Development and Workspace Analysis of Smart Actuation based Planar Parallel Robotic Motion Stage

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Abstract. The applications of light weight planar parallel robotic manipulators are increasing enormously because of their various desirable characteristics such as low weight, lower inertia, higher stiffness, energy efficiency etc. Higher accelerations and accuracies can be achieved using planar parallel manipulators (PPMs). Also, Shape Memory Alloy (SMA) based actuators are replacing huge and bulky actuators as SMA actuators provide higher work per unit mass as compared to other actuators and also undergoes silent actuation by simple actuation process. In the present study, three configurations (3PRP, PPR-2PRP and PRR-2PRP) of 3 degrees of freedom U-shaped base planar parallel robotic manipulator have been presented using SMA based smart actuators. The manipulator constitutes of one fixed base and one moving platform. The SMA spring acts as linear actuators mounted on the base which is connected to the end effector with the help of three limbs. A detailed experimental study was carried out to understand the workspace associated with each configuration. The movement of manipulators was investigated with the various combinations associated with the input SMA translation joints. And the study showed that the various configurations acquire different areas of workspace in the manipulator region. This study also shows the essence of SMA springs in PPMs for precise and accurate positioning of the end-effector and also its tracking ability for the development of future micro-motion stage. Note: P refers to Passive Prismatic Joint, R refers to Passive Revolute Joint and P refers to Active Prismatic Joint.

1. Introduction
Currently, robotics has gained numerous applications in almost every field of engineering. The need to automate various tasks arouse the necessity of research in various robotic applications. Based on the applications, a lot of research have already been conducted. However, it still seems like a never-ending research field owing to its growing importance. Till date, different types of robotic manipulators have been studied and still, numerous types are being proposed and analyzed to automate in a bid to reduce human effort. The Stewart-Gough platform is one of the most famous parallel manipulators as per the literature which was initially depicted as a flight simulator [1,2]. Delta robot is a 3 DoFs parallel robotic manipulator which was introduced by Clavel [2]. The Agile Wrist is a pure rotational motion parallel robot, the behaviour of which has been studied by a few researchers [3].

The authors proposed a theorem and demonstrated the estimation of workspace geometrical characteristics for the robotic manipulator. In the spatial parallel manipulators, the kinematic chains
are symmetrical about a certain plane [4]. Although parallel manipulators provide limited workspace as compared to serial manipulators but there exist certain advantages that are much important such as low inertia, high stiffness. The parallel manipulators are more suitable for higher accelerations and accuracies. The 3-PRP planar parallel manipulator with an equilateral triangular base with a star-shaped platform mounted on it. The author proposed equations based on MATLAB/SIMULINK software which could be used for the design of various controllers for the said robotic manipulator [5]. The authors proposed five degrees of robotic manipulator which serves as goalkeeper in order to train football players. The kinematic and dynamic study was carried out along with the torque analysis [6]. The kinematic analysis of three degrees of freedom 3-RRR planar parallel robotic manipulator has been studied by Damien Chablet and Philippe Wenger with symmetric properties. Parallel manipulators exist with multiple direct kinematic solutions [7].

The kinematic equations for a parallel manipulator are complex and hence there is difficulty in determining the workspace. Without the kinematics or the workspace, it is not possible for the design and trajectory planning of the robotic manipulators [2]. Planar Parallel manipulators consist of various kinematic chains forming a mobile platform which is connected to a fixed base [2]. Manipulator configurations can be achieved by the nature of the kinematic chains and the fixed base shape as well. Most of the design for planar parallel robotic manipulators are based on symmetric topology because it enhances the structural stiffness along with the manufacturing and assembly simplicity [8]. Mohanta J. et al. proposed the family of three-legged U-shape base planar parallel manipulators (PPMs). This family possesses three degrees of freedom (DOF). The first joint of each leg of the manipulator serves as an active prismatic joint [9]. The eighteen unique configurations of the said family of U-base PPMs are shown in table 1.

| Table 1. Eighteen unique configurations of U-shaped three-legged PPM [9]. |
|-----------------|-----------------|-----------------|
| PPR-PPR-PPR    | PRP-PR-PRP-PR   | PPR-PR-PRP-PR   |
| PRR-PPR-PPR    | PRP-PR-PRP-PR   | PPR-PR-PRP-PR   |
| PRP-PR-PRP-PR  | PRR-PR-PR-PRP   | PRR-PR-PR-PRP   |
| PRR-PR-PRP-PR  | PRR-PR-PRP-PRP  | PRR-PR-PRP-PRP  |

Shape memory alloys (SMAs) are distinctive smart materials which hold the ability to restore its memorized shape upon heating. The thermal loading reorients the crystal structure from the monoclinic (martensite region) to a body-centered cubic (austenite region). This solid phase transition is also referred to as Shape Memory Effect (SME) [10]. SMA are light in weight and undergoes silent actuation. SMA yields higher power/mass in comparison to other actuators [11]. SMA imparts larger internal strain recovery [12]. Nitinol (NiTi), a shape memory alloy, recovers even larger strains under certain isothermal conditions due to its superelasticity character [13].

Based on the kinematic isotropy result of eighteen configurations, PPR-2PRP, 3PRP and PRR-2PRP possess better kinematic design aspects [9]. Hence, in this work, these three configurations were further studied in terms of the micro-motion positioning stage by incorporating an SMA based actuator. In the present study, three best configurations as discussed will be tested for their precise and accurate motion and also to analyze the manipulator’s workspace. The micro-motion stage can translate along X and Y axes and also could rotate about the Z-axis. In the literature, the authors studied the forward and inverse kinematics including the workspace of the three-legged U-shape base 3PRP planar robotic manipulator experimentally [11]. The active joints were comprised of nitinol (SMA) spring as an actuator. The actuators actuate by the joule heating process. The nitinol actuators were connected in an open-loop which consists of either ON or OFF. While ON the actuation was carried out for full contraction of the nitinol placed at several legs of the manipulator. The authors concluded that the simple ON/OFF actuation mechanism stands difficult to control the end-effector
motion. Also, for a given simple and complex trajectory, the tracking control of the end-effector is unsuitable without the feedback loop. This study determines the selected manipulators overall workspace and pose experimentally. Also, the range of each translational input joints is observed.

2. Kinematic of the manipulators
The cartesian space velocities are mapped to the task space velocities with the Jacobian matrix (J). The Jacobian matrix for the manipulators is given in table 2.

Table 2. Jacobian matrix of PPMs.

| 3PRP | PPR-2PRP | PRR-2PRP |
|------|----------|----------|
| \[ \begin{bmatrix} 1 & \tan(\theta) & y \sec^2(\theta) \\ -\tan(\theta) & 1 & E \\ -\tan(\theta) & 1 & D \end{bmatrix} \] | \[ \begin{bmatrix} 1 & 0 & \frac{2h}{3} \cos(\theta) \\ -\tan(\theta) & 1 & E \\ -\tan(\theta) & 1 & D \end{bmatrix} \] | \[ \begin{bmatrix} 1 & \frac{B}{l_2} & A + B \times C \end{bmatrix} \] |

\[ D = A_1 + \tan(\theta) A_3 + \sec^2(\theta)(s - x - A_4); \]
\[ A = \frac{2h}{3} \cos(\theta); \]
\[ B = \frac{-l_1 \sin(\theta) \dot{\theta}}{\sqrt{1 - (B_1 / l_1)^2}}; \]
\[ A_1 = \frac{2h}{3} \cos(30^\circ + \theta); \]
\[ A_3 = \frac{2h}{3} \sin(30^\circ + \theta); \]
\[ A_2 = \frac{2h}{3} \cos(30^\circ - \theta); \]
\[ A_4 = \frac{2h}{3} \sin(30^\circ - \theta); \]

where ‘s’ is the width or span of the base of manipulator, ‘h’ is height of the end-effector, ‘l_j’ (j = 1,2) is the link length of the connecting members from active joint to the end-effector, \((x,y,\theta)\) represents the cartesian space variables of the mobile platform.

3. Development of smart actuated manipulators
Multiple distinct parts were modeled and assembled in SolidWorks software to obtain the prototypes of 3PRP, PPR-2PRP and PRR-2PRP micro-motion stage as depicted in figure 1. The prototype was manufactured by Fused Deposition Modelling with acrylonitrile butadiene styrene (ABS) material. Figure 1 clearly depicts the U shape formed by three legs of the micromotion stage. One leg (leg 1) is placed along X-axis and the remaining two (leg 2 on the left and leg 3 on the right) are placed along Y-axis. All the links of the manipulators are oriented in the XY plane. At each leg, two numbers of nitinol springs are connected in series with the help of a pin or joint (7) which serves as active prismatic joint and the joint space displacements \((r_1, r_2, r_3)\). The active prismatic joint translates in the direction of contraction of spring in each leg. The two springs in each leg provide bi-directional movement to the joint. The translation of active joint leads to variation in the pose of the end-effector.

In each case, as shown in figure 1, the configuration of leg 1 is different as PRP in case (a), PPR in case (b) and PRR in case (c). In the case of PRP, the first P serves as a smart actuated active translation joint and at the point (7) it rotates as shown in figure 1(a), and another link connected to the end-effector slides about the same point. In the case of PPR, the first P serves as a smart actuated active prismatic joint as in the previous case but another link connected to the end-effector slides about point (7) as shown in figure 1(b), and it rotates at the point of connection at the end-effector. In the case of PRR, the first P serves as a smart actuated active translation joint similar to the previous two
cases but another link which is connected to end-effector rotates about the point (7) and also at the connection point with the end-effector as clearly mentioned in figure 1(c). The configuration of leg 2 and leg 3 of each manipulator is PRP and hence resembles the leg 1 depicted in figure 1(a).

![Diagram of 3PRP, PPR-2PRP, and PRR-2PRP configurations]

**Figure 1.** The conceptual figure for the three best smart actuated manipulators.

During the study, electrical current was supplied across the nitinol springs. Due to the springs electrical resistance, the temperature of it escalates resulting in a change in the crystal structure. This phenomenon is observed through our naked eye as contraction of nitinol spring.

Each configuration demands six SMA springs for the motion of end-effector as illustrated in figure 1 and figure 2.

### 4. Experimental procedure

The experimental setup designed for the smart actuated micro-motion stage is depicted in figure 2. The experimental setup is equipped with several devices as specified in table 3.

An electric current is supplied to only one spring in each leg which results in gradual contraction. The contraction stops as the spring reaches its minimum length. On the contrary, the other spring in the same leg extends. This results in variation in the position of the active translational joint. This motion leads to a change in the pose of the end-effector. Once the end-effector reaches a new position, a digital camera (Sony DSC WX220) captures the image. The pose of the end-effector is then extracted from the digital image.
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Figure 2. Experimental setup.

Table 3. List of devices used for the experiment.

| Sl. No. | Device                  | Specifications                              |
|---------|-------------------------|---------------------------------------------|
| 1       | Extension Board         | NA                                          |
|         |                         | Model – LX1250;                             |
| 2       | AC/DC Adapter           | Input – 100-240 V, 50/60 Hz, 1.6 A;         |
|         |                         | Output – 12 V, 5 A (DC)                     |
| 3       | Variable DC Power Supply| Output – 0-1300 mA                          |
| 4       | Digital Multimeter      | Model – DT830D                              |
|         |                         | (a) 3PRP                                    |
|         |                         | (b) PPR-2PRP                                |
| 5       | SMA spring based manipulators | (c) PRR-2PRP                           |

The three active translational joints are referred to as inputs to the manipulator while the rest of the joints are passive joints. The passive joints are dependent on the movement of the input joints. The base of the manipulator is rigid and has a fixed size of 218 mm x 194 mm.

The nitinol shape memory alloy springs considered for the experimentation are 0.75 mm in diameter with 19 helical windings. This study mainly aims at the implementation of smart actuation in the PPMs with the open-loop system.

5. Results and discussion

The position of the end-effector obtained based on the smart actuation of various legs in combination for all the three manipulators are illustrated in figure 3 - 5.

The pose of the end-effector is observed by providing direct current to the smart actuators at various legs of the manipulator in different conditions due to the coupled kinematic relations of the manipulators. The pose of the end-effector continuously varies with contraction of nitinol springs at the legs. The input translational joints play a vital role in coordinating the linear actuation to the end-effector. The motion of the active prismatic joint in leg 1 along positive X-axis represents forward movement and along negative X-axis represents the backward movement as illustrated in figure 1.
Figure 3. Actuation of SMA springs of 3\textsubscript{PRP} (Condition 7).

Figure 4. Actuation of SMA springs of PPR-2\textsubscript{PRP} (Condition 5).

Figure 5. Actuation of SMA springs of PRR-2\textsubscript{PRP} (Condition 2).

Experiments similar to the 3\textsubscript{PRP} manipulator has also been conducted for the in-house fabricated prototypes of PPR-2\textsubscript{PRP} and PRR-2\textsubscript{PRP} as depicted in figure 3 - 5.

Six sets of data similar to 3\textsubscript{PRP} were obtained for PPR-2\textsubscript{PRP} and PRR-2\textsubscript{PRP} manipulators as well. Similarly, the motion of active prismatic joints in leg 2 and leg 3 along positive Y-axis represents forward movement (F) and along negative Y-axis represents backward movement (B) as illustrated in figure 1.
Table 4. A set of end-effector positions of 3PRP manipulator with seven conditions.

| SMA actuators (Conditions) | Direction of the actuation of SMA springs | End-effector position Q_x (mm) | Q_y (mm) |
|----------------------------|-------------------------------------------|-------------------------------|----------|
| r_1                        | r_1:F (Forward direction)                 | 125.710                       | 86.360   |
|                            | r_1:B (Backward direction)                | 134.640                       | 88.330   |
|                            | Initial position                          | 75.160                        | 87.450   |
| r_2                        | r_2:F (Forward direction)                 | 82.000                        | 87.730   |
|                            | r_2:B (Backward direction)                | 96.640                        | 108.660  |
|                            | Initial position                          | 75.690                        | 78.280   |
| r_3                        | r_3:F (Forward direction)                 | 77.620                        | 91.030   |
|                            | r_3:B (Backward direction)                | 65.550                        | 97.490   |
|                            | Initial position                          | 85.200                        | 84.030   |
| r_1 and r_2                | r_1:F and r_2:B                          | 125.370                       | 81.170   |
|                            | r_1:B and r_2:F                          | 96.120                        | 108.290  |
|                            | Initial position                          | 120.200                       | 86.770   |
| r_1 and r_3                | r_1:F and r_3:F                          | 108.500                       | 104.880  |
|                            | r_1:B and r_3:B                          | 77.040                        | 85.220   |
|                            | Initial position                          | 78.900                        | 86.080   |
| r_2 and r_3                | r_2:B and r_3:F                          | 64.570                        | 91.860   |
|                            | r_2:B and r_3:B                          | 86.210                        | 78.980   |
|                            | Initial position                          | 85.910                        | 85.130   |
| r_1, r_2 and r_3           | r_1:F, r_2:B and r_3:F                   | 103.300                       | 101.130  |
|                            | r_1:B, r_2:F and r_3:B                   | 97.800                        | 105.180  |

Note: Q_x, Q_y = Position of end-effector from origin along X and Y axis respectively; r_1, r_2, r_3 = Translational inputs.

Experiments were conducted on the in-house fabricated 3PRP manipulator to interpret the pose of end-effector under seven variant conditions as listed in table 4. The first condition is the actuation of the r_1 joint. At first, the initial pose of the end-effector was determined. Then for forward actuation, SMA spring on the right of leg 1 was actuated. Once it contracts (regains its original shape and size), the end-effector pose was extracted. As the spring reaches room temperature, the left spring is actuated for backward movement and the end-effector pose is determined as indicated in table 4.

Similarly, experiments were conducted for six more variant conditions as discussed and the end-effector pose was determined as disclosed in table 4. In condition 7, all the active prismatic joints are under actuation in the combination of forward and backward movements. The entire experiment was conducted for a total of six times and six sets of data were obtained of which only one set has been tabulated in table 4.

Table 5. Total joint space and end-effector positions of 3PRP.

| Parameters | Position from the Origin (mm) | Total stroke length (mm) |
|------------|-------------------------------|--------------------------|
|            | Minimum                       | Maximum                  |                         |
| r_1        | 76.600                        | 114.770                  | 38.170                  |
| r_2        | 78.130                        | 125.500                  | 47.370                  |
| r_3        | 81.600                        | 129.130                  | 47.530                  |
| Q_x        | 61.145                        | 134.640                  | 73.495                  |
| Q_y        | 77.626                        | 121.825                  | 44.199                  |
Table 6. Total joint space and end-effector positions of PPR-2PRP.

| Parameters | Position from the Origin (mm) | Total stroke length (mm) |
|------------|------------------------------|-------------------------|
|            | Minimum                      | Maximim                 |
| r1         | 79.980                       | 128.340                 | 48.360 |
| r2         | 82.750                       | 133.360                 | 50.610 |
| r3         | 64.460                       | 113.410                 | 48.950 |
| Qx         | 70.460                       | 132.460                 | 62.000 |
| Qy         | 70.620                       | 135.510                 | 64.890 |

Table 7. Total joint space and end-effector positions of PRR-2PRP.

| Parameters | Position from the Origin (mm) | Total stroke length (mm) |
|------------|------------------------------|-------------------------|
|            | Minimum                      | Maximim                 |
| r1         | 76.780                       | 123.050                 | 46.270 |
| r2         | 82.580                       | 124.870                 | 42.290 |
| r3         | 77.760                       | 130.100                 | 52.340 |
| Qx         | 29.280                       | 151.390                 | 122.110 |
| Qy         | 77.400                       | 116.240                 | 38.840 |

The outcome of the experiment revealed gradual variation in the pose of the manipulators end-effector due to gradual contraction and elongation of SMA springs. These SMA spring manipulators are advantageous in the actuation process as compared to conventional actuation methods. The forward and backward motions of the active prismatic actuators have a certain stroke length along X and Y axes. Table 5 - 7 indicates the total stroke lengths of r1, r2 and r3 and the end-effector coordinates (Qx, Qy) as observed during experimentation.

The experimental results unveiled that r2 possess larger translation range in case of 3PRP and PRR-2PRP manipulators as compared to other active translational joints on account of its structural arrangement. Likewise, r3 has a larger range of translation in the case of PPR-2PRP manipulator.

![Figure 6. Workspace of the in-house fabricated 3PRP manipulator.](image1)

![Figure 7. Workspace of the in-house fabricated PPR-2PRP manipulator.](image2)
The graphs depicted in figure 6 - 8 represents the workspace area for the selected manipulators under variant combinations of translation inputs. The result obtained in table 5 - 7 and the graph plotted in figure 6 - 8 illustrates that the total workspace area is in the order \( \text{PRR-2PRP} < \text{PPR-2PRP} < \text{3PRP} \) and the figure 9 confirms that as well. The maximum possible orientation of the end-effector during the entire period of experiment was \( 130^\circ \), \( 140^\circ \) and \( 140^\circ \) for the SMA spring-based manipulators 3PRP, PPR-2PRP and PRR-2PRP respectively. The respective active joints of the manipulators can be actuated in order to pose the end-effector anywhere within its workspace by proper control of the active translation joints.

Figure 9 depicts the workspace of the selected configurations of U-shaped planar parallel robotic manipulators. Also, it can be cited from figure 9 that the total stroke length along X-axis is maximum for PRR-2PRP and minimum for PPR-2PRP manipulator. Similarly, the total stroke length along Y-axis is maximum for PPR-2PRP and minimum for PRR-2PRP manipulator. The best configuration manipulator for the development of the micro-motion stage can be selected based on the required region of workspace.

6. Conclusion
In this study, the experiments of three different configurations of U-shaped PPMs (3PRP, PPR2PRP and PRR-2PRP) were carried out and a detailed investigation of each manipulator was performed. The study showed variation in total workspaces of the manipulators with PRR2PRP being the highest and 3PRP being the lowest. Also, the workspace in each configuration for various combinations of joint actuation was determined. The total stroke length along both the axes was also determined for each
manipulator in order to understand the motion behaviour of the manipulator. Also, the maximum orientation of the end-effector was determined for each case with 130°, 140° and 140° for the manipulators 3PRP, PPR-2PRP and PRR-2PRP respectively.

This manipulator can be applied to perform various task that requires micro-level positioning. It can be used for various manufacturing and production tasks such as micro level 3D printing, micro-drilling machine, micro-milling machine wherein this stage will perform the task to position either the workpiece or the tool. It can also perform other operations which require micro-motion in the desired plane.

This is a preliminary test that was performed on three configurations of the U-shaped base PPMs with translational input joints being at its extreme positions. Being an open-loop control system, full extension and contraction were possible. This work can be extended at a later stage to understand the behaviour of the SMA spring and incorporating closed feedback control in order to obtain the desired end-effector pose within the workspace which will also thereby make complex trajectory control easier and possible. These manipulators can thereby replace conventional actuation process with SMA spring-based actuators (SMART actuation) which will also lead to build a better and efficient micro-positioning stage.

7. References
[1] Tsai K Y, Lo I T and Lin P J 2014 Compatible reachable workspaces of symmetrical Stewart Gough parallel manipulators Mechanism and Machine Theory 77 111-21
[2] Merlet J P, Gosselin C M and Mouly N 1998 Workspaces of planar parallel manipulators Mech. Mach. Theory 33 7-20
[3] Angeles J 2002 Fundamentals of robotic mechanical systems Springer 2
[4] Zhao J S, Chen M, Zhou K, Dong J X and Feng Z J 2006 Workspace of parallel manipulators with symmetric identical kinematic chains Mech. Mach. Theory 41 632-45
[5] Farhadmanesh M, Abedloo E and Molaei A 2015 Dynamics formulation and motion control of a planar parallel manipulator 3rd RSI International Conference on Robotics and Mechatronics 205-9
[6] Singh D and Singh Y 2018 IOP Conf. Ser.: Mater. Sci. Eng. 402 012092
[7] Chablat D and Wenger P 2004 The kinematic analysis of a symmetrical three-degree-of-freedom planar parallel manipulator
[8] Merlet J P 1996 Direct kinematics of planar parallel manipulators Proceedings of the 1996 IEEE International Conference on Robotics and Automation 4 3744-49
[9] Mohanta J, Singh Y and Mohan S 2018 Kinematic and dynamic performance investigations of asymmetric (U-shape fixed base) planar parallel manipulators Robotics 36 1111-43
[10] Paik J K and Wood R J 2012 A bidirectional shape memory alloy folding actuator Smart Materials and Structures 21
[11] Singh Y and Mohan S 2017 Development of a planar 3PRP parallel manipulator using shape memory alloy spring based actuators Proceedings of the Advances in Robotics 10
[12] Leng J, Yan X, Zhang X, Huang D and Gao Z 2016 Design of a novel flexible shape memory alloy actuator with multilayer tubular structure for easy integration into a confined space Smart Materials and Structures 25
[13] Leng J, Yan X, Zhang X, Qi M, Liu Z and Huang D 2017 A novel bending fatigue test device based on self-excited vibration principle and its application to superelastic nitinol microwire study Smart Materials and Structures 26