Modeling a Flexible Miniature Module Actuated by Shape Memory Alloys

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Abstract—Miniature manipulators have a special role in applications that limited spaces exist. Some attractive applications are actuating catheters suitable tools in minimally invasive surgery and gripping and manipulating in small spaces. On the other hand, modular robotic systems are fast growing solutions for cases where the manipulator should be extended for different applications. The features of the applied module direct affect the overall property and performance of the developed system.

The major application of SMA actuators is developing miniature systems. In this paper, first of all, a basic concept for developing a flexible module is introduced. In the presented work, by attaching the wire on a flexible beam, the small strain of the SMA actuator resulted in a larger deformation in the module. The module incorporates several Shape Memory Alloy (SMA) actuators to create relative deflection between two parallel plates connected to each other through a flexible beam. SMA actuators are embedded around the flexible beam to produce deflection in different directions after actuation. By connecting various modules in a serial manner, a manipulator could be developed. In the design process of manipulator, a mechatronics approach is considered. Through the design process, the dynamic modeling of the system is simulated in Simulink of Matlab. In this way, previously verified model of Brinson is used for SMAs model. The provided platform of simulation assists in optimizing the dimensions of the designed module. Finally, the specification of a module working properly is suggested for applying as a manipulator.

Keywords—Modeling, Flexible, Shape Memory Alloy, Module.

I. INTRODUCTION

MICROMECHATRONIC technology is used to develop highly dexterous manipulators. One of the applications of micro manipulators is microcatheters which are long and slender surgical instruments used to treat vascular abnormalities. In classic catheters, actuating cables are used actively to bend the distal tip to look around the body cavity and also to position a surgical tool for interventive purposes. The drawbacks of the present endoscope are its lack of dexterity and the technical difficulties involved in introducing the scope efficiently into the human body without traumatizing the patient [1].

On the other hand, actuators based on shape memory alloys are becoming increasingly popular due to their characteristics of high power to weight ratio and smooth, silent operation. Another advantage of SMA actuators is their simultaneous actuation and sensing. These properties make them ideal for use in robotics. Furthermore, the stiffness benefit show through the application of shape memory alloys may provide much interest for application. This tends to shock absorption capability which is the weakness of classic actuators.

The main feature of SMAs is their ability to undergo large strains in the martensite phase and recover the strain after phase transformation to austenite through heat treatment afterward. SMAs as a group of smart materials show two distinct behaviors: shape memory effect (SME) and the super-elasticity. In the shape memory effect, the material has the ability to restore a previously defined shape or size when an appropriate thermal procedure is applied. In the super-elastic behavior, the material shows a large reversible strain. These two behaviors caused through the material crystalline phase change between two different phases called martensite and austenite. Martensite which is thermodynamically stable at the low temperatures is relatively soft whereas austenite, the high temperature phase, is relatively hard. The change in SMAs’ crystalline phase is not thermodynamically reversible which result in a temperature hysteresis behavior.

SMA seems to be the favorite actuator in developing micro catheters by researchers. Ikuta et al. used SMAs to develop an automated endoscope [2]. They made use of the resistance of the SMA actuators in their feedback control scheme to guide their snake-like robot around obstacles. The SMA springs are connected mechanically in parallel to actuate every part of the system. Fukuda et al. have developed a microactive catheter (MAC) with two DOFs [3]. The MAC is basically made up of three strips of SMA wires embedded at 120° intervals in a cylindrical housing made of elastic material. Haga et al. designed an active microcatheter actuated by distributed SMA coils [4]. The microcatheter actively bend towards the renal calyces, a part of the kidney was unreachable by conventional catheters. Tanimoto et al. incorporated a microforce sensor at the distal tip of their microcatheter [5]. With their device, they aim to measure the contact forces between the catheter’s distal tip and the walls of blood vessels. Microtactile sensors are also implemented using Multifunction Integrated Film technology [6]. These are mounted at the distal tip of the microcatheter and are used to detect the vessel walls for navigation purposes.

SMA materials are usually found in classic form of wire or
spring. The wire form of SMA although produce large forces, it provides very small deflection for robotic applications. This limitation has enforced the designers to add mechanisms for increasing the general deflection of the mechanism actuated by SMA wires. Kai [7] and Yang [8] introduced a Spatial-bending muscle SMA Actuator.

However, in some works, through special manufacturing methods, a special SMA actuator is developed to be a basic unit of a manipulator. Although this has resulted in suitable tools, it requires complex manufacturing methods like etching or laser cutting [9,10].

Connecting many interchangeable modules into a mechanical and functional assembly provides a modular system approach which may have many benefits in contrast to classical robotic systems. Robustness, versatility, low cost and wide range of applicability are the major properties of these systems [11]. Yoshida et al showed a miniaturized self-reconfigurable system actuated by SMA actuators [12]. Lee [13] presents a fabricated locomotive mechanism of a SMA biomimetic capsule type micro robot for endoscopy. Yoshida et al [14] introduced a modular system consists of micro modules with SMA torsional actuators. Hadi et al. developed a robotic module using shape memory alloy springs [15].

However some weaknesses such as slow speed of operation, nonlinear and hysteresis behavior and complexity of modeling has so far limited their potential application. Among the presented modular systems, few modules applied SMA as actuators. In addition, these actuators are used just in on/off mode and no positioning control system is implemented in applications.

In this paper a flexible module which employs shape memory alloy wires as the actuation mechanism is considered. Dynamic modeling of the module coupled to SMA as the actuator element is discussed in detail. The modeling is used to simulate the module behavior in different dynamic loadings.

A mechatronics concept is considered in the design process. It means that the hardware requirements of the system in miniaturizing, actuation and application is considered from the beginning of the design. The results show the applicability of the module concept and modeling for applying to real conditions. Further, a platform for designing real modular manipulators through the conceptual design of this paper is provided.

II. FLEXIBLE MODULE DESIGN

The structure of the module consists of a flexible beam which is elastic in large bending. Three SMA wires are stocked on the surface of the beam and provide a differential system to move the tip in the space. The position of tip is defined by two coordinates, \( \theta \) and \( \phi \) in Fig. 1. As the manufacturing technology is not under the focus of this paper, the methodology of construction is not elaborated in this paper.

As the SMA actuators act in one direction (usually in tension), a differential form of design is used for actuation. In order to providing the location of the module after activation, three strain gauges are mounted on the surface of the tube. The provided strains on the surface of the tube may be used to calculate the coordinates of the module in real. However, in this paper the SMA lengths are extracted from the simulated model. The module main parameter is the maximum deflection. This is mainly related to the module length and diameter. One of the goals of this paper is providing a method for estimating these geometrical parameters. The conceptual design of the module and the positional coordinates are presented in Fig. 1.

![Fig. 1 General concept of the module](image1)

![Fig. 2 deflected flexible module and the loading on the rigid end plate](image2)

![Fig. 3 A few combinations of three modules in developing a manipulator](image3)
transmission of electrical wires. Actuation and signal transmission between modules in a modular combination requires the wires. Fig. 2 shows the loading of the rigid plate mounted at the end of each module. Fig. 3 illustrates a few modular combinations produced by three actuated modules.

III. MODELING

A variety of models have been developed to describe the thermo-mechanical behavior of SMA. Among them, the constitutive Tanaka based models have been more interested for engineers, because of simplicity of application and measurable states. Brinson [16] developed a phenomenological model based upon previous works by Tanaka [17] and Liang [18]. Additionally, Elahinia worked on nonlinear control strategies for SMA wires and implemented his work for a rotary SMA actuated manipulator [19].

Based on the one-dimensional constitutive relation of Brinson, stress, strain, martensite fraction and temperature are related to each other by:

\[ \sigma - \sigma_0 = E(e - e_0) + \Omega(x_0 - x_0) + \theta_T(T - T_0) \]

where zero indices define the initial conditions of every state. In Eq. 1, \( \sigma \) is stress, \( e \) is strain, \( x \) is the martensite fraction, \( T \) is temperature, \( E \) is young modulus and \( \Omega \) is transformation coefficient.

Brinson provided a better description of SMA behavior by dividing the martensite fraction into two kinds, twinned and detwinned [16] in comparison to previously developed model of Liang and Rogers [18]. However, a major part of her contribution was related to calculating the martensite fraction in different thermodynamic loading. The first work of Brinson was improved at 2007 to better define the martensite fraction in more complex thermodynamic loadings [20]. This work is implemented in this paper for calculation of martensite fraction in the simulations.

In addition to the SMA model, equation 4 is used for defining heat transfer of the SMA:

\[ mc \frac{dT}{dt} = I^2R - hA(T - T_\infty) \]

where \( m \) is mass per unit length, \( c_p \) is specific heat coefficient, \( I \) is current, \( R \) is electric resistance, \( h \) is convection heat transfer coefficient and \( A \) is the SMA area for heat transfer.

In the module, three SMAs are coupled to make the configuration of the flexible beam. For simulating the module, the bottom plate in the module is fixed. So when the module is activated the movement of upper plate toward the bothom plate is considered.

Brinson have developed a model for a one-dimensional flexible beam [21,22]. In this paper the flexible beam provide two degrees of freedom. For developing the dynamic activation of the module, the upper plate loading may be considered as Fig. 2. So, the dynamic equation would be presented by:

\[
\begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix} =
\begin{bmatrix}
I_x & 0 & 0 \\
0 & I_y & 0 \\
0 & 0 & I_z
\end{bmatrix}
\begin{bmatrix}
\theta_x \\
\theta_y \\
\theta_z
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]

Considering the Z axis along the Mb, we can write:

\[ (M_{SMA})_z - M_b = I_z \ddot{\phi} \]

where \( M_{SMA} \) defines the moment produced by SMA forces, \( M_b \) is the bending moment, \( ID \) is the rigid plate inertia and \( c \) is a damping constant. \( M_b \) is calculated by:

\[ M_{SMA} = r_1 \times F_{SMA1} + r_2 \times F_{SMA2} + r_3 \times F_{SMA3} \]

where \( r_1, r_2 \) and \( r_3 \) define the location of SMAs and are illustrated in Fig. 2. The change in coordinate \( \theta \) is much lower than \( \phi \) in activation. In addition change of \( \phi \) mainly affects the SMA lengths. By a logical simplification through the low response of SMAs, the problem is considered semi-static for change of \( \theta \) and it is extracted from the static balance of SMAs’ forces and the bending moment. \( \theta \) is extracted from the direction of MSMA, so the direction defining \( \theta \) is perpendicular to MSMA. For a common beam, the curvature radius, bending moment, young modulus and moment of inertia would be related by:

\[ \frac{1}{\rho} = \frac{M_b}{E_b b} \]

For a deflected beam, from Fig. 2, \( \rho \phi = L \). Consequently (4) may be rewritten as:

\[ M_{SMA} - \frac{EL}{L} \phi - c \phi = ID \phi \]

In the following the equations are solved through simulations.

IV. SIMULATION

The model is simulated in MATLAB through the Simulink environment. In the simulations, a block concludes the model of every SMA actuator. In this block which is illustrated in Fig. 4, voltage and deflection are the inputs and force is the output.

Required blocks are coupled to make a dynamic system as presented in Fig. 5. A block solve equation (7), calculates the angular position of the module from the three SMA forces. In addition to \( \phi \) coordinate, \( \theta \) is extracted from the MSMA vector. Through the slow activation of the beam, \( \theta \) line has 90 offset with MSMA vector.

Another function solves the inverse kinematics of the module calculates the SMAs lengths from the angular coordinates by:

\[ l_i = (\rho - r_i \cos(\theta_i)) \times \phi \]

Consequently the loop is made and module angular positions are calculated knowing the input voltages of the SMAs.
In the designed module in this paper, the elasticity of the flexible beam is important in the maximum provided deflection after activation. It seems that low strength materials provide more deflection. However, it should be verified through simulations.

By a general look to the usual materials, the range of Young's modulus is reported in Table I.

### TABLE I
THE RANGE OF YOUNG MODULUS FOR DIFFERENT MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>200</td>
</tr>
<tr>
<td>Balls</td>
<td></td>
</tr>
<tr>
<td>Fiberglass Yarn</td>
<td>72</td>
</tr>
<tr>
<td>Cellophane Film</td>
<td>3</td>
</tr>
<tr>
<td>Nylon Sheet</td>
<td>2</td>
</tr>
<tr>
<td>Nitrile Rubber</td>
<td>Very low</td>
</tr>
</tbody>
</table>

In addition to Young's modulus, the diameter of the flexible beam also affects the maximum deflection. To show this effect in the simulations, the maximum value of coordinate $\phi$ provided in the flexible beam is calculated for different Young's modulus and beam diameters. The results of simulation when one of the actuators is activated are reported in Table II.

### TABLE II
MODULE MAXIMUM DEFLECTION FOR DIFFERENT YOUNG MODULUS AND BEAM DIAMETER.

<table>
<thead>
<tr>
<th>$D_b$ (mm)</th>
<th>$E=.5$ GPa</th>
<th>$E=1$ GPa</th>
<th>$E=2$ GPa</th>
<th>$E=3$ GPa</th>
<th>$E=4$ GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.5</td>
<td>52.7</td>
<td>41.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.75</td>
<td>-</td>
<td>35</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>88.5</td>
<td>59.2</td>
<td>34.5</td>
<td>24.2</td>
<td>18.6</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>20.9</td>
<td>11.1</td>
<td>7.6</td>
<td>5.8</td>
</tr>
<tr>
<td>4</td>
<td>17.3</td>
<td>9.3</td>
<td>4.8</td>
<td>3.2</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>5.5</td>
<td>2.9</td>
<td>1.5</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>8</td>
<td>2.4</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>1.3</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The results are also presented in figure 5 through a graph. It is illustrated that increasing the Young's modulus decrease the deflection of the beam. In the simulations, it is found that the range of 0.5 to 4 GPa for Young's modulus provide reasonable values for the goal parameters. As a result using elastomer, a polymer with the property of elasticity generally having notably low Young's modulus and high yield strain compared with other materials, is a proper material for this application. However through the guidelines of Table III, a proper value for geometrical parameters in every special design would be extracted by running a few simulations.

### TABLE III
THE VALUE OF CONSTANTS USED IN THE MODEL

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Definition</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_L$</td>
<td>Maximum shear strain</td>
<td>0.067</td>
<td>-</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Phase transformation contribution factor</td>
<td>$G\gamma_L$</td>
<td>Gpa</td>
</tr>
<tr>
<td>$\theta_T$</td>
<td>SMA spring thermal expansion factor</td>
<td>0.55</td>
<td>MPa/°C</td>
</tr>
<tr>
<td>$T_\infty$</td>
<td>Temperature of environment</td>
<td>20</td>
<td>°C</td>
</tr>
<tr>
<td>$m$</td>
<td>SMA wire mass</td>
<td>1.14e-4</td>
<td>Kg</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat of SMA spring</td>
<td>840</td>
<td>J/Kg. °C</td>
</tr>
<tr>
<td>$R_A$</td>
<td>SMA resistance in austenite</td>
<td>45</td>
<td>Ω</td>
</tr>
</tbody>
</table>
VI. CONCLUSIONS

In this paper, a novel robotic module is designed based on shape memory actuators. Simplicity, low size and weight in addition to flexibility of the module may be interested for applying to miniature manipulators. Further, the modular concept considered in the conceptual design, help fast change in manipulator configuration.

The SMA model used in this paper has been verified before. Adding this model to model of the flexible beam developed in this paper resulted to a complete model of system. The integrated model is able to be used in different thermodynamic loadings. The model was implemented in the simulations of this paper. The results present a reasonable behavior of the module. Further, the major parameters of the module which are the produced deflection and geometrical parameters would be extracted for a common design. The nonlinear behavior of SMA makes it difficult to calculating this value without an exact model. Using the simulations conclude a detail model helps providing the parameters. As shown, it generally depends on young modulus of flexible material of the beam could be followed for a common design.

REFERENCES


