many opportunities for further study. First of all, the performance of the proposed SSC actuators need to be improved. For example, the stiffness changing speed of the proposed actuators with shape retention should be improved or other solutions should be developed. Secondly, for the construction of DSCSs, it is worth mentioning that the proposed modules are not limited to the suggested deployable structures and could be used to form different types of deployable structures. Moreover, it should be pointed out that deployable modules and structures are not limited to using a single type of actuator or module and can be made by using different combinations of actuators, modules and structures.

Furthermore, for the performance of DSCSs, further works will focus on the precision of the deploying process, improvement of reliability, optimized design of structure and assembling methods for larger scale deployable structure with flat or even curved shapes.

Finally, in engineering practice, deployed configuration with high performance is the most important design consideration. How to achieve this aim through the current approach will be a natural step forward to make this work more attractive to practical engineers.
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초 르

본 논문에서는 형상기억합금과 지능형 연성 복합재로 구성된 지능형 연성 구동기를 활용한 전개형 구조물의 체계적인 설계 및 제작의 가능성을 제시하고 연구하였다.

논문의 첫 번째 파트에서는 형상기억합금 기반의 지능형 연성 구동기의 작동원리 설명하고 전개형 구조물에 적용하기에 용이한 새로운 기초 구동기를 제시한다. 기초 지능형 연성 복합재 구동기에 대한 설계는 간단한 굽힘 구동기에서부터 경첩 구동기와 선형 구동기까지를 포함한다. 제안된 지능형 연성 복합재 구동기의 변형을 예측하기 위하여 간단한 수학적 모델을 제시하였다. 제자리에 고정하고 많은 변형량을 가진 이러한 구동기들은 제작하는 것이 용이하고, 경제적이며, 경량인 동시에 구동하기 편리한 특성을 가지고 있다. 이러한 장점들을 기초로 한 기어가능 로봇과 유연 그리퍼와 같은 유연 로봇들이 설계 및 평가되었다.

유연 변형 움직임을 생성하고 형상 고정 능력을 갖도록 제안된 지능형 연성 복합재 구동기에 가변적 강성 원리를 기초로 한 구조가 적용되었다. 지능형 연성 복합재 구동기 구조 내의 발열 요소와 함께 삽입된 저융점 재료를 통하여 구조를 구현하였다. 원래의 형상을 유지하는 이 구동기는 저융점 재료 구조가 굳어진 후 높은 강성 상태 등의 다양한 강성의 구조를 통해 변형된 형태를 유지할 수 있다.

세 번째 파트에서는 조합의 기본 요소로 가변적 강성 원리를 사용한 구동기를 사용한 전개형 구조물에 제시하였다. 이 기초 구동기
다른 종류의 변형을 가능하게 하는 모듈을 형성하는데 이용될 수 있으며, 이러한 모듈들은 전개형 구조물을 구성할 수 있다. 전개형 구조물의 설계는 기초 구동기의 설계, 모듈들의 조합 그리고 대형의 전개형 구조물을 위한 모듈 조합 등 세 가지 원리를 기초로 하였다. 삼각형, 사각형을 주원으로 구성된 평면형 구조 그리고 단일 고리의 사각형 모듈로 구성된 반지형 구조 등의 다양한 전개형 구조물이 이 접근법을 확인하기 위해 설계 및 제작되었다.

논문의 마지막 부분에서는 제안된 지능형 연성 복합재 경첩과 선형 구동기를 기초로 한 평면 구조 전개형 네트워크의 구성을 위한 참고연구로써 타일링 방식에 대한 연구를 다루었다. 평면 구조 전개형 네트워크에 대한 일반적 접근법을 세가지 단계로 나누어 제시하였다 (적합한 타일의 선택과 설계, 결합 마디의 설계와 평가, 네트워크의 구성). 조합된 구조물을 활용한 여러 가능한 배열들을 다루고 설명하였다.

주요어: 지능형 연성 복합재, 형상기억합금, 전개형 구조물, 가역적/가변형 강성, 타일링

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