Synthesis of Novel Integrated Actuators Powered by Shape Memory Alloys

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École polytechnique fédérale de Lausanne

pour l'obtention du grade de Docteur ès Sciences
par

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Lausanne, EPFL, 2021

Wings are a constraint that makes
it possible to fly.
— Robert Bringhurst

To my parents…

Acknowledgements

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Lausanne, June 7, 2021 D. K.

Preface

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Lausanne, 12 Mars 2011 T. D.

Abstract

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Zusammenfassung

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Résumé

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Introduction

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1 Overview of SMA Actuator Design

In this chapter, the traditional design methodology of the SMA actuator is presented. Here, the different building blocks and state-of-the-art of various SMA actuators are presented. An in-depth look at the advantages and limitations of the methodology is conducted.

1.1 Introduction

1.2 Traditional SMA Actuator Design

1.3 Building Blocks of SMA Actuator Design

1.4 SMA Powered Robotic Systems

1.5 Summary and Conclusion

2 Predicting the Shape Memory Effect

In this chapter, different modelling strategies, such as finite element modelling and analytical modelling, are presented. Here, the modelling techniques are employed in the context of the traditional SMA actuator design methodology. Furthermore, the bias spring actuator model and a simplified model are presented.

2.1 Introduction

2.2 Analytical Modelling of the SME

2.3 Finite Element Modelling

2.4 Stroke Estimation of SMA Actuators

2.4.1 Mechanical Modelling

2.4.2 Thermal Model

2.5 Simplified SMA Actuator Model

2.6 Summary and Conclusion

3 Sizing Methodology for Integrated SMA Actuators

3.1 Introduction

In the past few decades, there has been a growing need for miniaturisation. Modern devices have come to require actuators that are compact and lightweight. As mentioned previously, since SMAs have been known to show the highest volumetric work density, they have been increasingly used in applications where compactness and low weight are required.

As previously presented in chapter 1, SMA actuators require an active element, a biasing element and a kinematic stage for motion control. These components, usually discrete elements, when combined together create an SMA actuator that can preform a specific reversible work, such as gripping or crawling motionscite. With the objective of miniaturisation, most work has been conducted into rendering these individual components as compact and lightweight as possiblecite. But the fact that these stages are discrete, lowers the overall volumetric work density of the complete actuator. Furthermore, as multiple systems are needed, the actuator also requires various pieces and assembly increasing the complexity and decreasing the compactness.

Recently, there has been a shift in creating novel motion control mechanisms using flexure-based mechanisms. These flexures are multiple compliant elements designed so as to only be compliant in specific degrees of freedom while being rigid in the others. These mechanisms, which can be fabricated using a monolithic piece of material, are lightweight and require virtually no assembly. These flexural stages, when paired with SMAs, have greatly increased the overall work density of the traditional SMA actuatorscite.

These flexure-based mechanisms are still often integrated into the SMA actuators as discrete mechanisms. In this chapter, the concept of integrating the biasing element as a flexural mechanism is explored. In this case, the kinematic stage and the biasing element are combined and are no longer discrete systems within the mechanism. Some research has been shown to take into account flexure mechanisms in SMA actuators but they lack a suitable sizing strategy due to the complexity of the shape memory effect and the nonlinear nature of flexurescite.

Thus, in this chapter, this novel design methodology is presented and analysed using an analytical model.

3.2 Adapted Design Concept

As mentioned previously, most SMA actuators are composed of an active element, a biasing element and a kinematic stage charged with converting the linear output of the actuator into a more complex one. In general, these elements are discrete components ranging from SMA coils, passive biasing springs and the kinematic stage comprised of hinges and linear slides. As presented in fig. 3.1, the design methodology consists of integrating the kinematic stage and the biasing element.

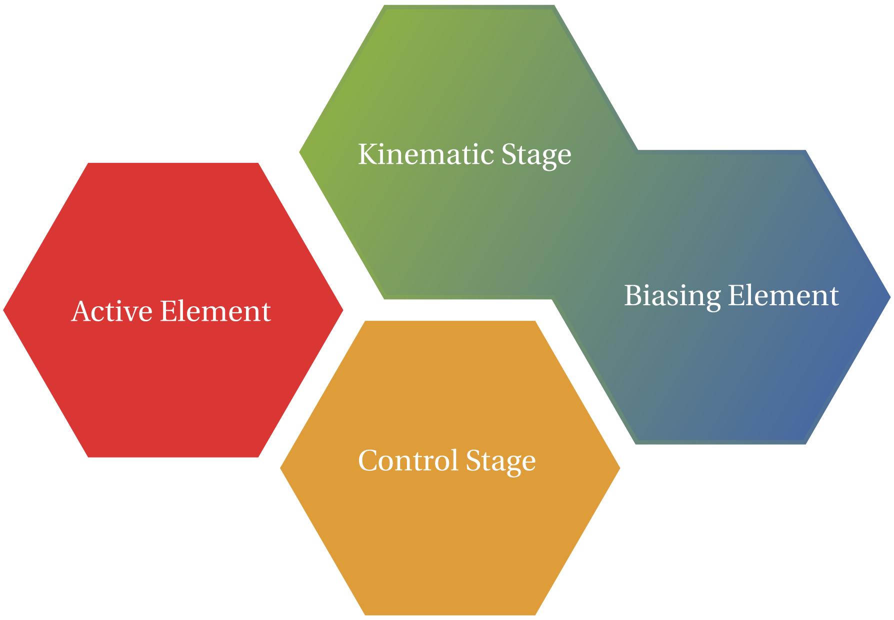

Figure 3.1: Diagram of the adapted building blocks of the SMA actuator.

This integration can be accomplished with the use of flexure-based mechanisms. Generally, flexures have been used in creating an alternative solution for traditional hinges and linear slides. These flexures are comprised of cantilever beams which allows the mechanism to be compliant in a specific degree of freedom while being rigid in the others. The advantages of such a system is that when adequately design can result in a kinematic stage that is lightweight, lacks any assembly and has high precision.

The main drawback to such a system compared to traditional bearings is the inherent stiffness of the mechanism. As these flexures are composed of compliant beams, the rigidity of the beam must be taken into account. In the case of an SMA actuator, this rigidity of the compliant structure can be harnessed as the biasing element. This implies that by pairing the active SMA element with a flexure, the kinematic stage and the biasing element can be combined. This novel approach can be used to create biased SMA actuators that are precise, lightweight and with a limited number of pieces to be assembled.

3.3 Challenges of the Approach

Due to the complex nature of the shape memory effect, the principle challenge when it comes to designing such SMA actuators is the difficulty in sizing the active SMA based on the flexure mechanism. Based on the configuration of the flexural stage, this mechanism can present highly nonlinear behaviour as well. When paired with an SMA wire or coil, this can results in unintended behaviours or secondary operating points.

Recently there has been research such as the work by Maffiodo et al. (2017) that shows the advantages of pairing SMA wires with flexure-based structures. As with this case, the sizing of the SMA element is disregarding and the biasing advantage of the flexure is neglected.

In the case of grippers and mesoscale actuators where the SMA element is passively cooled, the accurate sizing of the SMA is important. In designs, where passive cooling is used, the geometry of the active element is critical as the shape and structure of the active element is directly related to the cooling times. In the case of SMA coils and wires, thinner diameters imply a shorter cooling time. These thinner wires, however, result in smaller forces when heated. This implies that by accurately sizing the SMA element for the biasing flexure, the actuator can be made as thin as possible while still being able to deform the flexure during heating. Thus, by adapting the traditional sizing methodology of bias-spring SMA actuators for flexure-based designs, the SMA actuator can be designed with faster response times.

3.4 Adapting the Simplified Models

In section 2.5, a simplified model of the SMAs are used to size the active element for bias-spring and antagonistic SMA actuators. In the traditional sizing strategy, a simplified linear model of the SMA and the curve of the spring are used to find the operating points of the actuator which is represented by the intersection of the two curves. This simplification allows a relatively simpler sizing of the components by abstracting the complex nonlinear behaviours of the shape memory effect.

3.4.1 Passive Biasing Compliant Mechanisms

The compliant mechanism, as mentioned previously, acts as the biasing element and as the kinematic stage that produces the desired actuator motion. Here, the basic principle is that the inherent stiffness of the compliant flexure mechanism is harnessed to pre-load the SMA for activation. In this case, at lower temperatures, the SMA is deformed using the energy stored in the compliant mechanism while at higher temperatures, the strain recovered by the shape memory effect is used to deform the compliant mechanism. Based on the design of the compliant mechanism, the SMA actuator can be made to actuate reversibly in a single degree of freedom while being rigid in the others.

In order to size the actuator and its corresponding passive biasing compliant element, an analytical model can be devised and exploited to predict the various operating points of the final SMA actuator. A pseudo-rigid body model (PSBM) based on the work by Henein (2005) can be used to devise the analytical models of the flexures. The flexure hinges are considered to behave like torsional springs with constant angular stiffness, K_θ. The analytical model can be derived by considering the reaction force exerted by the mechanism on the SMA wire or coil when acting as the biasing element.

While a Newtonian approach is possible, the simplest way to compute the force is to consider the elastic potential energy stored in the flexure hinges as the mechanism deforms. This potential energy stored in one torsional spring as a function of the input displacement of the mechanism, x, as given by :

$$U(x) = \frac{1}{2} K_\theta \left(\theta(x) - \theta_0\right)^2 \tag{3.1}$$

where, in the case of a notch flexure hinge, as shown in fig. 3.2, when rotating by an angle of θ, has a stiffness, as described in Henein (2005), equal to:

$$K_\theta = \frac{2Ebe^{2.5}}{9\pi\sqrt{r}} \tag{3.2}$$

Here, E is the Young modulus of the material, and e,b and r the design parameters of the flexure hinge shown in fig. 3.2.

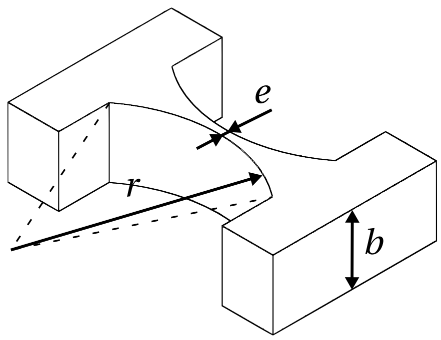

Figure 3.2: A diagram of the notch flexure hinge.

In this approach, the important relationship to obtain is the influence of the contraction of the SMA on the rotation of the hinge, $\theta(x)$. When the flexure-based system is comprised of multiple flexural hinges, the total potential energy can be calculated by the sum of the potential elastic energy of each flexure, $U_{\text{tot}} = \sum U(x)$. The required force to deform the structure can be deduced using :

$$F(\theta(x)) = \|-\nabla U_{\text{tot}}(x)\| = \frac{\partial U_{\text{tot}}(x)}{\partial x} \tag{3.3}$$

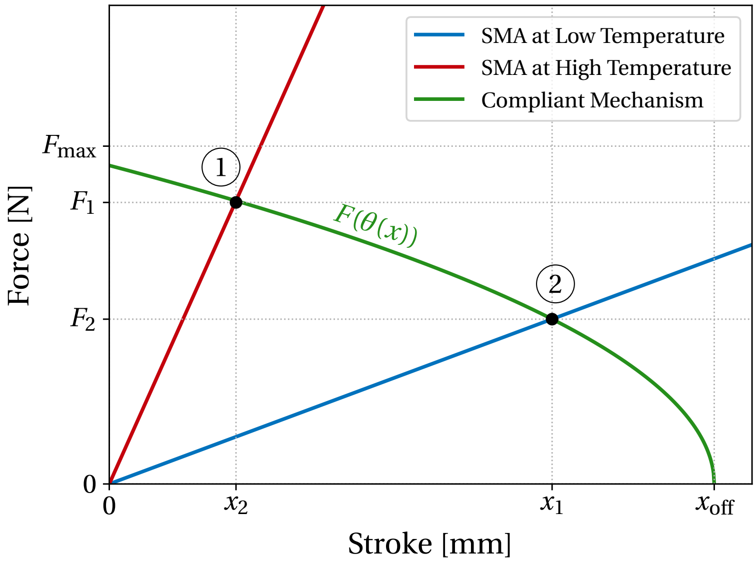

Figure 3.3: The adapted sizing principle of the novel biasing compliant mechanism SMA actuator based on the simplified SMA curves.

As in the case of the traditional SMA sizing methodology, the intersection between the adapted biasing curve and the simplified SMA curves represents the operating points of the SMA actuator, visualised in fig. 3.3 as ① and ②. The stroke of the actuator can be estimated by taking the different between the x-coordinate of the operating points, $\Delta x = x_1 - x_2$. It is important to note that the there is a maximum pull force that the SMA wire or coil can exert, as seen in table cite. Thus, the SMA element must be sized such that $F_1 < F_{max}$ so as to obtain the thinnest SMA wire or coil which can still exert enough force to deform the compliant mechanism to the required stroke.

In fig. 3.4, the design methodology for sizing a biased-compliant mechanism SMA actuator is presented. The methodology consists of designed the SMA active element based on the desired time response (τ) specifications of the application. As explained previously, in the case of passive cooling applications, the wire diameter can be reduced to decrease cooling times and increase τ. Once the diameter of the SMA wire or coil is determined, the biasing element can be designed. In the case of a biasing compliant mechanism, the flexure hinges can be designed based on the desired stroke of the application. As fig. 3.4 details, the operating points must be estimated using the design of the compliant mechanism. The structure and design of the compliant mechanism can be used to determine the relationship between the strain recoverd by the SME and rotation of the flexural hinges, $\theta(x)$. This relationship can be used to determine the force-displacement curve of the resulting biasing element using the equation presented in eq. (3.1). Finally, the individual flexural hinges can be adjusted such that the desired stroke,x, is obtained and that the maximum pull force of the SMA wire or coil is not exceeded.

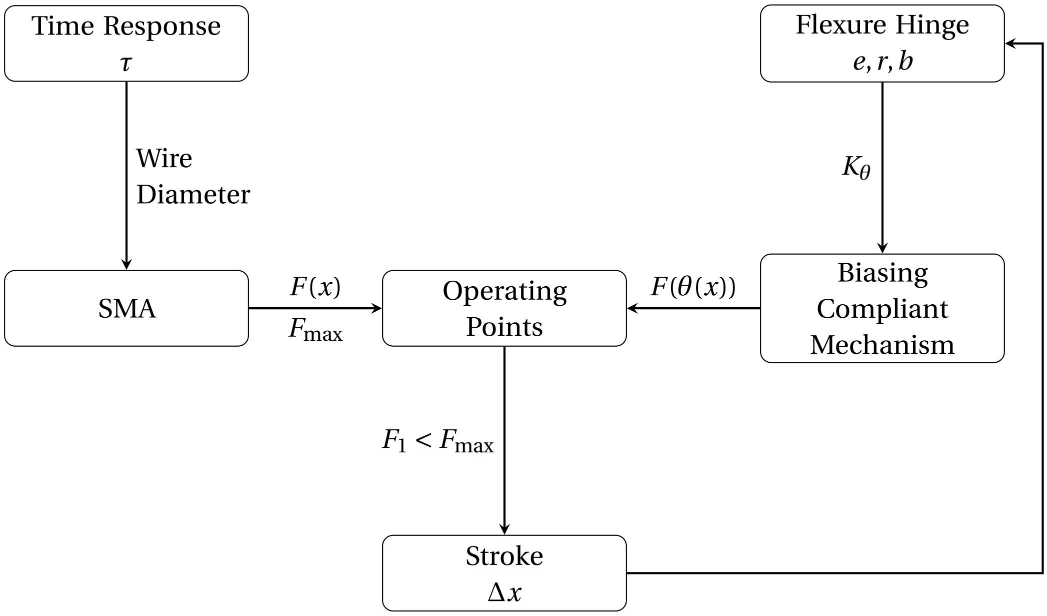

Figure 3.4: Design methodology for sizing biased-compliant mechanism SMA actuators.

Flexure-based hinges, however, exhibit a limited anuglar stroke. The maximum angle allowed before plastic deformation occurs has to be considered when designing such hinges. This admissible deformation, as described in the work by Henein (2005), can be calculated using :

$$\Delta\theta_{adm} \cong \frac{3\pi\sigma_{adm}\sqrt{r}}{4E\sqrt{e}} \tag{3.4}$$

By using the relationship between the input displacement and the hinge rotation, $\theta(x)$, the maximum admission stroke of the compliant mechanism, Δx_{adm}, can be computed. With this theoretical model complete, the entire mechanism can be sized such that the output stroke is maximised while avoiding failures during the deformation of the biasing compliant mechanism.

With $\mathbb{X}_{eq}$ being the set of possible equilibrium positions (see fig. 3.3) and $\mathbb{X}_{el}$ being the set of admissible positions for elastic deformation as defined below :

$$\mathbb{X}_{eq} = \{x \mid x_2 \leqslant x \leqslant x_1\} \tag{3.5}$$

$$\mathbb{X}_{el} = \left\{x \mid x_{off} - \frac{\Delta x_{adm}}{2} \leqslant x \leqslant x_{off} + \frac{\Delta x_{adm}}{2}\right\} \tag{3.6}$$

The set of feasible operating points for the biased-compliant mechanism SMA actuator, $\mathbb{X}_f$, is given by their intersection:

$$\mathbb{X}_f = \mathbb{X}_{eq} \cap \mathbb{X}_{el}. \tag{3.7}$$

Using this principle, if the mechanism is designed such that $\mathbb{X}_{\text{eq}} \subseteq \mathbb{X}_{\text{el}}$, then, the safety of the flexure hinges will not depend on precise control of the SMA which can be difficult to achieve. Furthermore, using these principle, various design trade-offs can be deduced, as shown in table 3.1

Table 3.1: The trade-offs observed during the sizing of the biasing compliant mechanism for the SMA actuator with a given SMA wire or coil. Here, S_{mech} and t_{mech} are the surface area and the thickness of the compliant mechanism, respectively.

Parameter	Effects	
$\frac{e}{r}\uparrow$	$\Delta\theta_{\text{adm}}\downarrow \Rightarrow \mathbb{X}_{\text{el}}\downarrow$	
$e\uparrow \mid \frac{e}{r}$ fixed	$S_{\text{mech}}\uparrow$	$K_\theta\uparrow \Rightarrow \begin{cases}\mathbb{X}_{\text{eq}}\uparrow \\ F_{\text{grip}}\downarrow\end{cases}$
$b\uparrow$	$t_{\text{mech}}\uparrow$	
$x_{\text{off}}\uparrow$	$\mathbb{X}_{\text{eq}}\uparrow$, $\mathbb{X}_{\text{el}}$ shifted away from $\mathbb{X}_{\text{eq}}$	

3.4.2 Integration of Compliant Mechanisms in Antagonistic SMA Actuators

The concept of augmenting traditional bias-spring SMA actuators with compliant mechanisms can be extended to Antagonistic SMA actuators. Traditionally, these actuators consist of a pair of active SMA elements where the SMAs are heated and cooled alternately. These actuators are relatively more complex due to the nonlinear nature of the SME. But, antagonistic SMA actuators have the advantage of an additional degree of freedom during activation. As the first SMA is heated, the antagonistic SMA is deformed and activated. Similarly, only upon heating the antagonistic SMA will the actuator be actuated in the opposite direction.

As with most SMA actuators fabricated using SMA wires or coils, the actuation of the actuator results in a linear motion. In application where complex motions are required, the antagonistic SMA actuator is paired with a kinematic stage that converts the linear movement to the required complex motion. Furthermore, they can be implemented into these antagonistic SMA actuators such that they present different behaviours based on the direction of actuation. As mentioned previously, flexure-based kinematic stages have the advantage of increased precision and reduced weight but presents with an inherent stiffness. Thus, this increased rigidity must be taken into account when sizing the SMA active elements.

In the traditional antagonistic SMA actuator, the first SMA, when heated and returns to its original length, deforms the antagonistic SMA. Thus, in this case, the heated SMA must overcome the rigidity of the cold SMA. The operating points of such a system can be deduced by taking the intersections between the hot and cold SMA curves as shown in chapter cite. In the case of a compliant mechanism, the system is connected to both SMAs at all times. Thus, the inherent stiffness of the compliant mechanism must be taken into account when actuated both SMAs. Therefore, the force-displacement curve of the compliant mechanism, $F_C(x)$, can be added to the curve of the antagonistic cold SMA, $F(x)$, to obtain the apparent load observed by the heated SMA, as shown in fig. 3.5. The design methodology can thus be adjusted, as shown in fig. 3.6, such that when the SMA elements are sized and operating points are determined, no unintended behaviours occur. It is important to note that due to the complexity of the compliant mechanism curves, these unintended operating points can emerge causing shorter strokes.

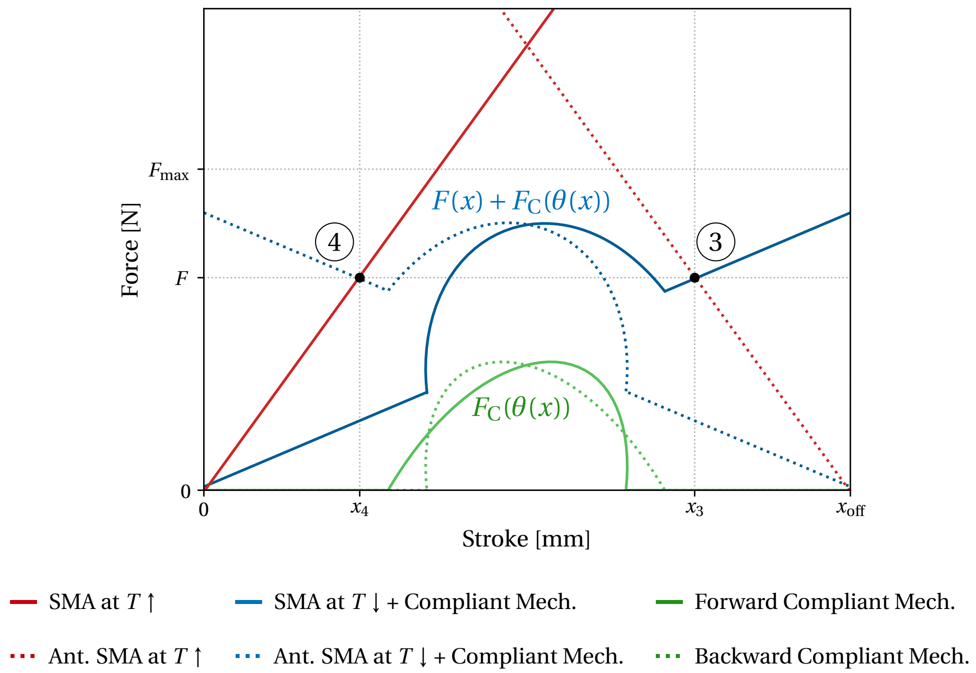

Figure 3.5: The adapted sizing methodology of an antagonistic SMA actuator paired with compliant mechanism using the simplified SMA curves.

In summary, as illustrated in fig. 3.6, the design methodology consists of deriving the force-displacement curves of the SMA elements and the relationship between the input displacement, x, and the hinge rotation, $\theta(x)$. Once these relationships are deduced, the force-displacement relationship of the compliant mechanism, $F_C(\theta(x))$ can be added to the force-displacement curve of the cold antagonistic SMA element. An important parameter to note is the prestretched length, x_{off} of the SMAs. As the SMA is prestretched, when heated, the SMA can exert higher levels of force but could result in forces that exceed $F_{\max}$. Using the two curves, the operating points can be estimated and verified such that the resulting stroke, Δx, fits within the requirements of the application. Furthermore, the geometric parameters of the hinge design of the compliant mechanism can be adjusted such that there are no unintended operating points and that the maximum pull force of the SMA is not exceeded.

Recently, there has been considerable work in developing bistable or multistable actuators. These actuators are able to main a stable position without required any holding energy. This property could be highly beneficial in applications such as grippers. Here, the gripper can stay in the open or closed position without requiring any additional energy. These bistable systems

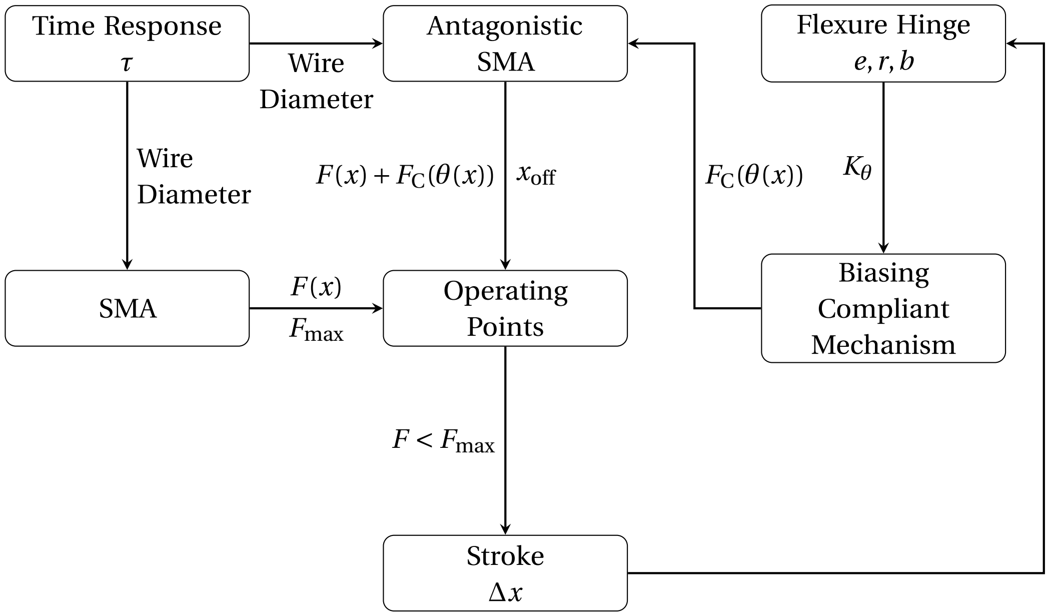

Figure 3.6: Design methodology for sizing antagonistic SMA actuators paired with compliant mechanism.

can be created using flexure-based structures, as shown in the work by Jin Qiu et al. (2004). A axially compressed cantilever beam exhibits bistability and has been implemented in various smart material actuators. In the work by Chouinard and Plante (2012), a dielectric elastomer actuator is paired with a buckled beam to create a compact bistable actuator. Furthermore, in the work by Zhang et al. (2020), a bistable drone-ready gripper is fabricated and is actuator using an electric motor. This principle can be implemented and actuated using SMAs, as shown in the work by Welsch et al. (2018). However, the sizing of such a system are missing due to the complex nature of the bistable mechanism and the nonlinear nature of the SMA. Using the proposed, methodology, as shown in fig. 3.6, the SMA can be sized to present with higher time responses while still able to trigger the bistable positions of the actuator. The accurate sizing of such a bistable SMA actuator is validated later in section 6.3.

3.5 Summary and Conclusion

In this chapter, the traditional sizing methodology has been adapted to fit the case where biasing springs are replaced with passive biasing compliant mechanism. This approach stems from the concept where the traditional SMA actuators consisting of an active element, a biasing element and a kinematic stage is transformed into a more integrated solution where the biasing element and the kinematic stage are combined.

Using pseudo-rigid body models described in the work by Henein (2005), the analytical models of the compliant mechanisms are used to estimate the stroke and behaviour of the novel SMA actuator. Using the simplified SMA curves, these alloys can be sized such that the time response of the SMA actuator is minimized.

Furthermore, this novel approach to designing SMA actuators paired with compliant mechanisms has been adapted for antagonistic SMA actuators. By altering the design methodology, the often used antagonistic SMA actuators can be sized such that when paired with compliant mechanisms, the actuator does not present any unintended behaviours and reduces the time response.

Most SMA actuators that make use of kinematic stages to convert the linear motion of the actuator into more complex behaviours, also integrate a passive spring in the design. By applying the presented design approach, SMA actuators can be designed such that compliant mechanisms can be used as biasing elements. This methodology will be further validated using case studies in chapter cite.

4 Designing Compliant SMA Actuators

Using topology optimization to create a compliant SMA actuator can be used to develop novel compact multi-output actuators.

4.1 Introduction

4.2 Integrated Active Elements

4.2.1 Compliant SMA Actuators

4.2.2 Kirigami inspired SMA Actuators

4.3 Heating Strategies

After a brief state of the art for heating strategies, the principle of wireless heating is extended to actuate the novel SMA actuators with complex shapes.

4.4 Summary and Conclusion

5 Designing Integrated Control Systems

5.1 Introduction

Shape Memory Alloys, often referred to as artificial muscles, are often used in applications where a compact and lightweight solution is required. When paired with a biasing element such as a spring or compliant mechanism, a lightweight reversible actuator can be fabricated. By heating and cooling the active SMA element, a reversible back and forth motion can be created.

Due to the complex nature of the shape memory effect, sensors or complex control strategies are required for the accurate control of the SMA element, as shown in the work by citeand cite. The SMA, if overheated, can result in the permanent reprogramming of the shape or the destruction of the SMA wire or coil. In the case of smaller, more compact applications, the SMA element used are thin wires or coil. In these cases, using sensors that can measure the temperature can be quite difficult to implement due to the low thermal mass of the SMA element. Recent work such as cite, have implemented sensorless systems where the change in resistivity is measure as the SMA changes phase to create more compact control solutions. Here, due to the complex nonlinear nature of the shape memory effect requires complex control strategies and micro-controllers to efficiently control the SMA and prevent overheating.

Often, when considering the volumetric work density of SMA actuators, the electronics, sensors and control strategies are not taken into account. In certain applications, for example untethered crawling robots, the control plays an important role in the final work-weight density of the robot as seen in the work by cite. Improvements made in the sensorless and control strategies can, thus, have a major impact in the final dimensions and weight of the SMA actuator.

In this chapter, a novel design concept is presented to further integrate the discrete building blocks present in the traditional SMA actuator. By exploiting the dependence of the mechanical behaviour of the SMA and its temperature, a mechanical oscillator system can be developed such that an electronics-free SMA actuator can be designed. This design language can be implemented into SMA actuators to create a simple but effective solution to create a sensorless, micro-controller-free control strategy that intrinsically present SMA overheating. Furthermore, in this chapter, a crawling robot is conceived using this methodology to validate this novel design approach.

5.2 Design Methodology for the Control System

As mentioned previously, due to the complex behaviour of SMAs, the sensors and control strategies required to actuate an SMA actuator can be cumbersome and reduce the overall work-weight density of the resulting robotic systems. The shape memory effect and the corresponding phase transitions are directly dependant on the temperature of the alloy. By exploiting this mechanical relationship between the temperature of SMA, the control system can be integrated into the kinematic stage, as represented in cite.

5.2.1 Working principle

A basic linear SMA actuator consists of an SMA and a biasing spring that when heated and cooled, results in a simple back forth oscillating motion. By accurately controlling the temperature of the SMA above its transition temperature and below a critical overheating temperature, the SMA can be made to provide a reliable actuation. This reversible actuation results in a back and forth mechanical movement of the biasing spring and the cyclical movement of the kinematic stage, if any. The basic concept of this methodology consists of tying the mechanical behaviour of the actuator into the control.

The SMA element in most cases is heating using Joule's heating by simply passing a current through the SMA and allowing the internal resistance of the SMA element to heat up by Joule's losses as shown in the work by cite. The cooling of the SMA generally consists of passively extracting the heat from the active element using natural convection with the cooler surrounding air. This simple strategy is often used in the control of SMA actuators due to not requiring any additional mechanisms and thus, does not reduce the work-density of the actuator while keeping the system compact.

Thus, by using the mechanical behaviour of the actuator to cut the current flow across the SMA will immediately cool the active element before it has a chance to overheat. In this manner, the control of the SMA actuator is mechanical controlled by the shape memory effect. Here, as a current is passed through the SMA wire or coil, it heats up the SMA resulting in a strain recovery and the SMA returning to its original length. This change in length, after a certain threshold, can be made to physically cut the electrical contact between the SMA element and the power supply. This cause the immediate cooling of the SMA through heat exchange with the surrounding air. As the SMA cools down, the biasing element will, once again, deform the SMA which will re-establish the electrical contact across the SMA, restarting the oscillating motion. Thus, this design strategy when integrated into the kinematic stage can render the entire SMA actuator compact and electronics-free.

This approach, when properly implemented, can result in an robotic system where a reversible actuation can be observed without the need for any electronics, micro-controllers or sensors, preserving the work-weight density of the system. A mechanical control of the SMA element can result in a system where the SMA element, due to the physical electrical contacts being interrupted, can never overheat.

5.2.2 Implementation

The basic implementation of such as system consists of using a latch system or multi-stable mechanism where after a certain stroke or force threshold results in a snap-through effect that can be exploited to disconnect the electrical contacts across the SMA wire or coil. The rapid bifurcation or spring back from a latch system is used to cut the flow of current across from the SMA and the slow return of the SMA actuator due to cooling can be used to re-establish the electrical connection to create this oscillating effect.

The implementation of this oscillator mechanism in the scope of a simple biased-spring SMA actuator consists of a magnetic or mechanical latch system. A diagram of the working principle of the proof-of-concept can be in fig. 5.1. The latch, here, consists of a magnet mounted on a leaf spring that is attracted to the end-effector of the bias-spring SMA actuator. The electrical current, in this case, is made to flow across the conductive magnet and into the SMA coil. Thus, only as the the magnet attaches to the end-effector of the SMA actuator will the SMA coil be heated using Joule's losses. Essentially, as the magnet and the SMA coil makes contact, the SMA element is heated and reduces in size due to the shape memory effect. During this phase, the magnet, which is mounted to a leaf spring, experiences a return force, F_S, and will continue to follow the actuator. Once, this force exceeds the attractive magnetic force, F_{mag}, between the magnet and the SMA coil, the latch detaches and immediately returns to its original location. This spring back occurs due to the resting return force of the leaf spring attached to the magnet. This concept can be implement in numerous ways including a mechanical latch mounted on a passive spring. Once this snap-through occurs, the electrical connection and the electrical current across the SMA is cut and will only be re-established when the bias spring of the SMA deforms the SMA coil and extends it back towards the latch. In this manner, the oscillating behaviour is observed without any sensors, micro-controllers or electronics.

As mentioned earlier, using a flexure-based mechanism permits the omission of a dedicated spring in the design. As seen in fig. 5.2, a proof-of-concept of this design methodology is implemented. Here, the linear stage is comprised of two parallel cantilever beams that also behaves as leaf springs. These biasing leaf springs apply a tractional return force on the SMA coil at a lower temperature while also preventing any unwanted degrees of freedom in the other axis. Another leaf spring is used to apply the return spring force required in the magnetic

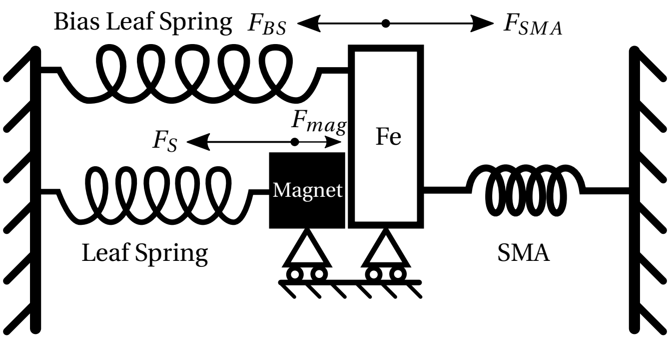

Figure 5.1: Diagram showing the working principle of the magnetic latch system implemented in the SMA oscillator.

latch. Here, the SMA actuator is heated using the magnetic latch system and the snap-through of the latch occurs when the return force of the leaf spring exceeds the attractive force of the magnet, $F_S > F_{mag}$. Therefore, the required contraction of the SMA coil, ε, can be controlled by sizing the leaf spring associated with the magnet.

$$\varepsilon = \frac{F_{mag}}{K_s} \tag{5.1}$$

where K_s is the rigidity of the leaf spring which depends on the dimensions of the cantilever beams and can be calculated using the analytical model described in the works by Rubbert et al. (2016) and Henein et al. (1998).

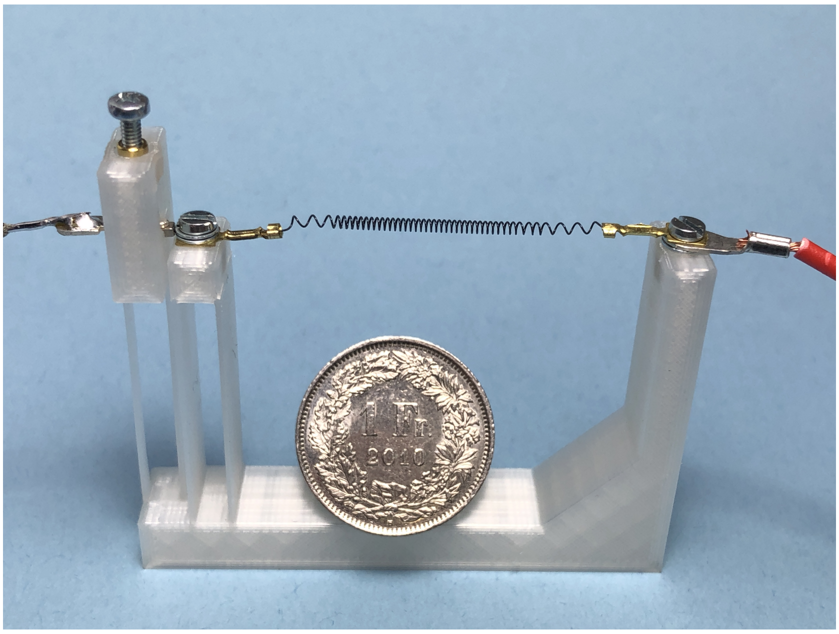

Figure 5.2: The integrated SMA control system implemented using a flexure-based magnetic latch creating an SMA mechanical oscillator.

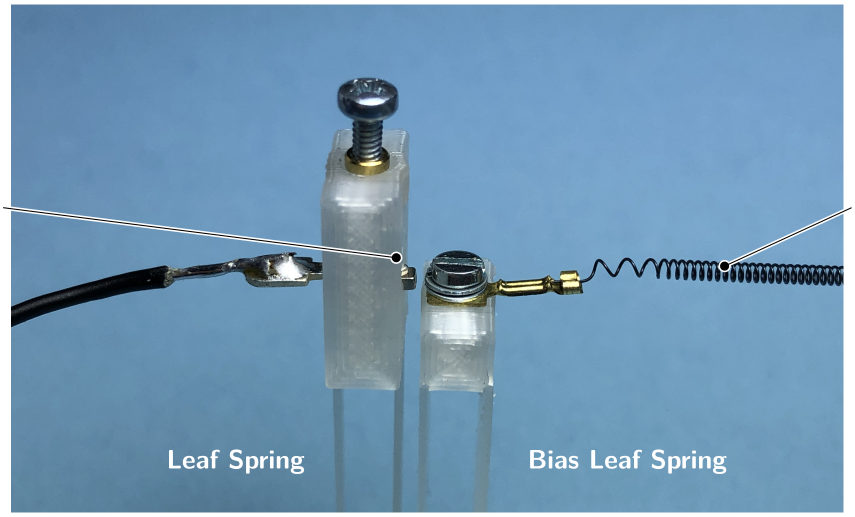

Figure 5.3: The close-up structure of the magnetic latch system that acts as the oscillating electrical contact for the SMA coil. Here, the biasing leaf spring also act as a linear stage for the actuator.

Here, in this proof-of-concept, the magnetic latch consists of a small magnet, with an attractive force of 150 g, mounted on a thin leaf spring measuring 500μm × 2.5mm × 30mm. An M2 screw is used to clamp an electrically conductive wire to the magnet and acts as the ground of the electrical circuit. The magnet latches onto another ferromagnetic M2 screw which is mounted to the end-effector of the SMA actuator, as seen in fig. 5.3. The SMA is supplied by *Dynalloy, Inc* (Irvine, CA) and is a 90°C Flexinol® coil with wire diameter of 200 μm and an outer diameter of 1.4 mm. The coil contains around 40 coils and with a solid length of 8 mm. The SMA is mounted on a 3D printed support containing a flexure-based linear stage which supports the free end of the SMA. The linear stage is 3D printed from PLA and consists of 2 parallel leaf springs with dimensions 500 μm x 10 mm x 30 mm.

5.2.3 Sizing of the oscillator

5.3 Validation of the Approach

5.4 Summary and Conclusion

6 Validation using Novel SMA Gripper Systems

In this final chapter, the novel design methodology is validated using 3 different case studies. These case studies employ the strategies and analytical models presented in chapter 3. While validating the different analytical models, these case studies also validate the basic premise of the methodology.

6.1 Introduction

6.2 Case Study: A Multi-Ouput SMA Mandrel

6.3 Case Study: A Bistable SMA Gripper

6.4 Conclusion

Conclusion

A An appendix

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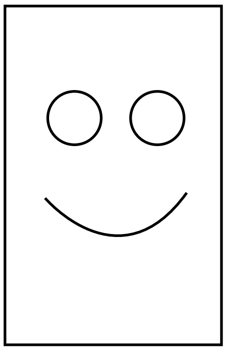

Name :	Mr. Sample CV
Address :	Samplestreet 70 6005 Luzern Switzerland
Date of Birth :	2nd of October 1981
Nationality :	Swiss
Legally work :	legally work in EU
Marital status :	with partner
Children :	none
Languages :	Chinese/Mandarin, English, French, German
Education level :	Bachelors degree
Hospitality work experience :	3-5 years
Special experience :	Europe work experience
Date of availability :	September 2009
Current location :	Africa
Travelling Status :	will be travelling single status
Telephone :	0041 41 370 6759
Email address :	jeff@h-g-r.com
Position(s) sought :	Permanent position for graduates
Department(s) sought :	Food & Beverage Bar/Sommelier

Personal profile:

As a Bachelor of Business Administration and after obtaining first relevant international work experience within the hospitality industry, I am now ready to take on new responsibilities to further my professional career.
My key strengths include strong analytical and logical skills, an eye for detail, communication and interpersonal skills.
I enjoy working in a team and help others progress. At the same time I work well independently.
As a highly motivated and driven individual I strive on taking up challenges.

Interests:

Travelling
Foreign Cultures
Photography
Sports

Educational qualifications:

Oct 99 - Feb 02	Higher Diploma (Hotel Management) Swiss Hotelmanagement School, SHL

Employment history:

Mar 04 - Ongoing	Assistant Manager (Rooms Division/Food & Beverage) Hotel Atlantic Kempinski Hamburg www.kempinski.com 5 star business hotel, part of Leading Hotels of the World 412 guest rooms, large function facilities, 3 food & beverage outlets Optimization of bar procedures, reinforcing SOPs Developing & implementing promotions Responsible for day-to-day operations Optimization and streamlining of housekeeping and laundry procedures Implementation of new SOPs Analyzing monthly reports for rooms division performance and sub departments
Mar 03 - Mar 04	Management Trainee Hospitality Graduate Recruitment www.h-g-r.com Leading company for placements within the Hospitality industry. Traineeship covering all aspects of an online recruitment agency.
Mar 02 - Mar 03	Management Trainee (Rooms Division) Hyatt Regency Xian, China www.hyatt.com 5 star business hotel 404 guest rooms, 4 food & beverage outlets Traineeship covering all rooms division departments on operational as well as supervisory level.

Training courses attended:

Mar 02 - Ongoing	OpenOffice - IT Courses
May 01 - Jan 03	Language Course - Chinese

References:

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