Synthesis and Evaluation of A High Precision 3D-Printed Ti6Al4V Compliant Parallel Manipulator

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Abstract. A novel 3D printed compliant parallel manipulator (CPM) with $\theta_x - \theta_y - Z$ motions is presented in this paper. This CPM is synthesized using the beam-based method, a new structural optimization approach, to achieve optimized stiffness properties with targeted dynamic behavior. The CPM performs high non-actuating stiffness based on the predicted stiffness ratios of about 3600 for translations and 570 for rotations, while the dynamic response is fast with the targeted first resonant mode of 100Hz. A prototype of the synthesized CPM is fabricated using the electron beam melting (EBM) technology with Ti6Al4V material. Driven by three voice-coil (VC) motors, the CPM demonstrated a positioning resolution of 50nm along the Z axis and an angular resolution of ~0.3" about the X and Y axes, the positioning accuracy is also good with the measured values of ±25.2nm and ±0.17" for the translation and rotations respectively. Experimental investigation also shows that this large workspace CPM has a first resonant mode of 98Hz and the stiffness behavior matches the prediction with the highest deviation of 11.2%. Most importantly, the full workspace of $10^\circ \times 10^\circ \times 7\text{mm}$ of the proposed CPM can be achieved, that demonstrates 3D printed compliant mechanisms can perform large elastic deformation. The obtained results show that CPMs printed by EBM technology have predictable mechanical characteristics and are applicable in precise positioning systems.

1. Introduction

Compliant parallel manipulator (CPM), which is developed based on the merits of elastic deformation and closed-loop parallel architecture, plays an important role in high precision motion systems. This is because elastic deformation offers a low-cost solution to deliver frictionless repeatable motions [1] while the closed-loop parallel architecture makes the CPM less sensitive to external disturbances and achieves higher non-actuating stiffness compared to the serial counterpart [2]. Based on the past literatures, most of the developed multiple degrees-of-freedom (DOF) CPMs were limited to few hundred micrometers in translation axes and less than a degree in the rotation axes [3–9]. With the assembly of next-generation optical fiber, optics and silicon photonics devices demanding for high
precision motion systems with larger workspace and higher positioning resolution, CPM needs to meet these requirements to extend its application into the automation and production of those emerging technologies. However, only a handful of multi-DOF CPMs managed to achieve larger workspace in recent literatures. Examples include the 3-DOF spatial motion \((\theta_x - \theta_y - Z)\) CPMs that demonstrated workspace of \(5^\circ \times 5^\circ \times 5\text{mm}\) [10, 11] and \(8^\circ \times 8^\circ \times 5.5\text{mm}\) [12], the 3-DOF planar-motion \((X - Y - \theta_2)\) CPM that demonstrated a workspace of \(2\text{mm} \times 2\text{mm} \times 2\text{mm}\) [13]. Yet, having larger workspace also lead to poor dynamic performance. In particular, the developed 3-DOF spatial-motion \((\theta_x - \theta_y - Z)\) in [11] only has a low first resonant mode of 15Hz; and 84.4Hz is the dynamic response that one of the largest workspace CPMs [12] has been achieved.

Electron Beam Melting (EBM), a powder-based 3D printing technology that is able to build nearly full-dense metal parts with good mechanical properties [14], is used to fabricate the synthesized CPM with Ti6Al4V material so as to reduce or avoid any form of undesired assembly error. Recently, a 3D printed 3-DOF CPM has been developed with a limited work range of \(6^\circ \times 6^\circ \times 4\text{mm}\) [15]. In this work, the beam-based method [12] is employed to synthesize a new design of 3-DOF \((\theta_x - \theta_y - Z)\) CPM with large workspace of more than \(8^\circ\) and 5.5mm and the targeted first resonant mode of 100Hz. The factor of 1.27 proposed in [15] is used to correct the actual thickness of EBM printed thin features. Experiments are conducted to investigate the mechanical characteristics of the synthesized CPM, especially the large elastic deformation of the 3D printed structure. Subsequently, three voice-coil (VC) motors are used to drive the CPM and experimental investigations are conducted to evaluate its positioning performance.

The rest of this paper is organized as: the synthesis of the 3-DOF \((\theta_x - \theta_y - Z)\) CPM is presented in Section 2 and the performance evaluation of the 3D-printed prototype is discussed in Section 3. Lastly, several conclusions are summarized in Section 4.

2. Synthesis of the 3-DOF \((\theta_x - \theta_y - Z)\) CPM

2.1. Problem formulation

The beam-based method presented in [12] is employed to design a 3-DOF spatial motion \((\theta_x - \theta_y - Z)\) CPM, which requires to have a workspace of at least \(8^\circ \times 8^\circ \times 5.5\text{mm}\) and a targeted first resonant mode of 100Hz. Subsequently, the CPM is fabricated by EBM technology and a common titanium alloy for EBM, Ti6Al4V, is chosen as the fabricating material. The mechanical properties of Ti6Al4V are as follows: elastic modulus of 111GPa, Poisson ratio of 0.34 and density of 4.5g/cm³. To obtain a 3-DOF motion, a symmetrical parallel configuration with three compliant limbs is adopted and the design domain of a limb is chosen as \(50 \times 50 \times 50\text{ mm}^3\) as shown in figure 1a. The construction of each compliant limb is illustrated in figure 1b. Elastic deformation of two reflecting curved-and-twisted (C-T) beams is used to generate the desired motions for the entire CPM. The C-T beam is created by sweeping a rectangular area through a cubic Bezier curve with different orientations of two ends. Finite element method (FEM) is used to model the entire CPM structure and the C-T beams are discretized by a number of 2-node beam elements. As the CPM will then be fabricated by EBM technology, the coefficient factor of 1.27 [15] is implemented in the synthesis process to correct the thickness of the printed prototype.

2.2. Synthesis process

The synthesis process is separated into two steps; the stiffness optimization and the dynamic optimization as shown in figure 2. The objective of the synthesis is to optimize the stiffness characteristics of the CPM with desired dynamic property. Hence, the stiffness optimization process is first carried out to define the most suitable structure for the C-T beams in order to achieve the largest workspace and the lowest actuating stiffness as well as the highest non-actuating stiffness. The fitness (objective) function for the stiffness optimization has been formulated using the works done by recent literatures. Examples include the 3-DOF spatial motion \((\theta_x - \theta_y - Z)\) CPMs that demonstrated workspace of \(5^\circ \times 5^\circ \times 5\text{mm}\) [10, 11] and \(8^\circ \times 8^\circ \times 5.5\text{mm}\) [12], the 3-DOF planar-motion \((X - Y - \theta_2)\) CPM that demonstrated a workspace of \(2\text{mm} \times 2\text{mm} \times 2\text{mm}\) [13]. Yet, having larger workspace also lead to poor dynamic performance. In particular, the developed 3-DOF spatial-motion \((\theta_x - \theta_y - Z)\) in [11] only has a low first resonant mode of 15Hz; and 84.4Hz is the dynamic response that one of the largest workspace CPMs [12] has been achieved.

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center. Six displacements of the end effector ($\Delta x$, $\Delta y$, $\Delta z$, $\theta_x$, $\theta_y$ and $\theta_z$) caused by $P$ are denoted by the vector $U$ as illustrated in figure 3.

Figure 1. (a) Symmetrical 3-limb configuration of the CPM and (b) construction of a limb.

Figure 2. Synthesis steps of the beam-based method.

Desired DOF and specifications

Stiffness optimization (structural optimization)

Dynamic optimization (Size/mass optimization)

Final design

Figure 3. Load-displacement relation.

By letting $W_i$ be the work done by $P_i$ and $U_i$, their relationship is expressed as

$$W_i = \int_0^P U_i dP_i = \int_0^P \frac{P_i}{K_i} dP_i = \frac{P_i^3}{2 K_i}, \text{ where } P_i = K_i \cdot U_i$$

(1)

Here, $K$ is the $6 \times 6$ matrix represents the stiffness property of the entire CPM and $K_i$ indicates the diagonal component of $K$ that corresponds with $P_i$ and $U_i$. By referring to [12] and equation (1), the fitness function for the stiffness optimization process is derived by the ratios between the works done of undesired displacements, i.e., $W_{\Delta y}$, $W_{\Delta y}$, $W_{\Delta z}$, and the works done of desired displacements, i.e., $W_{\theta_x}$, $W_{\theta_y}$, $W_{\Delta z}$, written as

$$\min f = \frac{W_{\Delta y}^3 \cdot W_{\Delta y}^3 \cdot W_{\Delta z}^3}{W_{\theta_x}^3 \cdot W_{\theta_y}^3 \cdot W_{\Delta z}^3} = \kappa \cdot \frac{K_{\Delta y}^3 \cdot K_{\Delta y}^3 \cdot K_{\Delta z}^3}{K_{\theta_x}^3 \cdot K_{\theta_y}^3 \cdot K_{\Delta z}^3}, \text{ where } \kappa = \frac{F_{\Delta y}^6 \cdot F_{\Delta y}^6 \cdot F_{\Delta z}^6}{M_{\theta_x}^6 \cdot M_{\theta_y}^6 \cdot F_{\Delta z}^6}$$

(2)

Note that $f$ is dimensionless and $\kappa = 1$ when $P$ is a unit load vector. Equation (2) is solved via the genetic algorithm (GA) solver from MATLAB and figure 4a shows the CPM structure after the stiffness optimization. It is observed that the C-T beams became flat and two reflecting C-T beams cut each other at the free ends to generate a V-shape flexure for each compliant limb. This structure is able to provide the largest workspace and good decoupled motions for the CPM.

Next, the dynamic optimization process is done to distribute the masses within the CPM to achieve the targeted first resonant mode. The fitness function of the dynamic optimization consists of two equations as shown in equation (3). In the first equation, the first resonant frequency, $F_{i1}$, is guaranteed to match the desired value of 100Hz by minimizing their difference. On the other hand, the large work range of the CPM can be obtained via maximizing the total desired works done as expressed in the second equation.
\[
\begin{align*}
\min & \left| F_1 - 10 \dot{q} \right| \\
\max & \left( W_{\dot{x}} + W_{\dot{y}} + W_{\dot{z}} \right)
\end{align*}
\]

\( (3) \)

The dynamic optimization problem is also solved by GA solver as the stiffness optimization. The final design of the CPM has a predicted first resonant mode of 99Hz, which is very close to the targeted value. The structure of the final design is shown in figure 4b. The compliant matrix, \( C \), that represents the stiffness characteristic of the CPM is written as

\[
C = \text{diag} \left[ 5.53e - 8 \quad 5.53e - 8 \quad 1.99e - 4 \quad 1.32e - 1 \quad 1.32e - 1 \quad 2.33e - 4 \right]
\]

\( (4) \)

Equation (4) shows that the CPM has better decoupled motion property as compared to the existing designs \([11, 12, 15]\) since all non-diagonal components are zeros. The stiffness characteristics of the final CPM are shown by two ratios, expressed as

\[
\frac{K_{\Delta x}}{K_{\Delta z}} = \frac{K_{\Delta y}}{K_{\Delta z}} = C_3 = C_2 \approx 3599 \quad ; \quad \frac{K_{\dot{\theta}_x}}{K_{\dot{\theta}_z}} = \frac{K_{\dot{\theta}_y}}{K_{\dot{\theta}_z}} = C_4 = C_6 \approx 567
\]

\( (5) \)

Here, \( C_i \) represents the \( i^{th} \) diagonal component within the compliant matrix. Equation (5) shows that the non-actuating translational stiffness along the X and Y axes is higher than the actuating translational stiffness along the Z-axis by 3599 times, the non-actuating rotational stiffness about the Z-axis is higher than the actuating rotational stiffness about the X and Y axes by 567 times. Such large ratios suggest that the CPM is very stiff in non-actuating directions and other resonant modes will be much higher than the first resonant mode. It is seen that the obtain lowest ratio of 567 is significantly improved as compared to the corresponding values of the previous designs \([12, 15]\). In addition, the stress analysis via ANSYS is also carried out to evaluate the workspace of the CPM. With the Ti6Al4V material providing a yield strength of 850MPa, the synthesized CPM can deliver a large workspace up to \( \pm 5^\circ \times \pm 5^\circ \times \pm 3.5\text{mm} \), which satisfies the desired requirements and much larger than the existing CPMs \([11, 12, 15]\).

3. Experimental investigation and results

3.1. Stiffness evaluation

A prototype of the CPM was built by EBM method with Ti6Al4V material and experiments were carried out to evaluate the stiffness characteristics. Figure 5 shows the experimental setup for measuring the compliance about the Y-axis. It is seen that two rigid rods with sharp tips were placed below the end effector constraining the motion along the Z-axis as well as creating the rotation axis for the CPM. The input displacement was applied by a micrometer and the actuating force was measured by a force/torque (F/T) sensor (ATI Mini-40). The bending moment and rotation angle were defined.
based on the distance between the loading point and the Y-axis. The similar setup was adopted for evaluating the compliance about the X-axis. Figures 6b and c plot the measured compliance about the X and Y axes respectively. Results are compiled from five separate measurements with fourteen data points in each run. The experimental setup for evaluating the translational compliance along the Z-axis is similar except that the two constraints along the Z-axis were removed and the loading point was shifted to the end effector's center. The experiment was also conducted with five measurement runs and the results are plotted in figure 6a.

![Graphs of compliance](image)

**Figure 6.** Measured compliance (a) along the Z-axis, (b) about the X-axis and (c) about the Y-axis.

In figure 6, the predicted data is given by equation (4). It is observed that the predicted data agrees with the measured results within a small deformation range, e.g., up to <2° for the rotation and <1mm for the translation. Yet at larger deformation range, the compliance of the CPM becomes nonlinear and higher than the predicted data, which are linear because the beam-based method uses FEM to determine the stiffness. The nonlinear stiffness characteristic that occurs during the large deformation is due to the over-constrained design of the synthesized CPM. Such design not only requires the C-T beams to bend but they also need to be elongated/stretched during large deformation. For better prediction of such nonlinear stiffness characteristic, the elongation of the C-T beams was calculated by the pseudo-rigid-body model [12, 16] and added to the initial predicted data. As a result, the predicted data with such compensation is also plotted in figure 6. After considering the elongation of the beams, the predicted data with compensation agrees with the experimental results. For the rotations about the X and Y axes, the average deviations between the prediction and measured results are 8% and 11.2% respectively. For the linear displacement along the Z-axis, the average deviation is 9.5%.

### 3.2. Dynamic evaluation

The experiment for measuring the dynamic behavior of the CPM was carried out using a standard modal analysis equipment. As the first resonant mode of the CPM is along the Z-axis, an impact hammer was used to apply a knock on the end effector perpendicularly. An accelerometer attached on the opposite side of the end effector was used to measure the acceleration in the same direction. Their outputs were then processed by the signal acquisition device. The first mode of the 3D printed CPM after analysis is plotted in figure 7. The measured resonant frequency is 98Hz, which matches well with the prediction of 99Hz with a small deviation of 1%.

### 3.3. Positioning evaluation

Three VC motors were used to actuate the 3D printed CPM, each VC motor has a direct feedback via a high-resolution encoder (MicroE System MII5000/6000 series). With all three limbs of the CPM having direct positioning feedback, a joint-space control by having a proportional-integral-derivative (PID) controller to control individual limb is implemented on the CPM. A three-axes laser interferometer (SIOS SP 2000 TR) was employed to monitor the positioning performance of the system. Figure 8 shows the experimental setup for measuring the positioning accuracy of the 3D
printed manipulator. The CPM was placed at a distance away from the laser interferometer and the laser beams were reflected back to the interferometer by a mirror attached to the end effector.

At this stage of research, the motion of the end effector is considered open-loop since there is no direct positioning feedback control implemented on it. Using just the joint-space control, figure 9a shows a 50nm step resolution of the end effector along the Z-axis that was measured directly from the laser interferometer. It is observed that the accuracy and the maximum positioning error are ±25.2nm and 14.2nm respectively.

**Figure 7.** The first resonant frequency of the 3D printed CPM.

**Figure 8.** Setup for measuring the positioning accuracy of the CPM.

**Figure 9.** Measured step displacement (a) along the Z-axis, (b) about the X-axis and (c) about the Y-axis.

By controlling each VC motor to achieve a step resolution of 50nm and having a fixed distance between each VC motor, the end effector of the 3D printed CPM was able to achieve an angular resolution of 0.34" and 0.3" about the X and Y axes respectively. Figures 9b and c show the measured data of the step angular displacements about the X and Y axes respectively. Both results show that the 3D printed CPM achieved an accuracy of ±0.17" for the angular motions and maximum positioning errors of 0.21" and 0.24" about the X- and Y-axis respectively.

4. Conclusion

This paper presents a high precision 3D printed Ti6Al4V CPM with 3-DOF (θx – θy – Z) out-of-plane motion. The CPM was designed by a novel beam-based method to achieve optimized stiffness characteristics with targeted dynamic performance. The synthesized CPM delivers a large work range of ±5° × ±5° × ±3.5mm with good stiffness ratios of ≥ 567 and fast dynamic response of 98Hz. The 3D printed CPM was fabricated by EBM technology to eliminate assembly errors and several experiments were carried out to evaluate its performance. Experimental results show that the 3D printed CPM provides large elastic deformation and the actuating compliance also matches the prediction with the
highest deviation of 11.2% over the full workspace. Most importantly, the 3D printed CPM demonstrated predictable dynamic response since the deviation between the measured first resonant mode and the predicted value is only 1%. The experimental results suggest that the 3D printed Ti6Al4V CPM can produce predictable stiffness and dynamic characteristics. In addition, the CPM can provide repeatable motions with the end effector achieving a positioning resolution of 0.34'' × 0.3'' × 50nm and accuracy of ±0.17'' × ±0.17'' × ±25.2nm. The obtained results demonstrate that the 3D printed CPMs can be used in precise positioning systems with predictable mechanical properties and large workspace. The future work is to focus on exploiting advantages of 3D printing technology to fabricate compliant mechanisms with good performance.

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