Lightweight Robotic Arm Actuated by Shape Memory Alloy (SMA) Wires

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Abstract—The current paper discusses the design, modeling and control of a Light weight robotic arm actuated by Shape Memory Alloy (SMA) actuators, usable for applications such as Aerial Manipulator. Compared to servo motor based robotic arm the proposed design has an added advantage of light weight and high force to mass ratio, but further introduces the problem of nonlinearity such as Hysteresis into the system. A nonlinear dynamic model of the hysteresis robotic arm is systematically developed to perform closed loop simulations. A Joint Space control is performed using Variable Structure Control and the closed loop performance is successfully verified by simulation studies.

Keywords—Light weight robotic arm, aerial manipulator, Shape Memory Alloy (SMA), joint space control

I. INTRODUCTION

The design and development of Light Weight Robotic arms have attracted more attention recently in the context of Aerial Applications. By attaching a robotic arm one can increase the capability of aerial vehicles such as quadrotors or vehicles with hovering capabilities. Aerial Manipulators that is an Aerial Vehicle attached with a manipulator can transform an Unmanned Aerial Vehicle (UAV) from passive sensor to an active actuator by performing tasks such as object manipulation, assembly, transportation etc. The limited availability of payload on Micro Aerial Vehicle has motivated the robotic community further study the problem [1]–[3].

Let us continue here briefly with the existing literature. In [1], [4] the authors had designed and controlled a hyper-redundant manipulator for Mobile Manipulating Unmanned Aerial Vehicles. Here the objective was use the redundancy of the manipulator to minimize the influence of the manipulator on the stability of the Aerial Vehicle. Here at least 9 servo joints were used which lead to a total weight of approximately 1.3 Kg. In [5] the authors discussed the mechanical design of a 6 degree-of-freedom (DOF) aerial manipulator for the purpose of assembly using UAVs. Here they used commercially available servos for the actuation which lead to a total weight of 1.5 Kg. In [6] a light weight compliant 2 DOF robotic arm was developed using linear servos where the total weight of the arm was about 325 grams. In [7] the authors modeled and controlled a 3D printed 5-DOF light weight robot arm which had lead to a total weight of 250 grams.

With respect to the above contributions the current paper proposes a light weight robotic arm actuated by Shape Memory Alloy (SMA) wires which weighs only 48 grams. SMA actuators, which can be categorized under smart material systems with Shape Memory Effect (SME), have special characteristics like high force to mass ratio, small size, noiseless operation, and bio-compatibility which makes them a great alternative to conventional hydraulic, electric and pneumatic actuators. In spite of all its advantages they are still slow and highly nonlinear systems with Hysteresis problem, which is challenging to perform precise control operation. SMA wires are being used in applications from medical implants like inter-arterial supports [8], [9], dental applications [10], car mirror actuators [11] or SMA based motors [12], and robotic manipulators as arms, hands or robotic fingers [13]–[15] to general purpose actuators [16]–[21].

The key contributions of this article can be categorized into two. The first contribution include Mechanical design and modeling of a light weight robotic arm based on an existing SMA joint actuator [18]. Secondly the contributions include application of a Nonlinear control technique to perform simulation studies on a Nonlinear Manipulator with hysteresis problem. The reminder of the paper is organized as follows. First we describe the SMA based robot arm design including SMA actuation and mechanical design. This is followed by modeling of SMA based robotic arm and the independent joint space control. Finally the simulation results and conclusions are presented.

II. SHAPE MEMORY ALLOY (SMA) BASED ROBOT ARM DESIGN

The robotic arm presented here consists of two links with one degree of freedom (DOF) actuated by two antagonistic SMA wires. The main goal of this work is to design and develop a light-weight robotic arm to be later used with robotic aerial vehicles, since it is a great challenge to make an optimal use of available payload of an aerial vehicle such as a quadcopter. We propose a light-weight design, which enables the arm to be implemented without significantly decreasing the quadcopter’s available payload. Here we will first discuss the concept of SMA based actuation and then the mechanical design of robotic arm.
A. **SMA based Actuation**

The SMA are a group of metallic alloys with Shape Memory Effect (SME). This phenomenon is the ability of the material to recover its original shape after being deformed when subject to the appropriate thermal procedure. This effect is caused by a transformation of the material’s crystalline structure. The most common types of SMA are the NiTiTium SMA wires (NiTi wires). When the NiTi wire is at lower temperature (martensite state) it can be deformed with a relatively low stress. When heated, a phase change occurs and the material transforms to austenite state and recovers its original form and size. The capability to recover form and shape supports their usage in actuation but at the same time introduces significant challenges due to the presence of nonlinearity such as hysteresis. The hysteresis present in our current light weight robotic arm can be seen in Fig. 1. Here we can see the presence of a double loop hysteresis due to the interaction of the antagonistic SMA wires.

B. **Mechanical Design**

A Computer Aided Design (CAD) model of the proposed robotic arm is shown in Fig. 2. The robotic arm is actuated by two antagonistic SMA wires. These wires apply force over a mechanical joint couple with a torsion spring, this coupler was proposed in [18]. The end effector is attached to the Coupler 1 (Fig. 2) by a 15 cm long carbon fiber link. This coupler is joined through a torsion spring to the Coupler 2 (see Fig. 2), that allows to control the overall stiffness of the mechanical system by adjusting the position of the second coupler so the force of the spring adapts as necessary. The winding wheels are a winding mechanism for the SMA wires, which enables the use of longer SMA wires for larger movement range without increasing the size of the links.

The end effector is actuated by a third SMA wire with bias spring, so the model is completely motor-free. The design is planned to be constructed partially by 3D printing and partially by custom made carbon fiber parts, achieving a total weight of 48 g. In spite of the light-weight characteristic, the arm is capable of lifting a load up to 500 g, and can be increased by implementing thicker SMA wires. This amount of load is not far from the limit payload of a small quadcopter.

III. **SYSTEM MODELING**

The robotic arm proposed by our team was modeled by two highly coupled subsystems: the SMA wires model and the dynamics of the robotic arm. This two subsystem are related through the kinematic model as shown in Fig. 3. The SMA wires model is further divided into three more subsystems: thermal dynamics, phase transformations and constitutive model. The SMA wire model was proposed in [17] and adapted to fit the characteristic of dynamic stress of an antagonistic SMA wire actuator. Fig. 4 shows the block diagram of the SMA wire model. Each sub-model will be explained in more detail in the next sub-sections.

A. **Heat Transfer Model**

The heat transfer model consists of natural convection for cooling and electrical heating by Joule effect [17]:

\[
\frac{m_w c_p}{dt} \frac{dT}{dt} = \frac{V^2}{R} - h A_w (T - T_{amb})
\]

where \( V \) is the voltage, \( R \) is the electric resistance per unit length, \( c_p \) is the specific heat, \( m_w \) is the mass per unit length, \( A_w \) is the wire surface area, \( T_{amb} \) the ambient temperature and \( T \) the SMA wire temperature. The heat convection factor \( h \) is approximated by a second order polynomial of the temperature as:

\[
h = h_0 + h_2 T^2
\]
respectively. The Young’s modulus $E$ for martensite and austenite transformation $M$ where the sub-index indicates $M$ for martensite and $A$ for austenite. And
\[
\sigma = E\dot{\varepsilon} + \Omega \dot{\xi} + \Theta \dot{T}.
\] (5)

Here $\Omega$ and $\Theta$ represent the thermal expansion coefficient and phase transformation constant respectively. The Young’s modulus $E$ was adapted to meet the dynamic stress characteristic of antagonistic SMA wire
\[
E = \xi E_M + (1 - \xi) E_A,
\] (6)

where the sub-index indicates $M$ for martensite and $A$ for austenite. And
\[
\Omega = -E\varepsilon_0
\] (7)

where $\varepsilon_0$ is the initial strain.

D. Kinematic and Dynamic Model

1) Kinematic Model: This model relates the SMA wire model with the dynamics of the robotic arm. The SMA wires strain is directly proportional to the angular position of the robotic arm. They are related kinematically as
\[
\dot{\varepsilon}_i = -\frac{r_i \dot{\theta}_i}{l_0}
\] (8)

where $r_i$ is the respective coupler radius, $l_0$ the initial length of each wire and $\dot{\theta}_i$ the angular velocity of each coupler.

2) Dynamics: The dynamic model describes the dynamic behavior of the robotic arm mechanism. This model shows the relation between couplers, applied external forces (torsion spring and SMA wires) and load effects. The mechanical system dynamic behavior can be described by the follow general dynamic model:
\[
J \ddot{\theta} = \begin{bmatrix} \tau_{w1}(\sigma) - \tau_s(\theta) - \tau_g(\theta) - \tau_{load}(\theta) - b_1 \dot{\theta}_1 \\ -\tau_{w2}(\sigma) + \tau_s(\theta) - b_2 \dot{\theta}_2 \end{bmatrix}
\] (9)

where $b$ is the friction of the couplers and $\tau$ is the torque applied over the mechanical system by the SMA wires ($w$), the torsion spring ($s$), the weight of the gripper ($g$) and the load. This model was developed in two parts: First the couplers mechanism, gripper, load and links dynamics and second the mathematical model of $\tau_{w}$ and $\tau_s$. The first part of the dynamics was directly obtained from the CAD design shown in Fig. 2 developed in Autodesk/Inventor environment. The use of this approach brings great advantages as the automatic inclusion of the exact geometry of the pieces, masses, inertias and centers of mass, which are critical parameters for the dynamic analysis. The CAD model is imported via the SimMechanics toolbox in order to obtain a continuous dynamic MATLAB/Simulink model of the mechanical system.

The second part of the dynamics was derived from basic physical laws. The SMA wire force is inversely proportional
to the stress ($\sigma$) which can be calculated by integration of Eq. (5). Then the torque can be computed as follows:

\[ \tau_{wi} = F_w i r_i = A \sigma \nu r_i \]  

(10)

where $r$ is the coupler radius and $A$ the transversal area of the wire. The torsion spring torque $\tau_s$ is calculated as

\[ \tau_s = k_s (\theta_1 - \theta_2) + b_s (\dot{\theta}_1 - \dot{\theta}_2) \]  

(11)

where $k_s$ is the spring constant and $b_s$ is the spring's friction factor, $\theta_1$ and $\theta_2$ are the angular position of each coupler respect to $X$-axis.

IV. JOINT SPACE CONTROL

The joint space control regulates the angular position of the end effector, which is attached to the coupler 1 (see Fig. 2) so the controlled variable is the angle of coupler 1 with respect to the $X$-axis ($\theta_1$). For this regulation problem a Variable Structure Control (VSC) is implemented. This is a sliding mode control law. SMA 2 adjusts the stiffness of the joint. This means that the sliding mode control was set as follows: The boundary layers $\phi_1 = 10^\circ$, $\phi_2 = 7^\circ$ degrees, and voltage constraint $V_{1H} = 6.5$ V, $V_{2H} = 6.5$ V. The results of this simulation are shown in Fig. 5. In Fig. 5 it can be seen that the system is not capable of tracking the reference during the first semi-cycle, it takes around 20 seconds for the system to reach the reference. This is attributed to the sudden increased of the reference during the first cycle. During this period there is a maximum overshoot of 6.6$^\circ$. After 20 seconds, the system follows the reference with good accuracy, the error oscillates between -0.2$^\circ$ and 0.3$^\circ$ but during the inflection points, as shown in Fig.6. The error increases when the reference goes trough an inflection point, and at these points the error range is between -2.8$^\circ$ and 2.5$^\circ$. This increased error last around 4 seconds, after this transitory period the average tracking error is $\pm 0.3^\circ$. Figure 7 illustrates the inputs of the system during the closed-loop test. The inputs are given in Volts and they are limited to avoid thermal damage to the SMA wires, which can destroy its memory effect. Both SMA wires have the same high voltage limit, however, the boundary layer for each wire is set at different levels as mentioned before. The higher limit for $\phi_1$ is fixed in order to achieve a faster response from the control law. SMA 2 adjusts the stiffness of the joint. This means that the SMA 2 does not directly actuate over the end effector, and thus its velocity of response is not as critical as SMA 1. In Fig. 7 we can see the rough reaction of the controller during the first cycle of tracking and inflection points. However, after

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### Table I

<table>
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Fig. 5. Tracking response for sinusoidal reference
The given SMA based robotic arm is currently under construction. Future work will be oriented to construct and to test experimentally the presented design. In addition, the proposed SMA based robotic arm will be attached to a small quadcopter for flying manipulation analysis. Furthermore an ON/OFF control will be develop for grasping control.

REFERENCES


