Mechatronics Design and Kinematic Analysis of SMA Spring Actuated Parallel Manipulator

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Abstract. Flexible parallel manipulators can be used as an orienting device because of their precise position ability and better stiffness. The flexibility to the manipulator induces challenges in the selection of actuator, sensors and control. The paper presents a novel mechatronics design of a flexible symmetric parallel manipulator with minimum number of actuators used as an orienting device. Shape memory alloy springs (SMA) are used as an actuator because of ease of integration and higher deflection. In order to avoid any contact type sensor which could affect the compliance of the manipulator, the position of SMA spring is calculated indirectly from the kinematic model with the end effector orientation data measured from IMU sensor. The complete experimental set up design including electrical and control circuitry is explained in detail in the work. Preliminary open loop test is conducted on the prototype to understand the SMA response to various current input and to verify the effectiveness of the kinematic model in the actuator length measurement. Closed loop control based on ON/OFF control is implemented in the controller and is tested for step input.

1. Introduction

Parallel manipulators have closed loop kinematic chain which provides better positioning accuracy and stiffness [1-2]. They are popularly used as motion simulators, orienting devices or tools for precise positioning. Flexibility in the structure requires the use of non-conventional actuators and sensors which does not affect the compliance of the mechanism [3]. Shape memory alloy (SMA) are popular actuator used in the development of the flexible miniature robots. SMA changes its crystalline structure from soft martensite to stiff austenite on heating. Joules heating method is popular for actuating SMA in robotics application. Many popular robotic mechanism using SMA can be found in literature. Sreekumar et.al [4] has presented a compliant miniature parallel mechanism fabricated from Be-Cu and actuated by 3 SMA wires placed 120 degrees apart with Nitinol super elastic beam as central hinge. Alireza et.al [5] developed a flexible parallel robot using SMA springs to overcome the limitation of low strain of SMA wire. The top and base plate are square shaped connected by universal joint at the center. The use of SMA spring even though increases the overall strain but complicates the control due to the high hysteresis and actuation delay due to inductive effect. Eric et.al [6] have demonstrated the use of SMA based mechanism for the automatic control of orientation of automotive mirror.
The paper has presented a design of a parallel manipulator actuated by minimum number of SMA spring actuator and model based feedback mechanism to avoid any contact type sensor which could affect the flexibility of the mechanism. The electrical and control circuitry used in the experimental set up is explained in detail. Kinematic model is derived and presented in the work which is used along with the end effector orientation data to compute actuator length and also the workspace is plotted with the model. Preliminary tests are conducted on the manipulator prototype and the results are discussed in the experimentation section.

2. Mechatronics Design
The experimental set up is a typical example of a mechatronic system consisting of 4 subsystems namely parallel mechanism, actuators, sensor system and the controller (electrical and control circuitry). The subsystems are described below in detail

2.1. Manipulator Design
The parallel mechanism is a closed loop structure with a base plate and the moving plate called as end effector. The base plate and the end effector are triangular shaped of side 100 mm and width 4mm made from acrylic sheet. The size and dimension of the base plate and the end effector plate is same to reduce the actuator coupling effects [7] and maintain symmetry to assist antagonistic mechanism for the actuators. The end effector (moving plate) is connected to the base plate using universal joint of length 80 mm with the help of male and female coupler attached to the end effector and base plate respectively. The inclusion of universal joint to the mechanism restricts the end effector to 2 DOF motion namely roll (rotation about X axis) and pitch (rotation about Y axis). The end effector is manipulated using three SMA actuators connected at the vertices of the triangular base and moving plate using a pin joint connector. The pin joint connector is electrically conductive and holds the electrical wires which provide activation current to the SMA actuators. The use of acrylic sheet plate for the end effector and base plate has helped in insulating the pin joint from rest of the robot body. The manipulator is a lightweight manipulator of height 88 mm and overall weight of 260 gm. including the sensor and all peripherals. The manipulator is a general purpose manipulator intended to be used as and orienting device. The dimension and the CAD model of the manipulator is shown in Figures 1(a) and 1(b).

![Figure 1. (a) CAD model of the proposed manipulator (b) Dimension of the manipulator](image)

2.2. Actuators
The actuators in the manipulator is an important factor which defines the flexibility and the compliance of the manipulator. The use of conventional actuators like motors or hydraulic limits the flexibility and miniaturization possibility and scaling down the size of such actuators drastically affects the output forces. Non-conventional smart actuators like Shape Memory Alloy (SMA) are popular choice for miniature and flexible robots due to its ease of integration, simple actuation and easy availability and cost effectiveness. SMA actuators are available in different forms, wires and springs are popular for robotic application. The wires provide limited strain (max. 5% of total length)
which require additional amplification techniques to provide larger deflection [8] but the springs on the hand provide larger deflection but suffers from larger hysteresis and time delay due to inductive nature [5]. The manipulator in our study has used SMA springs to provide larger deflection to the end effector without any use of complex amplification techniques. The SMA used is an alloy of Nickel-Titanium (49%-51%) procured from Dynalloy with spring diameter of 6mm and wire diameter of 3mm. The SMA actuators works on the principle of crystallographic transformation when temperature is changed from low temperature martensite to high temperature austenite. At martensite temperature, the SMA can be deformed easily and on reaching the austenite temperature, it regain the predefined shape. The SMA actuation is done using Joules heating technique where controlled current is passed through SMA to attain desired activation temperature. The maximum current limit is maintained to 2.2 A to avoid overheating of SMA. The SMA actuators used is a one way SMA and the bidirectional motion is achieved by the antagonistic mechanism or cocontraction of antagonistic pair of actuators. In order to assist the antagonistic mechanism, the actuator connecting point as well as the manipulator plates (base and end effector) are made symmetric as possible.

2.3. Sensors and Data Acquisition
The sensors are most important part of the manipulator which provide feedback data for closed loop control and also provides sufficient information of important system states during experimentation. The main objective of the orientation control of the end effector is achieved by the actuation of the linear SMA spring actuator which requires the position information of the SMA spring during the trajectory for the proper control. The flexibility of the SMA spring does not allow the use of stiff sensor or any contact type sensor which could thereby affect the compliance of the manipulator [3]. Hence, to avoid the use of any contact type sensor for position measurement, an IMU (Inertial measurement Unit) placed at the center of the end effector along with the kinematic model is used to determine the instantaneous position of the SMA spring actuator. The IMU (MPU6050) consists of gyroscope and accelerometer which is fused using complimentary filter to obtain accurate X and Y axis orientation of the end effector. The IMU is connected to Arduino Mega board and uses I2C serial communication protocol to transfer data. The experimental set up also uses current sensor (LEM LTS 6-NP) to observe the current through the SMA actuators during experimentation. The current sensor is an analog type and the signal is acquired using the data acquisition device (NI cDAQ9174).

2.4. Controller
The controller is the core brain of the setup which runs the control algorithm, gets all the input sensory data and delivers the output control signal to the system under control. The controller as a whole consist of the core processor, data acquisition device and the driver circuits. The workstation with INTEL Xeon 64 bit, 3.7 GHz processor and 24 GB internal RAM is used as the core processor which runs the control algorithm. The control algorithm is developed in MATLAB/Simulink environment for ease of control prototyping and the data acquisition toolbox manages the communication between the controller and input/output modules. NI cDAQ9174 is used as a data acquisition device which carries analog input ( NI 9219) and analog output modules (NI 9264) and uses serial communication to communicate with the processor. The analog input module gets the data from the current sensor and the output module delivers the control signal from the processor to the current driver. The current driver (L298D) is used to amplify the control signal to the desired current output to actuate the SMA actuators. The driver takes 0-5V as input and delivers the maximum current of 3A at 5V. The Arduino Mega board which holds the IMU data is also connected to the controller through USB serial communication. The overall system architecture is shown in Figure.2
3. Kinematic Model

The manipulator prototype considered in the research is a 2 DOF parallel manipulator with roll and pitch motion. The frame assignment and vector notation is described in Figure 3(a). The top view at the initial position is shown in Figure 3(b). The frame assignment and the vectors used in the study can be described as follows. Let \( \{B\} \) define the fixed coordinate frame attached at the centroid of the base plate with axes represented as \((XB, YB, ZB)\), \(\{E\} \) define the moving end effector frame attached at the centroid of the end effector plate with axes represented as \((XE, YE, ZE)\) and \(\{J\}\) define the universal joint frame attached at the center of the orientation point with axes represented as \((XJ, YJ, ZJ)\). \(r\) define the radius from the base or end effector center, \(\alpha_i\) is the symmetric distribution angle where \(i=1,2,3\), \(d_i\) is the length of the SMA actuator which is the controlled parameter, \(l_1\) and \(l_2\) is the fixed link length and movable link length of the universal joint. \(A_i\) and \(B_i\) define the actuator connecting point on the end effector plate and the base plate respectively. \(BR_J\) define the transformation matrix between frame \(\{J\}\) and \(\{B\}\). As only two among the six cartesian pose variables of the end effector are independent, the end effector point \(P\) can be located by orientation angles (roll and pitch) or by end effector position \(X, Y, Z\) which is again a function of end effector orientation angles expressed in the base frame \(\{B\}\). Referring to Figures 3(a) and 3(b), the position of \(A_i\) in frame \(\{E\}\), position of \(B_i\) in frame \(\{B\}\) and transformation matrix \(B_{RE}\) can be expressed as follows:

\[
(EA_i)_E = \begin{bmatrix} r \cos \alpha_i \\ r \sin \alpha_i \\ 0 \end{bmatrix}
\]

\[\text{(1)}\]

\[
(BB_i)_B = \begin{bmatrix} r \cos \alpha_i \\ r \sin \alpha_i \\ 0 \end{bmatrix}
\]

\[\text{(2)}\]

\[\text{Where } \alpha_i = \frac{2i - 3}{3} \pi / 3\]

The overall rotation matrix can be written using the roll and pitch rotation as

\[
R^B = rot(Y, \theta_y) \times rot(X, \theta_x)
\]

\[\text{(3)}\]

\[
R^B = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}
\]

\[\text{(4)}\]

\[
R^B = \begin{bmatrix} \cos \theta_y & \sin \theta_x \sin \theta_y & \sin \theta_y \cos \theta_x \\ -\sin \theta_y & \cos \theta_x & -\sin \theta_x \\ 0 & \cos \theta_y \sin \theta_x & \cos \theta_y \cos \theta_x \end{bmatrix}
\]

\[\text{(5)}\]

\[
(BE)_B = [X \\ Y \\ Z] = (BJ)_B + (JE)_B
\]

\[\text{(6)}\]

\[
= \begin{bmatrix} 0 \\ 0 \\ l_1 \end{bmatrix} + R^B \begin{bmatrix} 0 \\ 0 \\ l_2 \end{bmatrix}
\]

\[\text{(7)}\]
3.1. Inverse Kinematic Solution

The inverse kinematics for a parallel manipulator aims to compute the actuator length for a desired pose of the end effector. In our case, computing the SMA actuator length \( d_i \) for a given end effector orientation \( (\Theta_X, \Theta_Y) \).

From the Figure 3(a), the vector loop equation can be written as

\[
d_i \overline{u}_i = (A_i B_i) = (BE)_B + (EA)_B - (BB)_B
\]

\[
d_i \overline{u}_i = (A_i B_i) = \begin{bmatrix} X + r_1 \cos \alpha_i + r_2 \sin \alpha_i - r \cos \alpha_i \\ Y + r_2 \cos \alpha_i + r_2 \sin \alpha_i - r \cos \alpha_i \\ Z + r_3 \cos \alpha_i + r_2 \sin \alpha_i \end{bmatrix} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}
\]

The length of the actuator can be computed by taking the Euclidean norm of eqn.(10)

\[
d_i = \| A_i B_i \| = \sqrt{a^2 + b^2 + c^2}
\]

3.2. Workspace Computation

The inverse kinematic equation is used to compute the workspace of the manipulator. The SMA actuator has a length of 8 cm at home position of the manipulator when both axis orientation are zero. The actuator limit for the manipulator is chosen such that maximum contraction is 5 cm from home position and 13 cm of maximum extension from home position. The overall Cartesian orientation limit for both the axis is limited to -15° to +15° which is under the maximum actuator limit considered. The workspace plot is computed using the algorithm 1. Figure 4 shows the workspace plot for the manipulator.
Algorithm 1 Computing the workspace of the manipulator

**Input:** $\Theta_X, \Theta_Y$
**Output:** $X,Y,Z$

**Initialization:** $a_i, l_1, l_2, r$

1: for $\Theta_X = -15^\circ$ to $+15^\circ$
do
2: for $\Theta_Y = -15^\circ$ to $+15^\circ$
do
3: Compute $X, Y, Z$ using eqn. (8)
4: Compute eqn. (11) and check for actuator limit
5: if (actuator length $\leq$ actuator limit) then
6: Store value of $X, Y, Z$ for every iteration
7: end if
8: end for
9: end for
10: return $X, Y, Z$

4. Experimentation and Results

Preliminary test is conducted on the manipulator prototype and the experimental set up developed in the laboratory.

4.1. Open Loop Test

Open loop test is conducted on the manipulator to understand the characteristics of the SMA actuator response coupled to a parallel mechanism. Four different current limits (0.5A, 1A, 1.5A and 2A) are applied to the individual actuators and also in the combination of two actuators as shown in Table 2 and the response of the manipulator orientation is tabulated. The length of the actuator is measured physically using vernier caliper as shown in Figure 5(a) and also using the kinematic model and is included in the Table 1 to understand the correctness of the kinematic model in calculating the actuator length while in motion. The average error of position estimation of each actuator by both the method is plotted as shown in Figure 5(b) which shows good estimation with average error of 0.03 cm and suggest the possibility of using the model to compute the actuator length for the closed loop control. The open loop response of individual axis is shown in Figures 5(c) and 5(d) for a current of 1 A applied to the actuator till 2 sec. For a positive Y axis orientation actuator 1 and actuator 2 is actuated and for positive X axis orientation, actuator 2 and actuator 3 is oriented as per the structural and frame axis property of the manipulator for the open loop response.
Figure 5. (a) Physical measurement of actuator length (b) Average error plot (c) open loop response for X axis (d) open loop response for Y axis

Table 1. Open Loop test result and actuator length measurement

| Active Time | Input current | Model measurement | Physical measurement | Orientation |
|-------------|---------------|-------------------|----------------------|-------------|
|             | I₁  | I₂  | I₃  | l₁  | l₂  | l₃  | l₁  | l₂  | l₃  | Θₓ   | Θᵧ   |
| 1.5 s       | 0.4 | 0   | 0   | 7.968 | 8.015 | 8.017 | 7.87 | 7.98 | 7.99 | 0.27 | 0.17 |
|             | 0   | 0.4 | 0   | 8.059 | 7.931 | 8.01  | 7.98 | 7.86 | 8.1  | -0.73 | 0.1  |
|             | 0   | 0   | 0.4 | 8.085 | 8.013 | 7.901 | 7.97 | 7.99 | 7.89 | -0.41 | -0.97 |
|             | 0.4 | 0   | 0   | 7.941 | 7.966 | 8.092 | 7.9  | 7.92 | 8.1  | 0.14 | 0.91 |
|             | 0.4 | 0   | 0.4 | 7.99 | 8.01 | 7.98 | 8.01 | 8.06 | 7.98 | 0.01 | -0.17 |
|             | 0   | 0.4 | 0   | 8.02 | 7.99 | 7.98 | 8.06 | 7.99 | 7.99 | -0.19 | -0.1 |

| 1 s         | 1   | 0   | 0   | 7.578 | 8.044 | 8.36  | 7.6  | 7.99 | 8.31 | 2.66 | 3.62 |
|             | 0   | 1   | 0   | 8.368 | 7.487 | 8.121 | 8.4  | 7.39 | 8.21 | -5.03 | 1.28 |
|             | 0   | 0   | 1   | 8.52 | 8.39 | 6.97 | 8.49 | 8.4 | 7 | -1.3 | -10.8 |
|             | 1   | 1   | 0   | 7.886 | 7.873 | 8.236 | 7.91 | 7.82 | 8.06 | -0.07 | 2.35 |
|             | 1   | 0   | 1   | 8.33 | 8.55 | 7 | 8.4 | 8.5 | 6.96 | 0.93 | -9.87 |
|             | 0   | 1   | 1   | 8.935 | 7.74 | 7.23  | 8.8 | 7.6 | 7.36 | -6.83 | -7.29 |

| 1 s         | 1.5 | 0   | 0   | 7.33  | 8.21 | 8.4 | 7.4 | 8.3 | 8.43 | 5.02 | 4.13 |
|             | 0   | 1.5 | 0   | 8.625 | 7.08 | 8.219 | 8.69 | 6.98 | 8.3 | -8.83 | 2.42 |
|             | 0   | 0.15 | 1.5 | 8.98 | 6.1 | 8.62 | 8.9 | 6.25 | 8.7 | -2.22 | -17.9 |
|             | 1.5 | 1.5 | 0   | 7.12 | 7.43 | 9.29  | 7.22 | 7.31 | 9 | 1.77 | 13.3 |
|             | 1.5 | 0   | 1.5 | 8.31 | 8.58 | 6.97 | 8.28 | 8.6 | 7.1 | 1.26 | -9.83 |
|             | 0   | 1.5 | 1.5 | 9.11 | 7.35 | 7.4 | 9 | 7.4 | 7.4 | -10.1 | -5.49 |

| 1 s         | 2   | 0   | 0   | 6.56 | 8.76 | 8.49 | 6.3 | 8.8 | 8.6 | 12.6 | 5.53 |
|             | 0   | 2   | 0   | 8.8 | 6.5 | 8.5 | 9 | 6.3 | 8.8 | -13.2 | 5.65 |
|             | 0   | 0   | 2   | 9.1 | 8.73 | 5.71 | 8.91 | 8.53 | 5.9 | -2.67 | -22.2 |
|             | 2   | 2   | 0   | 7.6 | 7.41 | 8.91 | 7.5 | 7.3 | 9 | -1.13 | 9.13 |
|             | 2   | 0   | 2   | 7.9 | 8.41 | 7.5 | 7.7 | 8.5 | 7.4 | 1.79 | -4.57 |
|             | 0   | 2   | 2   | 9.36 | 7.028 | 7.417 | 9.4 | 6.9 | 7.2 | -13.4 | -5.18 |
4.2. On/Off Closed Loop Control

Simple ON/OFF control is used for the preliminary closed loop control test for the input as defined in eqn.(12). The block diagram used for the control implementation is shown in Figure 6. Step test and sinusoidal trajectory test of individual axis is conducted on the manipulator. Step response helps to understand the changeover characteristics which defines the disturbance rejection of the manipulator to the sudden input change. A step input shift of 0° to 10° is applied at 2s and the response is as shown in Figures 7(a) and 7(b) for X and Y axis respectively. An overshoot of 0.84° is found about X axis with a rise time of 0.95s and similarly overshoot of 1.86° is found about Y axis with a rise time of 0.48s. The difference in overshoot illustrates the difference in actuator response along the individual axis mainly due to the impact of structure or actuator connecting points. This also confirm the importance of better control algorithm to handle the cross axis differences and nonlinearities.

\[
U_i = \begin{cases} 
3V & \text{if } e > 0 \\
0V & \text{if } e \leq 0 
\end{cases}
\]

(12)

Figure 6. Control block diagram

| Input                      | X axis | Y axis |
|----------------------------|--------|--------|
| RMSE          | AE     | RMSE   | AE     |
| Sinusoidal input at 0.1 Hz | 0.5404 | 0.1940 | 0.4966 | 0.0905 |
| Sinusoidal input at 0.2 Hz | 1.2932 | 0.5353 | 0.8831 | 0.3030 |

Table 2. Quantitative analysis result
Figure 7. Step response plot (a) about X axis (b) about Y axis ; Sinusoidal Response (c) about X axis at 0.1 Hz (d) about Y axis at 0.1 Hz (e) about X axis at 0.2 Hz (f) about Y axis at 0.2 Hz

5. Conclusion and Future Work

The paper has presented design and development of a flexible parallel manipulator which can be used as an orienting device. A novel simple design of manipulator incorporating minimum number of actuators and electrical and control circuitry is demonstrated. Preliminary experiments are conducted on the manipulator to understand the performance. The test results confirm the use of kinematic model for the feedback measurement using the end effector orientation data and maximum operating frequency is 0.2 Hz. The performance of the manipulator can be improved by the design of nonlinear controllers specific to handle cocontraction of antagonistic actuators thereby reducing the cross axis error and maintain similar response across axis.

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