Design and Modeling of Series-Parallel Compliant Device for Reliable Assembly Under Position/Angle Deviation

Du Xu  
Central South University  
https://orcid.org/0000-0001-6423-9713

XinJiang Lu (luxj@csu.edu.cn)  
Central South University

Research Article

Keywords: Compliant assembly, Series-Parallel compliant device, Position/angle deviation

DOI: https://doi.org/10.21203/rs.3.rs-516264/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.  
Read Full License
Design and Modeling of Series-Parallel Compliant Device for Reliable Assembly under Position/Angle Deviation

Du Xu, XinJiang Lu*

State Key Laboratory of High Performance Complex Manufacturing, School of Mechanical & Electrical Engineering, Central South University, Hunan 410083, China;
# Corresponding Author / E-mail: luxj@csu.edu.cn, TEL: +86-0731-88830327

KEYWORDS: Compliant assembly; Series-Parallel compliant device; Position/angle deviation;

Abstract: Automatic assembly using manipulator has attracted increasing attention due to low cost and high quality of assembly. As the manipulator is entirely rigid, it often causes assembly failure and even damages the manipulator when there is a position or angle deviation. A series-parallel compliant device is developed here to realize the reliable assembly under the position or the angle deviation and does not produce a significant contact force. Its core idea is that when the contact force exceeds a specific value, this device becomes compliant and can move in a particular direction. It guarantees that this assembly allows a relatively significant misalignment and produces a small force, protecting parts and manipulators. This device has two compliant components, and these two components are connected using a rigid block. Each compliant component consists of the rigid frame, the four elastic limbs with a similar ‘n’ shape, and the square block. Due to using the elastic material, each elastic limb is equivalent to a compliant hinge (or spring), making this designed device equal to a series-parallel compliant structure. In this way, this device becomes compliant and can move in a particular direction when the contact force exceeds a specific value. On this basis, the desired compliance of the device is realized in various directions depending on the compliant device, and an optimization method is designed to achieve the parameters of this device based on the kinematic model and the stiffness analysis. Experiments under different working conditions are carried out and demonstrate the reliable assembling performance of this designed device even if there exists the position deviation or the angle deviation.

1. Introduction

In recent years, automatic assembly using manipulator has a significant impact on the cost and quality of products [1-2]. A typical shaft-hole assembly using a manipulator is shown in Fig.1. As the manipulator is entirely rigid, it often causes assembly failure and even damages the manipulator when there is a relative error on positive or angle between shaft and hole. For example, when there are position deviation and angle deviation, as shown in Fig. 2, a big contact force will occur, which can damage the shaft or hole and result in assembly failure.

Compliance is vital in assembly for protecting parts and compensating for the misalignment between them. There are two methods to increase system compliance. One is the active compliant strategy, which uses force feedback to identify the misalignment and compensates the positioning error using the feedback control. In the active compliance strategy, many control strategies have been presented to improve the assembly performance, including the stiffness control [3-4], the impedance control [5-7], and the force/position hybrid control [8-12]. Although the active compliance strategy has gained many successful applications, its complex control algorithm is often challenging to implement. Besides, it is known that a good design can achieve a good performance only using a poor control strategy. However, a poor design cannot achieve a satisfactory performance even if using an advanced control strategy. Thus, in many cases, these control methods are challenging to achieve a satisfactory performance due to a poor design.

Fig.1. Shaft-hole assembly using manipulator
Another advisable method for assembly is the passive compliance strategy, which adds the compliance element in the manipulator from the perspective of design and hardware [13-14]. For example, various flexible grippers were designed to adapt to different objects [15-16]. Also, a specific mechanical structure was designed to produce the compliance to achieve variable contact force or reduce contact force during assembly. Chen [16] presented the remote centre compensation (RCC) structure to achieve robust assembly. Spatial remote centre compliance with an additional axial rotation was designed for accommodating the prismatic (non-axial symmetric) peg components [17]. Haskiya [18] [19] presented a chamfer-less vertical, horizontal remote centre compliance to reduce the insertion force and avoid the jamming conditions in the dynamic insertion of no-chamfer peg-in-hole assembly. Massimo [20] proposed variable remote centre compliance that could change the centre of compliance according to insertion depth. Kim [21] presented a variable passive compliance device for assembly. Kronander [22] and Liu [23] used the spring mechanism and the compliant linkage mechanism for assembly. Xing [24] used a multiple-compliant degree-of-freedoms (DOFs) mechanism (i.e., a spring) to facilitate compliant insertion in assembly. Chen [25] introduced a pneumatic mechanism to produce certain compliance. S.M[26] developed a human-robot hybrid cell for flexible assembly in manufacturing through the collaboration between a human and a robot, though most of these designs have many successful applications. However, their compliance centre is fixed and difficult to adjust, which causes that the adaptability and versatility of the operational requirements for different stiffness are poor. In addition, they cannot assemble the shaft and hole when there is a big relative error in position or angle between shaft and hole.

Here, a series-parallel passive compliance device is designed to assemble the shaft and hole under a significant relative error on position or angle. In this mechanism, the deformation of eight elastic limbs is used to transmit the force and realize the spatial freedom of the compliance device. Unlike the traditional parallel mechanism that transmits motion through rigid hinges between the fixed and moving platforms, this mechanism is a monolithic mechanism that avoids assembly errors and the gap between the moving pairs on the dynamic characteristics. On this basis, a deformation model and a stiffness model are established to describe the compliance in different directions, and an optimization method is developed to realize the parameters of the mechanism. The shaft-hole assembly experiments are carried out, which demonstrates that the designed device has reliable assembly performance even if there is position deviation or angle deviation.

### 2. Description of design

A series-parallel compliant device is designed to realize the reliable assembly under the position deviation or the angle deviation and avoid producing a considerable contact force, as shown in Fig.3, which is used to connect the manipulator and the tool (e.g. gripper). Its core idea is that when the contact force exceeds a particular value, this device becomes compliant and can move in each direction. This guarantees that compliant assembly allows a relatively significant misalignment and produces a small force, protecting parts and manipulator. This device has two compliant components, and each component consists of the rigid frame, the four elastic limbs with a similar ‘n’ shape, and the square block. One end of each elastic limb is fixed on the rigid frame, and the other end is fixed on the square block placed at the centre of the component. These two compliant components are connected using a rigid block.

![Fig. 3. (a) Structure of series-parallel compliant device; (b) Equivalent structure of each part; (c) Equivalent structure and deformation of compliant device.](image)
Due to the use of elastic material, each elastic limb is equivalent to a compliant hinge (or spring), and this device is equivalent to a series-parallel compliant structure, as shown in Fig. 3(b) and Fig. 3(c). In this way, this device becomes compliant and can move in each direction when the contact force exceeds a particular value. As an example, when there is a considerable force vector respectively from the x, y, z-axis, the compliant component will produce deformation as shown in Fig. 4(a), (b), and (c), respectively. Also, it can produce rotational deformation around the x, y, z-axis when there is a significant torque vector, as shown in Fig. 4(d), (e), and (f). For this device, when there is a prominent force or moment, the deformation will be produced to effectively offset the contact force, shown in Fig. 5. Thus, this new device can effectively guarantee reliable assembly under the position deviation or the angle deviation without prominent contact force.

For example, as shown in Fig. 6, when there is a position deviation during assembly, the big contact load will be converted to the deflection of compliant components, making the assembly process more accessible.

---

**Fig. 4. Deformation of component:** (a) Deformation $\Delta x$ along x-axis; (b) Deformation $\Delta y$ along y-axis; (c) Deformation $\Delta z$ along z-axis; (d) Deformation $\Delta \theta_x$ around x-axis; (e) Deformation $\Delta \theta_y$ around y-axis; (f) Deformation $\Delta \theta_z$ around z-axis.

**Fig. 5. Deformation of compliant device:** (a) Deformation $\Delta x$ along x-axis; (b) Deformation $\Delta y$ along y-axis; (c) Deformation $\Delta z$ along z-axis; (d) Deformation $\Delta \theta_x$ around x-axis; (e) Deformation $\Delta \theta_y$ around y-axis; (f) Deformation $\Delta \theta_z$ around z-axis.

**Fig. 6.** (a) Assembly under horizontal position deviation; (b) Assembly under angle deviation; (c) Vertical position deformation.

---

### 3. Analysis and optimization

This section mainly focuses on the kinematics modeling and stiffness analysis. On this basis, the structure of this designed device is optimized.

**A. Kinematic analysis**

Fig. 7 shows the equivalent model of the compliant device. The coordinate is defined as follows: $O_0-x_0y_0z_0$ is the base coordinate fixed on the manipulator; $O_1-x_1y_1z_1$ is the coordinate fixed on the B point; $O_2-x_2y_2z_2$ and $O_3-x_3y_3z_3$ are the coordinate fixed on the points M and N on the compliant components, respectively; $O_4-x_4y_4z_4$ is the coordinate fixed on the point $P_4$ of the contact point on the tool.

**Fig. 7. Equivalent model of compliant device**
The transformation matrix $T_M$ between $O_1-X_1Y_1Z_1$ and $O_2-X_2Y_2Z_2$ is the following:

$$T_M = \begin{bmatrix} 1 & 0 & 0 & r_p + \Delta u_x' \\ 0 & 1 & 0 & r_p + \Delta u_y' \\ 0 & 0 & 1 & l_p + \Delta u_z' \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(1)

Here, $r_p$ and $l_p$ is the length of $AP_p$ and $PP$, as shown in Fig. 7, $\Delta u_x'$, $\Delta u_y'$ and $\Delta u_z'$ are the translational deformation of each elastic limb along $x$, $y$ and $z$ respectively.

The rotational transformation matrix $R_u$ on $O_1-X_1Y_1Z_1$ is:

$$R_u = \begin{bmatrix} c(\beta)c(\gamma) + s(\alpha)s(\beta)c(\gamma) & -c(\beta)s(\gamma) + s(\alpha)s(\beta)c(\gamma) & c(\alpha)s(\beta) \\ s(\alpha)c(\gamma) - c(\alpha)s(\beta)s(\gamma) & c(\alpha)c(\gamma) - s(\alpha)s(\beta)s(\gamma) & c(\beta) \\ -s(\gamma) & c(\gamma) & 0 \end{bmatrix}$$

(2)

Here, $s$ and $c$ denote the trigonometric function $\sin$ and $\cos$; $\alpha$, $\beta$, and $\gamma$ are three Euler angles rotating around $x_u$, $y_u$ and $z_u$, respectively. The corresponding torsional deformation on the elastic limb is $\Delta \theta_x'$, $\Delta \theta_y'$, and $\Delta \theta_z'$, and satisfies

$$\alpha = \Delta \theta_x', \beta = \Delta \theta_y', \gamma = \Delta \theta_z'$$

(3)

The transformation matrix $T_M$ between $O_2-X_2Y_2Z_2$ and $O_3-X_3Y_3Z_3$ is

$$T_M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & MN \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(4)

Here, $MN$ is the length of connection block.

The transformation matrix $T_B$ between $O_3-X_3Y_3Z_3$ and $O_4-X_4Y_4Z_4$ is

$$T_B = \begin{bmatrix} 1 & 0 & 0 & r_p + \Delta u_x' \\ 0 & 1 & 0 & r_p + \Delta u_y' \\ 0 & 0 & 1 & l_p + \Delta u_z' \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(5)

Here, $r_p$ and $l_p$ is the length of $BP_p$ and $PP$, as shown in Fig. 7.

The rotational transformation matrix $R_B$ on $O_4-X_4Y_4Z_4$ is the following:

$$R_B = \begin{bmatrix} c(\beta)c(\gamma) + s(\alpha)s(\beta)c(\gamma) & -c(\beta)s(\gamma) + s(\alpha)s(\beta)c(\gamma) & c(\alpha)s(\beta) \\ s(\alpha)c(\gamma) - c(\alpha)s(\beta)s(\gamma) & c(\alpha)c(\gamma) - s(\alpha)s(\beta)s(\gamma) & c(\beta) \\ -s(\gamma) & c(\gamma) & 0 \end{bmatrix}$$

(6)

Here, $\alpha_1$, $\beta_1$ and $\gamma_1$ are three Euler angles rotating around $x_2$, $y_2$ and $z_2$, respectively.

The transformation matrix $T_e$ between $O_5-X_5Y_5Z_5$ and $O_6-X_6Y_6Z_6$ is

$$T_e = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

(7)

Here, $l$ is the length of $BP_6$.

According to the relation of these coordinates, the position $T_F$ of the end point $P_F$ can be derived:

$$T_F = a_T f_T \cdot R_B \cdot R_M \cdot a_T$$

(8)

B. Stiffness analysis

The compliant behavior of the compliant device depends on the stiffness of the elastic limb. The equivalent model of the compliance device is shown as Fig. 8.

![Fig.8. (a) Structure of elastic limb; (b) equivalent model of elastic limb and compliant component; (c) equivalent model of compliant device.](image)

According to the classical Euler-Bernoulli beam theory, the forces and moments applied at the beam can be related to each other employing a compliance matrix [27]. Based on this theory, as shown in Fig.8(a), each elastic limb consists of two beams, and the stiffness matrix of a beam can be derived as follows.
and \( L \) is the rotational compliance. 

Here, \( E, G, A \) and \( L \) denote the Young's modulus, the shear modulus, the cross-sectional area and the length of each limb, respectively; \( L_i, I_i, I \) are the moments of the moments around the x-axis, y-axis and z-axis, respectively, and satisfies, 

\[
I_i = bh^3 \frac{(1 - 0.21 b)}{12} + \left(1 - \frac{h^3}{12}\right), \quad I = bh^3 - \frac{h^3}{12}.
\]

(10)

Here, \( b \) and \( h \) are the geometric parameter of elastic limb.

The transformation matrix \( T_i(i=1,2) \) between the coordinate \( \{C_i, x, y, z\} \) fixed on a beam and the coordinate \( \{O_i, x, y, z\} \) fixed on the bottom of the elastic limb is the following,

\[
T_i(i=1,2) = \begin{bmatrix} R_{xi} & 0 \\ P_{yi} & R_{zi} \end{bmatrix}
\]

(11)

Here, \( R_{xi} \) and \( P_{yi} \) are the rotation matrix and the anti-symmetric matrix respectively and satisfy,

\[
R_{xi} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}, \quad P_{yi} = \begin{bmatrix} 0 & d & 0 \\ -d & 0 & L/2 \\ 0 & -L/2 & 0 \end{bmatrix}
\]

(12)

The stiffness matrix \( k_{xi} \) of each elastic limb is the following,

\[
k_{xi} = \sum_{i=1}^{2} T_{i}^{T} k_{con} T_{i}
\]

(13)

Here, \( \lambda \) is the number of beams.

The translation matrix \( T_{bij} \) between the coordinate \( \{O_i, x, y, z\} \) \((i=1, \ldots, 4)\) and \( \{B_j, x, y, z\} \) fixed on the center of the compliant component is the following,

\[
T_{bij}(i=1, \ldots, 4) = \begin{bmatrix} R_{bij} & 0 \\ P_{bij}R_{bij} & R_{bij} \end{bmatrix}
\]

(14)

The rotation matrix \( R_{bij} \) from \( \{B_j, x, y, z\} \) to \( \{O_i, x, y, z\} \) and \( P_{bij} \) can be calculated as follows,

\[
R_{bij} = \begin{bmatrix} \cos \left( \frac{\pi}{2} (i-1) \right) & 0 & \sin \left( \frac{\pi}{2} (i-1) \right) \\ 0 & 1 & 0 \\ -\sin \left( \frac{\pi}{2} (i-1) \right) & 0 & \cos \left( \frac{\pi}{2} (i-1) \right) \end{bmatrix}
\]

(15)

Here, \( m, n \) are the number of elastic limbs.

Substituting Eq.(16) into Eq.(17), the compliance matrix \( C \) of the whole compliant device in the coordinate system \( \mu_x - \gamma_y - z \) can be derived.

\[
C = \frac{1}{12} \begin{bmatrix} E &= &0 &0 &0 \\ n &= &0 &0 &-m \\ m &= &0 &0 &m \end{bmatrix}
\]

(16)

Here, \( \mu_x ^* \) and \( \gamma_y ^* \) are the distance between \( \{B, x, y, z\} \) and \( \{O, x, y, z\} \) \((i=1, \ldots, 4)\) along \( x \) and \( y \) respectively.

The stiffness matrix \( K \) of the compliant device is as follows,

\[
K = 2 \sum_{i=1}^{4} T_{ij} k_{xi} T_{ij}^{T}
\]

(17)

Here, \( i \) is the number of elastic limbs.

Parameter optimization

In order to guarantee the desired compliance of this device in each direction, the following objective function is constructed to optimize the geometry parameters of compliant components.

\[
L = \min \left[ \lambda(C_i(C_i - C_i^*)^2 + \lambda_i(C_i - C_i^*)^2 + \lambda_i(C_i - C_i^*)^2 + \lambda_i(C_i - C_i^*)^2 \right] \quad \text{s.t.} \quad \Delta x \leq \Delta x', \Delta y \leq \Delta y', \Delta z \leq \Delta z', \Delta \theta_x \leq \Delta \theta_x', \Delta \theta_y \leq \Delta \theta_y', \Delta \theta_z \leq \Delta \theta_z'
\]

(20)

Here, \( C_i, C_i', C_i^* \) denote the desired compliance, \( \lambda_i, \lambda_i', \lambda_i \) are the normalization coefficients; \( \Delta x', \Delta y', \Delta z', \Delta \theta_x', \Delta \theta_y', \Delta \theta_z \) are the desired range. The NSGA-II multi-objective optimization algorithm [28] is used to solve the above multi-objective optimization problem and the desired compliances can be achieved.

4. Experiment verification

In this design, the TPU material is used to manufacture the compliant component. The shrinkage, elastic modulus and Poisson's ratio of this material are 0.4% ~ 0.9%, 0.2Gpa and 0.394. According to the practical requirement, the desired compliance and movement range are set as follows,
By solving the optimization problem (20) and (21), the structure parameters of the elastic limb are obtained and shown in Table I, and the practical compliant device and its shape parameters is illustrated in Fig.9.

\[
\Delta x \leq \Delta x' = 30; \Delta y \leq \Delta y' = 30; \Delta z \leq \Delta z' = 14; \\
\Delta \theta_x \leq \Delta \theta_x' = 15^\circ; \Delta \theta_y \leq \Delta \theta_y' = 15^\circ; \Delta \theta_z \leq \Delta \theta_z' = 30^\circ; \\
C_i = C_{i'} = C_i = 2 \\
C_i' = C_{i'} = C_i = 0.4
\]

(21)

By solving the optimization problem (20) and (21), the structure parameters of the elastic limb are obtained and shown in Table I, and the practical compliant device and its shape parameters is illustrated in Fig.9.

| L(mm) | b(mm) | h(mm) | d(mm) | m(mm) | n(mm) |
|-------|-------|-------|-------|-------|-------|
| 40    | 10    | 10    | 20    | 20    | 30    |

Table I

**Structural parameter of elastic limb**

Fig. 9. (a) Overall dimensions; (b) the internal structure.

By solving the optimization problem (20) and (21), the structure parameters of the elastic limb are obtained and shown in Table I, and the practical compliant device and its shape parameters is illustrated in Fig.9.

Then, this designed compliant device is applied to connect the manipulator and the gripper (the tool). A JAKA ZU7S 6-DOF manipulator with the Advantech 610L PC and a force/Torque sensor (ATI Axia80) is used as the manipulator. The whole robot system is shown in Fig. 10.

**Experimental verification of compliant device**

The following tensile and torsional test experiments on a stretcher, as indicated in Fig.11, are conducted to test the compliant device’s stiffness,

1. **Horizontal stretching experiment**: the force \( F = 20N \) respectively along x and y is used to stretch the compliant device horizontally. The relation of force and the deformation along x and y as well as the model (19) are shown in the Fig.12;
2. **Vertical stretching experiment**: the force \( F = 20N \) along z is used to stretch the compliant device vertically. The relation of force and the deformation along z as well as the model (19) are shown in the Fig.13;
3. **Torsion experiment**: The torque \( T = 2N\cdot mm \) around x, y and z respectively, which is used to test the torsional deformation. The relation of torque and deformation around x, y and z as well as the model (19) are shown in the Fig.14 and 15, respectively.

From Fig.12-15, the established stiffness model and the experimental results fit very well. This demonstrates the effectiveness of this model with the measured deformation-force data. The actual stiffness of compliant device along x, y, z and around x, y, z are 1.63 N/mm, 1.74 N/mm, 1.95 N/mm, and 0.33 N·m/ rad, 0.35 N·m/ rad, 0.36 N·m/ rad, which satisfy the desired limitations in Eq. (21).

**Fig. 10. the manipulator, compliant device and gripper**

**Fig. 11. Tensile/torsion test**

**Fig. 12. Relation of force and deformation along x and y**

**Fig. 13. Relation of force and deformation along z**
Then, two kinds of assembly experiments, the shaft-hole assembly and the nut-stud assembly, are used to further verify the compliant performance of this device.

For the shaft-hole assembly experiments, four experiments, as shown in Fig. 18, are conducted under different conditions: (a) verticality between shaft and hole; (b) inclination angle between shaft and hole equal to 5°; (c) inclination angle equal to 10°; (d) inclination angle equal to 15°. The experimental results are shown in Fig. 19, from which assembly is very well as using this compliant device even if there is a big inclination angle between shaft and hole. Moreover, contact force from the shaft along x-axis is measured and shown in Fig. 20. From these figures, there has a big contact force at the whole assembly process as there is without this designed compliant device and under inclination angle equal to 15°. However, as indicated in Figs. 20(b-d), there has a small contact force with short action time as using this designed compliant device. Thus, this designed compliant device can effectively reduce the contact force and its action time.

**Figure 15. Relation of torque and deformation around z**

**E. Assembly Experiment**

Using Eq. (9), the workspace of the compliant device is calculated and shown in Fig. 15. Besides, based on the practical workspace in Fig. 16, the comparison is carried out to verify the effectiveness of this compliance device. It can be seen from the figures that this design can satisfy the desired movement range in Eq. (21).
Fig. 19. Shaft-hole assembly experiments: (a) verticality between shaft and hole; (b) inclination angle equal to 5°; (c) inclination angle equal to 10°; (d) inclination angle equal to 15°.

Fig. 20. Contact force from the shaft along x-axis: (a) assembly without the compliant device under inclination angle equal to 15°; (b) assembly with the compliant device under inclination angle equal to 5°; (c) inclination angle equal to 10°; (d) inclination angle equal to 15°.

Furthermore, the nut-stud assembly is used to verify the effectiveness of the designed compliant device. When it directly assembles nut and stud using the manipulator without the designed compliant device, this assembly cannot realize as the nut and stud are not aligned. As comparison, when using the manipulator with the designed compliant device, three experiments for the unaligned nut-stud assembly are conducted under the inclination angle equal to 5°, 10° and 15° respectively, as shown in Fig. 21. As an example, the process of unscrewing nut into stud under inclination angle equal to 15° is shown in Fig. 22. From these figures, even if there is a big unaligned error, the nut-stud can be well assembled with the designed compliant device.

Fig. 21. Nut-stud assembly conditions: (a) inclination angle equal to 5°; (b) inclination angle equal to 10°; (c) inclination angle equal to 15°.

Fig. 22. Process of unscrewing nut into stud under inclination angle equal to 15°.

5. Conclusions

In conclusion, a novel compliant device with an adjusted compliant centre was briefly developed to realize the reliable assembly under the position deviation or the angle
deviation and not produce a significant contact force. This designed device becomes compliant and can move in a particular direction when the contact force exceeds a particular value. Unlike the traditional parallel mechanism, it can avoid the influence of assembly errors and the gap between the moving pairs. Experiments on this device validate the effectiveness of the kinematic model and stiffness model of the compliant device and the correction of the workspace. These experiments further demonstrate that the designed device satisfies the desired design conditions. Besides, experiments on the shaft-hole assembly show a small contact force with short action time when using this designed compliant device even if there is a big inclination angle. Thus, this designed compliant device can effectively realize the reliable assembly under the position or angle deviation and avoid producing a considerable contact force. Also, even if there is a significant unaligned error, it can still effectively assemble the nut-stud with the designed compliant device.

Declarations

Funding
This work was partially supported by the National Key R & R&D Program of China (2018YFB1308202), National Natural Science Foundation of China (51675539), and the Hunan Provincial Science Fund Distinguished Young Scholars under Grant 2019JJ20030.

Conflicts of interest/Competing interests
The authors declare that they have no competing interests.

Availability of data and material
Not applicable.

Code availability
Not applicable.

Authors' contributions
Du Xu provides design and experiment tests. He is a major contributor in writing the manuscript. Pro. Lu provided valuable suggestions for the revision and sorting of the whole article. All authors read and approved the final manuscript.

Ethics approval
Not applicable.

Consent to participate
Not applicable.

Consent for publication
Not applicable.

Acknowledgment
We appreciated Pro. Lu for the revise of the manuscript.

References
[1] S. Liu, D. Xu, D. P. Zhang, and Z. T. Zhang, “High precision automatic assembly based on microscopic vision and force information,” IEEE Trans. Autom. Sci. Eng., vol. 13(1), pp. 382–393, Jan. 2016.
[2] J. Takahashi, T. Fukukawa and T. Fukuda, “Passive Alignment Principle for Robotic Assembly Between a Ring and a Shaft With Extremely Narrow Clearance,” IEEE/ASME Transactions on Mechatronics, vol. 21, no. 1, pp. 196-204, Feb. 2016.
[3] Ma, X., Wu, D., Gao, Y. et al. “An approach to countersink depth control in the drilling of thin-wall stacked structures with low stiffness.” Int J Adv Manuf Technol, vol.95, pp.785–795 Oct.2018.
[4] C. Vidrios-Serrano, M. Mendoza, I. Bonilla, et al., “A Generalized Vision-based Stiffness Controller for Robot Manipulators with Bounded Inputs,” Int. J. Control Autom. Syst, vol.19,pp.548–561, Apr.2021.
[5] J. Peng , S. Ding, Z. Yang, et al., “Adaptive neural impedance control for electrically driven robotic systems based on a neuro-adaptive observer,” Nonlinear Dyn,vol.100,pp.1359–1378, Apr.2020.
[6] Lakshminarayanan, S., Kana, S., Mohan, D.M. et al. “An adaptive framework for robotic polishing based on impedance control.” Int J Adv Manuf Technol, vol.112, pp.401–417, Oct. 2021.
[7] L. Liu, S. Leonhardt, C. Ngo and B. J. E. Misgeld, “Impedance-Controlled Variable Stiffness Actuator for Lower Limb Robot Applications,” IEEE Transactions on Automation Science and Engineering, vol. 17, no. 2, pp. 991-1004, April 2020.
[8] A. Izadbaksh, S. Khorsashizadeh, S. Ghandali, “Robust adaptive impedance control of robot manipulators using Szász–Mirakyan operator as universal approximator,” ISA Transactions,vol.106,pp.1-11,Nov.2020.
[9] N. Kumar, M. Rani, “Neural network-based hybrid force/position control of constrained reconfigurable manipulators,” Neurocomputing, vol.420, pp.1-14, Jan.2021.
[10] Zhang, H., Li, L., Zhao, J. et al. “The hybrid force/position anti-disturbance control strategy for robot abrasive belt grinding of aviation blade base on fuzzy PID control.” Int J Adv Manuf Technol, April 2021.
[11] C. Baspinar, “Robust Position/Force Control of Constrained Flexible Joint Robots with Constraint Uncertainties.” J Intell Robot Syst, vol.100, pp.945–954, Dec.2020.
[12] F Peng, H Wen, C Zhang, B Xu, J Li, H Su, “Adaptive Robust Force Position Control for Flexible Active Prosthetic Knee Using Gait Trajectory,” Applied Sciences., vol.10(8),pp.2755, Apr.2020.
[13] A Peidró, M Tavakoli, Maria Marin, Ó Reinoso, “Design of compact switchable magnetic grippers for the HyReCro structure-climbing robot,”Mechatronics, vol. 59,pp.199-212, Apr.2019.
[14] D. Xing, F. Liu, S. Liu, and D. Xu, “Efficient insertion of partially flexible objects in precision assembly,” IEEE Trans. Autom. Sci. Eng., vol. 16, no. 2, pp. 706–715, Apr. 2019.
[15] G. Rosati, S. Minto, and F. Oscari, “Design and construction of a variable aperture gripper for flexible automated assembly,” Robot. Comput.-Integr. Manuf., vol. 48, pp. 157–166, Dec. 2017.
[16] H. Chen, J. Wang, G. Zhang, et al. “High-precision assembly automation based on robot compliance.” Int J Adv Manuf Technol vol.45, pp.999 May.2009.
[17] R. H. Sturges, S. Jr and Laowattana, “Design of an Orthogonal Compliance for Polygonal Peg Insertion.” ASME. J. Mech., vol.118(1), pp.106–114,Mar.1996.
[18] W. Haskiya, H. Qiao, and Knight, J.A.G. “A passive compliant wrist for chamfer-less peg-in-hole assembly operation from vertical and horizontal directions,” Proceedings of the Institute of Mechanical Engineers., vol. 212,pp.473-478, Jun.1998.
[19] W. Haskiya, K. Maycock, and J. Knight, “Robotic assembly: chamfer-less peg-hole assembly,” Robotica.,vol.17,pp.621-634,Nov.1999.
[20] M. Callegari, M. Palpacelli, M Principi, “Dynamics modelling and control of the 3-RCC translational platform, Mechatronics,” vol.16, pp.589-605, Dec. 2006.
[21] H S Kim, I P Dong, H P Chan, et al., “Variable Passive Compliance Device for Robotic Assembly,” Journal of the Korean Society of Manufacturing Technology Engineers., vol.25(6), pp.517-521, Apr. 2016.
[22] K. Kronander and A. Billard, “Stability Considerations for Variable Impedance Control,” IEEE Transactions on Robotics., vol. 32, no. 5, pp.1298-1305, Oct. 2016.
[23] S. Liu, D. Xing, Y. Li, J. Zhang and D. Xu, “Robust Insertion Control for Precision Assembly With Passive Compliance Combining Vision and Force Information,” IEEE/ASME Transactions on Mechatronics, vol. 24, no. 5, pp. 1974-1985, Oct. 2019.
[24] D. Xing, X. Liu, F. Liu and D. Xu, “Efficient Insertion Strategy for Precision Assembly With Uncertainties Using a Passive Mechanism,” IEEE Transactions on Industrial Informatics, vol. 17, no. 2, pp. 1263-1273, Feb. 2021.

[25] Chen, G., Zhang, Z., Kong, L., and Wang, H, “Analysis and Validation of a Flexible Planar Two Degrees-of-Freedom Parallel Manipulator With Structural Passive Compliance.” ASME. J. Mechanisms Robotics., vol.12(1), pp.011011, Oct. 2019.

[26] S.M. Mizanoor Rahman, Y Wang, “Mutual trust-based subtask allocation for human–robot collaboration in flexible lightweight assembly in manufacturing,” Mechatronics, Vol.54, pp.94-109, Aug. 2018.

[27] J. S. Dai, and X. Ding, “Compliance Analysis of a Three-Legged Rigidly-Connected Platform Device.” ASME. J. Mech. Des., vol.128(4), pp.755–764, July 2006.

[28] A. Khavandi Khiavi, and H. Mohammadi, “Multi-objective Optimization in Pavement Management System Using NSGA-II Method.” Journal of Transportation Engineering Part B Pavements., vol.144(2), pp. 04018016, June 2018.
Figures

Figure 1

Shaft-hole assembly using manipulator
Figure 2

(a) Position deviation; (b) angle deviation

Figure 3
(a) Structure of series-parallel compliant device; (b) Equivalent structure of each part; (c) Equivalent structure and deformation of compliant device.

Figure 4

Deformation of component: (a) Deformation $\Delta x$ along x-axis; (b) Deformation $\Delta y$ along y-axis; (c) Deformation $\Delta z$ along z-axis; (d) Deformation $\Delta \theta x$ around x-axis; (e) Deformation $\Delta \theta y$ around y-axis; (f) Deformation $\Delta \theta z$ around z-axis.
Figure 5

Deformation of compliant device; (a) Deformation $\Delta x$ along x-axis; (b) Deformation $\Delta y$ along y-axis; (c) Deformation $\Delta z$ along z-axis; (d) Deformation $\Delta \theta_x$ around x-axis; (e) Deformation $\Delta \theta_y$ around y-axis; (f) Deformation $\Delta \theta_z$ around z-axis.

Figure 6
(a) Assembly under horizontal position deviation; (b) Assembly under angle deviation; (c) Vertical position deformation.

Figure 7

Equivalent model of compliant device
Figure 8

(a) Structure of elastic limb; (b) equivalent model of elastic limb and compliant component; (c) equivalent model of compliant device.
Figure 9

(a) Overall dimensions; (b) the internal structure.
Figure 10

the manipulator, compliant device and gripper
Figure 11

Tensile/torsion test.

![Graph showing force vs. deformation for x and y directions.]

Figure 12

Relation of force and deformation along x and y.

![Graph showing force vs. deformation for z-direction.]
Figure 13
Relation of force and deformation along z

![Figure 13](image1.png)

Figure 14
Relation of torque and deformation around x and y

![Figure 14](image2.png)

Figure 15
Relation of torque and deformation around z

![Figure 15](image3.png)
Figure 16

Workspace

Figure 17

Practical movement range
Figure 18

Shaft-hole assembly conditions: (a) verticality between shaft and hole; (b) inclination angle equal to 5°; (c) inclination angle equal to 10°; (d) inclination angle equal to 15°.
Figure 19

Shaft-hole assembly experiments: (a) verticality between shaft and hole; (b) inclination angle equal to 5°; (c) inclination angle equal to 10°; (d) inclination angle equal to 15°.
Figure 20

Contact force from the shaft along x-axis: (a) assembly without the compliant device under inclination angle equal to $15^\circ$; (b) assembly with the compliant device under inclination angle equal to $5^\circ$; (c) inclination angle equal to $10^\circ$; (d) inclination angle equal to $15^\circ$. 
Figure 21

Nut-stud assembly conditions: (a) inclination angle equal to $5^\circ$; (b) inclination angle equal to $10^\circ$; (c) inclination angle equal to $15^\circ$.

Figure 22

Process of unscrewing nub into stud under inclination angle equal to $15^\circ$. 