Contents

1 Name of Candidate and Provisional Thesis Title

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Provisional Thesis Title: Smart Grippers: Conception of a novel type of actuator powered by Shape Memory Alloys

2 Keywords

Shape Memory Alloy, Buckled Beam, NiTiNOL, Shape Memory Effect, Bistable system, Self-switching, Modeling and Optimization, Printed Electronics

3 Research Field and Motivation

3.1 Motivation

In an era where manual assembly is no longer possible in the majority of developed countries, it is necessary for companies offering alternative solutions to stand out from their competitors. Manufacturers of assembly lines must modify the capabilities of their robots in order to be as competitive as possible compared to the relocation of the assembly in countries with cheaper labour. In order to stand out, companies such as Mikron SA, seek to increase the efficiency of their installations while preserving the precision appreciated by their customers. The goal of this project would be to conceive and develop a novel and innovative type of Smart gripper. This small part plays a primordial role in the dynamics of the robot. Being at the end of the arm, a small gain in weight of this part would have great consequences on the acceleration and the maximum speed that the robot will be able to reach.

The *Laboratory of Integrated Actuators*, along with a Swiss company, *Mikron SA*, intend to develop a novel type of gripper that will harness the high work output per volume of Shape Memory Alloys (SMA). This gripper would be designed to be lightweight and compact so as to be used as a pick and place gripper in clean room application. The project strives to create an innovative technology that will exploit the characteristics of this smart material to create an actuator that is highly responsive, dynamic, lightweight and compact. These objective will motivate a doctoral thesis that is challenging and innovative.

3.2 Research Field

This project will focus on high response SMA actuation with a large stroke. The greatest challenge to overcome and the reason why this very promising technology is often left out of industrial application is due to its large response time which is in the order of a second. Heating the element is not the greatest challenge, the cooling time of the material must also be taken into account. It is important to note that it is often harder to dissipate heat rather than accumulate it. Thus, various heating and cooling solutions will be exploited and investigated during this project.

This investigation will consider the thermal and mechanical aspect of the material so as to create a highly responsive and dynamic actuator capable of achieving the required force output of traditional grippers. The main focus of the research will be the thermal and mechanical optimization. The conception of the gripper will include optimization of the geometrical topology of the SMA blades and the use of bistable systems such as buckled beams to create dynamic and high stroke actuators. The command strategies of the actuator will also be an important area of study due to the fact that the actuation of the SMA will involve the precise control of its temperature and resistance.

The symbiosis of the bistable system and the SMA technology can result in an innovative gripper system. The interplay between these two domains will be studied and explored in this thesis.

3.3 Specifications

The specifications of the actuator were obtained by comparing it with the specifications of the Schunk MPG-25 which is the most common pneumatic gripper used in industry, more specifically the primary gripper used by Mikron SA.

Table 1: Specifications of the required actuator

Criteria	Units	Value
Stroke	**mm**	3
Grip force	**N**	5
Commutation time	**ms**	50 - 100
Weight	**g**	100
Precision/Repeatability	**mm**	0.02
Number of stable positions	**#**	2
Volume	**mm^3**	120

4 State of the Art

This section will discuss the existing smart materials that are currently studied and used in the domain of actuators. The different techniques and integration systems will also be presented with the goal to compare the various approaches currently used.

4.1 Smart materials

In the field of engineering, ranging from haptics, automation and bio-medical fields, there has been a need to create actuators that are lightweight, compact and having force output. This creates a need for materials that can deliver high forces and strokes while remaining light and small meaning that the materials need to have a high work output.

On the basis of creating an actuator that can meet the demands of the currently implemented strategies while at the same time pushing the limits of the current technology, a thorough investigation of the available smart materials must be conducted. These materials have the ability to react to an external stimulus such as thermal electrical or magnetic and are thus referred to as *smart* or *active materials*. These materials have an inherent property that allows them to be exploited with a specific external stimulus so as to alter their mechanical characteristics or to create self-sensing technology.

There exist numerous types of smart materials and based on their properties, they can be classified into many types such as [1]:

- Piezoelectric materials

- Magneto-strictive materials
- Electro-active polymers
- Shape Memory Alloys

The aim of this project is to adapt these aforementioned smart materials to harness their specific behaviour and fabricate smart actuators. This implies that the system that incorporates the material is equally critical for the conception of the actuator. This section of the report will delved into different strategies used to harness the specific behaviours of the smart materials and integrate them into actuators.

4.1.1 Piezoelectric Materials

Piezoelectric (PZT) materials are a subgroup of smart materials that have the capability to produce voltages when a stress is applied. This behaviour is can also be expressed in the opposite direction i.e. a strain can be generated using an electric field. Piezoelectric materials are the most popular type of smart materials and the most commonly used piezoceramics, such as lead zirconate titanate, are available in the form of thin sheets. These sheets can then be stacked to create piezostack actuators.

PZT actuators are widely used due to the fact that they have small volumes, high output force and fast response times. But generally these materials have quite a small maximum stroke, generally around 10 μm. This implies that PZT actuators will require the integration of amplifiers that will increase the total displacement of the actuator.

The work performed by Lianf et al., 2018[2] displays a micro-gripper that is comprised of a PZT along with an integrated amplifying system. The study uses flexure-based mechanical structures as an amplifier so as to create a high stroke gripper without a great increase in the total volume of the gripper.

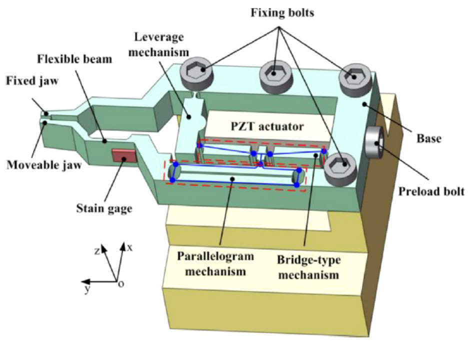


Figure 1: Mechanism of the PZT gripper[2]

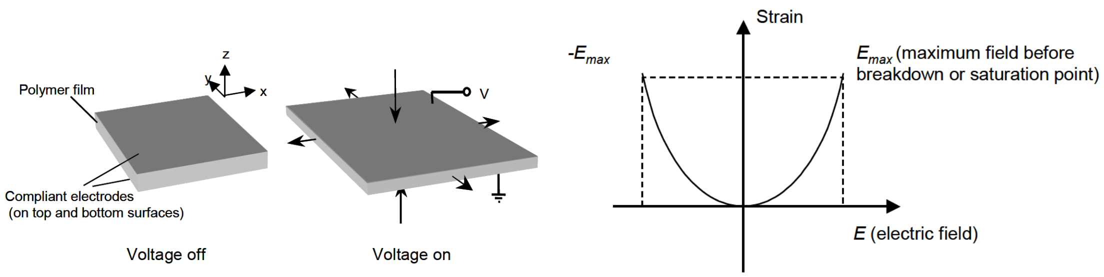
An interested approach to designing the amplification system has been observed in the study performed by Ruiz and Sigmund, 2018[3]. In this work, a large displacement PZT microgripper was designed from a rectangular plate using topology optimization. Here, the PZT plate is sandwiched between two electrodes and an input voltage is applied. This voltage will generate an electric field and will create a deformation in the PZT structure. The optimisation strategy is to increase the deformation by varying the shape and dimensions of the total structure. This strategy could be used in not just this instance but to optimize the actuation of any actuator built around an active smart material.

4.1.2 Electro-Active polymers

Electroactive Polymers (EAP) are smart material polymers that have the ability to alter their mechanical behaviour such as a change in shape or size when exposed to an electric field. They are most commonly used in the domain of actuators and sensors. EAPs emerged in the last few decades exhibiting large strains when exposed to electrical stimulus [4].

EAP can generate high strains, with Dielectric elastomers (DE) such as silicone exhibiting strains of about 63%[5]. Generally, these materials can generate strains much greater than rigid and fragile piezoeletric ceramics. EAP materials can also exhibit greater response times when compared to smart materials such as shape memory alloys, which will be explored in the next section. EAP can be very useful for their fast actuation times, low density and greater resilience and can, thus, be very convenient when create mechanical devices that are light weight and compact.

Dielectric Electroactive Polymers (DEAP) are based on the electromechanical behaviour of dielectric films when a compliant electrode is placed on each surface and a voltage is applied across them. This results in the DEAP to shrink in thickness and expand in area.



(a) Functional element of dielectric elastomer actuators. Polymer film compresses in thickness and expands in area when a voltage is applied across the film.

(b) Typical thickness or planar strain response to applied electric field for a film with no external loads.

Figure 2: Principle of operation of dielectric elastomer actuators[6].

The behaviour of the film is caused by the interaction of the electrostatic charges that are created on the opposing electrodes. By applying a voltage on the two electrodes, the electrodes are subjected to opposite charges cause an attractive force between them. The pressure, p, created can be calculated[7] using the following relationship :

$$p = \varepsilon_r \varepsilon_0 E^2 = \varepsilon_r \varepsilon_0 (V/t)^2 \tag{1}$$

where ε_r and ε_0 are the permittivity of free space and the relative permittivity of the polymer respectively, E is the electric field, V is the voltage applied across the electrodes and t is the thickness of the dielectric material.

Dielectric elastomer (DE) actuators are comprised of an elastomeric film that is platted on both sides with a compliant electrode as shown in figure 2a. The system is actuated when a high voltage is applied between the two electrodes. The main drawback of using DE actuators are the fact that they have very small fatigue life. By attempting to use the DE actuators in a continuous fashion, it will result in a short lifetimes and low reliability. In the paper written by Plante et al,. 2005[8, 9] or by Wang et al., 2018[10], the teams overcome the burdens of short fatigue life by coupling the DE actuator with a bistable element. Here the work displays DE actuators and a flip-flop bistable mechanism, where two agonistic-antagonistic actuators move a buckled beam back and forth. The DE actuator works as an external trigger mechanism that, when actuated, will force the bistable element into its opposing stable state.

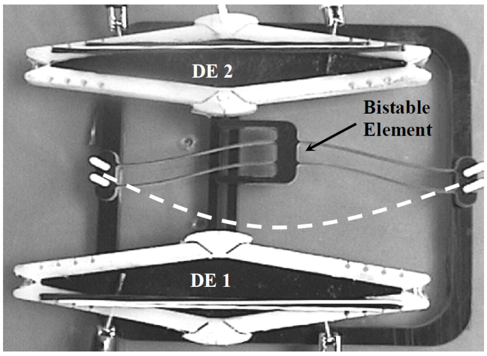


Figure 3: Flip-flop bistable actuator concept[11]

The work shows that the approach to use an antagonistic actuators with a smart present as a trigger mechanism are capable of approximately 10x greater volumetric energy density when compared to traditional flip-flop devices.

Another variant of the EAPs are the Ionic EAP which differ from the DEAP which are sometimes referred to as Electronic EAP[4]. The difference between the two variants arises from the fact that the actuation in Ionic EAPs is a result of diffusion of ions while in the traditional EAP, it is driven by Maxwell forces. An interesting Ionic EAP material are Ionic polymer-metal composites (IPMC). These IPMCs are a type of synthetic composite material that has a muscle-like behaviour under an applied voltage or electric field. In figure 4, the working principle is shown where as a voltage is applied, the diffusion of ions within the material causes a deformation. They are generally ionic polymers that are chemically plated with conductors[13].

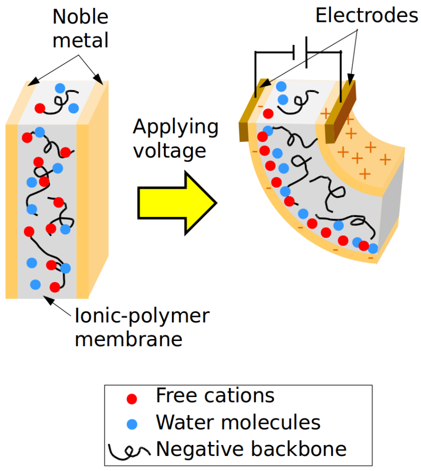
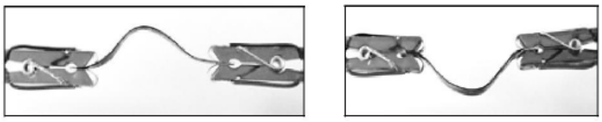
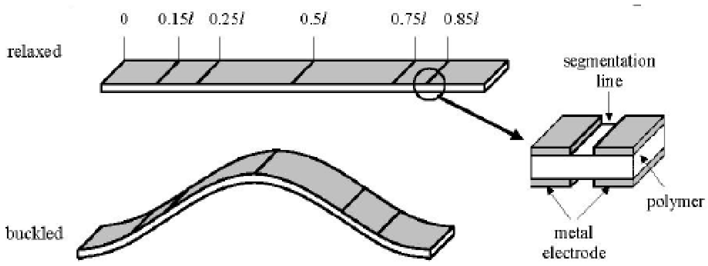


Figure 4: IPMC actuation principle[12].

IPMC bending actuators have been used primarily used as bending actuators and artificial muscles. A novel work conducted by Rossiter et al., 2006[14, 15] where a self-switching strategy is explored within the scope of a buckled bistable beam made entirely of the IPMC smart material. The work addresses many disadvantages experienced by using a classical bistable buckled beam system with an external trigger mechanism such as relaxation after actuation. low repeatability and the need for energy to maintain the stable states. The work concludes that by use of self-switching system, where the material itself is used as the buckled monolithic beam and switches from one stable state to another using applied voltage, the aforementioned disadvantages can be addressed. In this work, a buckled monolithic IPMC beam is separated into a number of electrically independent segments. The work, then, proposes various strategies to activate the segments so as to actuate the beam into transitioning or bifurcating from one of the stable positions to another.



(a) Nafion-based IPMC in the two buckled states.



(b) Segmentation at minimal static stress points.

Figure 5: Self-switching IPMC buckled beam[14].

4.1.3 Magneto-strictive materials

The magneto-strictive materials are category of smart materials that have the ability to alter their mechanical behaviour and shape when subjected to magnetic fields. Magnetic Shape Memory Alloys (MSMA) are an interesting type of magneto-strictive material. Here, the MSMA shows an interesting behaviour in which the material when deformed will tend to remain stable and retain its deformed shape. As the materials is introduced into a strong magnetic field, the crystals of the material are realigned and the material reverts back to its predeformed shape. These MSMAs are an attractive choice for an actuator using smart materials as they are capable of high strains around 10% while being able to prove fast response times[16].

The main drawbacks of MSMAs are the fact that they are quite a new technology implying that they are expensive and that finding suppliers is quite difficult. They are also quite brittle and are thus it makes it quite difficult to see them in different geometries and shapes.

The work presented by Gauthier et al., 2006[17] details the fabrication of a multistable actuator that is based on these MSMAs. Here the device is a push-pull actuator with a pair of agonistic-antagonistic MSMA beams. The active material is actuated using magnetic fields that are created using coils and concentrated using ferromagnetic cores. In figure 6, a working principle of the MSMA actuator can be seen.

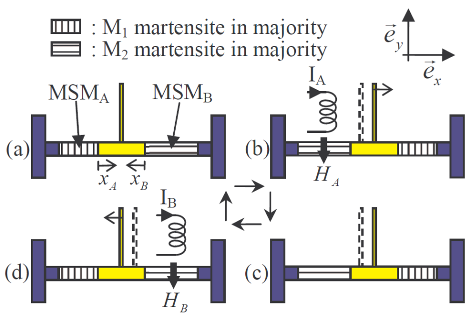


Figure 6: Principle of the actuator[17]

The shape memory effect (SME) seen in the MSMA requires the material to be deformed before the application of the magnetic field. Only after the deformation can the strain recover of the SME be observed. In this work, the team was able to create a multistable actuator by using a pair of MSMA. Here, the activation of the first MSMA deformed the opposing beam and vice versa. This results in a displacement and positioning of an end effector placed in between the MSMAs. This work shows the advantages and breakthrough of using an agonistic-antagonistic pair of material to resolve the problem of preconstraining the active material.

One of the important factors that leads to this technology not being widely used, is the fact that the activation of the MSMA requires magnetic fields of around 0.6 T. The work by Lu at al., 2009[18] shows the relationship between strain experienced by the material and the magnetic field density. The work shows an example of a differential rotating MSMA actuator that is powered using permanent magnets and ferromagnetic cores. This study shows that the limiting factor of these technology is the activation magnetic field required for the smart material. The resulting magnetic circuits will render the fabricated actuator to be heavy and bulky. Thus, the MSMA material will ultimately be unsuitable for the use in small and light weight actuators as desired by this research.

4.1.4 Shape Memory Alloys

Shape Memory Alloys (SMA) are a particular subgroup of smart materials that change their mechanical behaviour based on a thermal stimulus. Here, the material as with the MSMA, retains its shape when deformed and reverts back to its original shape when heated. Shape Memory Alloys (SMA) actuators provide us with an opportunity to create such actuators due to their high work output per volume which is around 10 J/cm^3[19]. This can be a 10-fold increase when compared to pneumatic actuators. The SMA actuators are thus able to provide large amounts of force when compared to their volume, making them particularly useful in compact, lightweight actuators.

NiTiNOL, the most used SMA, contains an interesting property known as the Shape Memory Effect (SME), which allows the material to return to its unloaded state when it is heated above its transition temperature.

Shape memory alloys such NiTiNOL show two important properties: the Shape Memory Effect (SME) and Superelasticity (SE)[20]. The property, this device aims to exploit is the SME. Materials exhibitng this property are able to return to a pre-defined shape when heated through a certain temperature range.

SMAs exist in various different stable phases which consists of the *Martensitic (M)* phase and the *Austenitic (A)* phase. The M phase can exist in either the *Twinned M phase* or the *Detwinned M phase* based on the stress experienced by the material. The SME is the effect that transforms the material from the A phase to its M phase, also known as the Martensitic transformation. The opposite transformation, from the M phase to the A phase, is known as Austenitic transformation. When the material reaches the Austentic transformation temperature ($\mathbf{A_s}$) threshold, the material will begin the Austenitic transformation. Inversely, as the material cools down to the Martensitic tranlsformation temperature ($\mathbf{M_s}$), it will begin the Martensitic transformation. Since these transformations occur over a range in temperature, we must heat and cool well beyond the transformation temperatures.

The SMA that in most likelihood will be used is a type of NiTiNOL variant with a relatively high transformation temperature (with A_s around 50°C) and thus exists primarily in the M phase at room temperature.

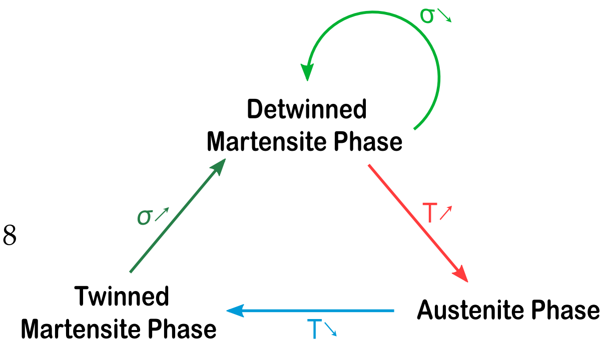


Figure 7: Phase transformation diagram of a shape memory alloy. Here σ represents the stress created

The phase transformations can be seen in figure 7. When a mechanical load is applied to the SMA while in its M phase, the material shears on an atomic level and this allows it to deform through a detwinning process at relatively low stress levels. This process allows the material to deform up to strains of 8%. Strains larger than this will cause dislocations which are irreversible. When the beam is then heated, the Austentite transformation from the detwinned M phase to the A phase, causes the beam to lose all the strain due to twinning, allowing the material to return to its original shape. This strain recovery allows the beam to revert to its pre-defined state while producing large forces.

4.2 Comparison

The aim of this section of the report is to find the most appropriate type of technology that can replace and innovate the current gripper that are employed in industry. In the current industrial era, most grippers employ the use of pneumatic actuators as their primary source of energy. Thus, to innovate the current domain of gripper, various important factors must be taken into account so as to have a point of comparison between the different smart materials and the presently used pneumatic grippers.

Table 2: Comparison of actuator performances

Actuator type	Stress [MPa]	Strain [%]	Efficiency [%]	Bandwidth [Hz]	Volumetric Work [J/cm^3]
Pneumatic [19]	0.7	50	90	20	0.175
NiTi SMA [19, 21, 16]	200	10	3	10^2	10
PZT [6, 16]	110	0.1	90	10^6	0.1
MSMA [21, 16]		6	90	10^3	0.15
EAP [6, 16, 21]	3	63	90	10^5	0.75
Human Muscle [22, 23]	0.8	100	35	173	0.035

5 Work Accomplished

6 Originality of the Research

The originality of this work lies in the pursuit of designing a gripper system that can harness the high work output of shape memory alloys. The gripper will be inspired by the various innovative smart technology explored within the state of the art. The state of the art shows that there exist many novel ideas for compact, light weight actuators using smart materials but non that are capable of delivering the high work output seen in SMAs. By harnessing the strengths of the SMA and the innovative strategies used in other smart material actuator systems, this research aims to explore the capabilities of the SMA material and develop an innovative gripper system. The following topics are expected to be studied over the course of this research project :

1. Investigation of the SMA capabilities through the study of an analytical and finite element model
2. Optimization of the topology of the active material component in the system for increased performances
3. Optimization of heating and cooling strategies of the SMA so as to decrease response times and bandwidth
4. Study of control strategies that will allow precise control of the gripper system using internal resistance of the SMA
5. Design and integration of a bistable system that incorporates an active smart material such as an SMA to achieve a responsive and powerful gripper system

7 Thesis Plan

The following list presents a non-definitive thesis plan :

1. Motivation of the Thesis
2. State of the art : smart materials and actuation structures
3. Topology optimisation
4. Thermal optimisation
5. Control
6. Prototyping and validation
7. Conclusion

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