A Multiple RCC Device for Polygonal Peg Insertion*

Chi-Cheng CHENG** and Gin-Shan CHEN**

This paper proposes a new passive compliant center device, the Multiple Remote Center Compliance (MRCC), for assembly tasks. The MRCC introduces a new azimuthal compliance over traditional passive compliance mechanisms that can effectively compensate the peg’s orientation deviation for polygonal insertions. Besides, a special feature of the adjustable compliance provides capability to overcome the gravity effect. Non-vertical insertions therefore become possible. A spring-supported object in space is also adopted for stability analysis of this compliant device. Actual experimental assembly processes demonstrate promising results on polygonal insertions in both traditional top-down and horizontal directions.

Key Words: Industrial Automation, Insertion Assembly, Polygonal Insertion, Remote Center Compliance

1. Introduction

The automatic assembly system plays a very important role in the automation production lines. It directly affects quality of product and manufacturing productivity. In order to successfully achieve the insertion assembly, most flexible automatic assembly systems are equipped with some sort of feedback for correction of positional and orientational inaccuracies during assembly processes. There are two standard methods: the passive compliance mechanism and the active compliance approach. The passive compliance mechanism uses inherent or designed flexibility to adjust the position or orientation to complete assembly tasks. Thus the advantages include fast response and sensorless control. However, insertions using this technique can only be accomplished for holes with chamfers. Besides, it seems to be impossible for assembly in the horizontal direction and this device can only be applied to insertions of round pegs and holes.

The remote center compliance (RCC) device, invented by Whitney and Nevins (1979, 1980), has been the most famous passive compliance mechanism for assembly tasks. Based on the RCC structure, Carnegie-Mellon University then built an automatically Adjustable Remote Center Compliance (ARCC) described in Mckerrow’s book (1995), which provided a self-adjustable compliance feature. Fazio et al. (1986) extended their achievements to the Instrumental Remote Center Compliance (IRCC) that combined engineered compliance with displacement measurement. The Selective Compliance Assembly Robot Arms (SCARA) have been widely used for the insertion assembly. Various kinds of assembly stations using a worktable with compliance were also developed by Araki and Kinoshita (1981). Recently, Sturges and Laowattana (1996) established a Spatial Remote Center Compliance (SRCC) for polygonal peg insertion.

The active compliance approach, intending to solve insertion problems from a more active way, incorporates position, force, and torque sensors into some feedback control strategies to monitor and accomplish the insertion tasks. Consequently, this approach appears to be more expensive and slow response. Brussel and Simons (1986) applied the active force feedback to two-dimensional active accommodation assembly experiments. A tactile-
controlled robot that could insert pistons in cylinders was also implemented by Goto et al. in 1992. In addition to employing conventional feedback control methods, researchers have been pursuing applications of advanced intelligent control strategies to insertion assembly. Gurock and Sam Lazaro (1995) have addressed a fuzzy logic algorithm on a manipulator for precision assembly. Jung and Gweon (1993) developed an intelligent flexible robot wrist by using neural network. Besides, the Magnetically Supported Intelligent Hand (MSIH) for precise peg-in-hole assembly was proposed by Tsuda et al. (1989). Vaaler and Seering (1991) focused on automated assembly by learning algorithm.

A new passive compliance device, the Multiple Remote Center Compliance (MRCC) mechanism, is developed in this paper. The RCC mechanism usually cannot work properly for insertions of non-vertical directions and for polygonal assembly. Three-dimensional prismatic parts in this design overcome these drawbacks of the traditional RCC device. The stability of a spring-supported object in space, which contributes the successful three-dimensional polygonal insertions, is also to be investigated. Actual assembly experiments will be extensively conducted by using a Mitsubishi RV–M1 robot.

2. The Assembly Process

Owing to constraints of robot’s accuracy, resolution, and repeatability, assembled parts may experience collision during the insertion process. Both positional and angular errors cannot be easily predicted because of indeterminate collision situations. If these assembly deviations are not compensated by modifying the insertion strategy, failure of the assembly may be caused.

Whitney (1982) classified the whole assembly process for round peg insertions into four stages: approach, chamfer crossing, one-point contact, and two-point contact. The two-point contact stage is the most difficult part. It is easy to bring about problems of wedging or jamming, which usually damages the mating parts and prohibits successful insertions. Nevertheless, Strip (1988) described the insertion strategy for triangular pegs with three phases: initial orientation, final orientation, and insertion. At first, the peg is tilted; secondly, the peg is moved to the upright position; then the insertion task is executed till the peg is into the hole.

A square peg on the chamfer crossing stage under the situation of small clearance can be characterized by the following procedures: one-point contact, two-point contact, three-point contact, four-point contact, and peg rotation for longitudinal alignment. Therefore, for a successful assembly, the orientation error between the peg and the hole should become null, when the peg departs from the chamfer surface. Line-plane contact and plane-plane contact are special cases of the two-point-contact and the three-point-contact, respectively.

Insertion operation is a geometric problem in relation with the dimensions, clearance, and tolerances of workpieces. The main difficulty is wedging in the subject of study. The phenomenon of wedging implies that the insertion depth is too shallow in the hole and the peg is over tilted, so the peg cannot go further no matter how large the force is presented. There already exist a number of literatures devoted on quasi-static assembly (e.g., Simunovic, 1979 and Whitney, 1982). A wedging diagram for a round peg in the hole has been presented and is shown in Fig. 1. The linear equation of the upper and lower boundaries can be described by

\[ \theta_0 + s_0 = \theta_{\text{min}} \]

where \( \theta_0 \) is the smallest angle at which the wedging could occur, and \( \theta_0 \) and \( s_0 \) denote the angular error and lateral error, respectively. The parameter \( s \) represents a slope between the peg and hole:

\[ s = \frac{L_o}{L_o^2 + \frac{K_s}{K_x}} \]

with

- \( L_o \): distance from a rigid support to the peg's tip,
- \( K_s \): lateral compliance, and
- \( K_x \): angular compliance.

In addition, Sturges (1988) investigated the three-dimensional wedging for the square-peg-and-hole problem and obtained the contact friction needed to support this condition. Recently, wedging in three-dimensional peg insertion tasks was deeply studied by Sturges and Laowattana (1996). Three types of wedging, two-point, virtual and redundant, were classified. The two-point wedge was clearly characterized by Whitney (1982). Virtual wedging occurs
when lines connecting each pair of contact points do
not fall within both friction cones. Whereas the
redundant wedging is created, when multiple cases of
two-point wedges and/or virtual wedges arise simulta-
nously. A similar wedging diagram for the ortho-
configuration has also been presented for comparison
purposes.

As a result, complete constrained conditions of
gometry for successful assembly can be concluded as
follows:
(1) The initial lateral error \( \varepsilon_0 \) must be smaller
than the chamfer’s width \( w \), i.e., \(|\varepsilon_0| < w\).
(2) The angle \( \theta_\alpha \) when two-point contact occurs
should be smaller than the wedging angle \( \theta_e \), i.e.,
\(|\theta_\alpha| < \theta_e\).
(3) \( \theta_\alpha \) must fall outside the virtual and redundant
wedging region.

Jamming is the other subject causing assembly
failure, where the insertion task cannot proceed due to
wrong proportions of the applied forces and moments.
We follow Simnović’s (1979) and Whitney’s (1982)
methods for the round peg in hole and yield
\[
\begin{align*}
\lambda & = \frac{1}{2\sigma \mu} \\
\frac{M}{rF_z} + \mu(1 + \lambda) \frac{F_x}{F_z} & = \lambda
\end{align*}
\]  
(2)
\[
\frac{F_x}{F_z} = \frac{1}{\mu}
\]  
(3)
\[
\lambda = \frac{1}{2\sigma \mu}
\]  
(4)
where
\( M \): moment applied on the peg
\( F_z \): force applied on the peg
\( \mu \): friction coefficient
\( r \): the radius of the peg
\( l \): the depth of peg in the hole

The 2-D Jamming diagram depicted in Fig. 2 can be
concluded by Eqs. (2) and (3). Two groups of
parallel lines represent critical conditions for two-
point contact and one point contact, respectively.
Strip (1988) proposed a hybrid force-position control
strategy with active compliance for convex polygonal
pegs. Analysis of the contact point’s force and
moment demonstrated human-like behavior. Strip
(1989) also designed a passive mechanism to avoid
jamming for 3-D convex peg insertion tasks. In
addition, Shahinpoor and Zohoor (1991) investigated
the dynamic equilibrium and constraints for successful
insertion operation. Six inequalities were derived
to avoid jamming for the insertion assembly of round
peg.

The three-dimensional jamming problem was
also studied by Sturges (1988). An extended jamming
diagram was presented. Following Sturges’s analysis
under some constraint conditions and hypothesis leads
to
\[
\begin{align*}
\frac{M_x + M_z}{rF_z} & = \frac{\mu(2 + \lambda)(\mu \lambda F_x + \mu F_z)}{F_z} = \lambda \\
\frac{\sqrt{F_x^2 + F_z^2}}{F_x} & = \frac{1}{\mu}
\end{align*}
\]  
(5)
(6)
where
\( M_x, M_z \): components of the moment exerted on the
peg
\( F_x, F_z \): components of the force applied on the peg
\( \mu \): friction coefficient
\( r \): half width of the square peg

As a result, the jamming space shown in Fig. 3 can be
obtained by solving Eqs. (5) and (6). Therefore,
conditions to prevent insertion from jamming become:
(1) The insertion force must be bigger than the
frictional force, i.e.,
\[
\sqrt{F_x^2 + F_z^2} < \frac{1}{\mu}
\]  
(7)
(2) The forces and moments must fall within the

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Fig. 4 The multiple remote center compliance device

jamming space, i.e.,
\[
\frac{M_x + M_y}{rF_z} - \mu(2 + \lambda) \frac{F_x}{F_z} + \mu\lambda \frac{F_y}{F_z} < \lambda
\]

(8)

3. The Multiple RCC

The traditional RCC device has compliance on both the lateral position and the tilted orientation. Although this design provides passive adjustability for misalignment of peg insertions, only round pegs and holes can be applied to. In order to enhance assembly ability of the RCC mechanism to polygonal insertion tasks, the Multiple Remote Center Compliance (MRCC) device shown in Fig. 4 is developed. The MRCC consists of a translational prism and a rotational prism, which are supported by four linear springs, respectively. Arrangement of these springs is illustrated in Fig. 5. It should be noted that the springs attached on the rotational block are intentionally placed by an angle deviation $\alpha$ with the springs on the translational one. This novel design contributes an axial compliance in addition to the lateral and orientation compliance. Moreover, the end of each spring attached on the housing is connected to an adjustable screw (not shown in the figure), which can supply a preset spring tension as needed. This feature is specially designed to balance possible external force disturbances such as gravity force, so that non-conventional top-down insertions can be accomplished.

Let the linear spring constants for the springs attached to the rotational and the translational prisms be denoted by $K_r$ and $K$, respectively. Under the assumption of small displacements, the rotational prism provides rotational compliances on $x$, $y$, and $z$ axes:

\[
C_r = \frac{1}{2K_rR^2}
\]

(9)

\[
C_a = \frac{1}{Kd^2 \cos^2 \alpha}
\]

(10)

where $R$ and $d$ are the radius of curvature with respect to the compliance center $C_1$ and the planar diameter of the rotational prism. Clearly, non-vertical angle $\alpha$ assures existence of the finite axial compliance $C_a$. Furthermore, magnitude of the axial compliance can be adjusted by changing the angle $\alpha$ depending on natures of different assembly tasks.

Translational compliances are contributed by both the translational and the rotational prisms. Since springs on the rotational prism and on the translational prism can be considered as serial components, the lateral compliances on the $x$ and $y$ directions become:

\[
C_x = C_{x(t)} + C_{x(r)}
\]

(11.a)

\[
C_y = C_{y(t)} + C_{y(r)}
\]

(11.b)

where $C_{x(t)}$ and $C_{x(r)}$ represent compliances on $x$ axis provided by the rotational prism and the translational prism respectively and can be formulated by
\[
C_{x(t)} = \frac{2}{K_x} \\
C_{y(t)} = \frac{2}{K_y}
\]  
(12.a)  
(12.b)

Because of symmetry of spring arrangement, similar expressions can be obtained for the \(y\)'s direction, i.e.,
\[
C_{y(r)} = \frac{2}{K_y} \\
C_{y(t)} = \frac{2}{K_y}
\]  
(13.a)  
(13.b)

As a result, a simpler form for the lateral compliances can be derived as
\[
C_x = C_y = 2\left(\frac{1}{K_x} + \frac{1}{K_y}\right)
\]  
(14)

If combination of a force and a moment is applied at the peg's tip, where is the rotational center \(C_1\) of the rotational prism, the peg will be tilted and rotated. As the total reaction force and moment caused by those springs can balance the external disturbance, the peg will be in static equilibrium. Since compliant forces produced by spring elongation or compression are always on the \(x-y\) plane, only planar reaction forces need to be examined. Under the assumption of small displacements, the linear displacements \(\delta_x\) and \(\delta_y\), and the rotational movements \(\delta_{xg}\), \(\delta_{yg}\), and \(\delta_{g}\) for the peg are
\[
\delta_x = C_x F_x = 2F_x \left(\frac{1}{K_x} + \frac{1}{K_y}\right)
\]  
(15.a)
\[
\delta_y = C_y F_y = 2F_y \left(\frac{1}{K_x} + \frac{1}{K_y}\right)
\]  
(15.b)
\[
\delta_{xg} = C_{xg} M_x = \frac{M_x}{2K_x K_y}
\]  
(15.c)
\[
\delta_{yg} = C_{yg} M_y = \frac{M_y}{2K_x K_y}
\]  
(15.d)
\[
\delta_{g} = C_g M_z = \frac{M_z}{K_a^2 \cos^2 \theta}
\]  
(15.e)

The total translation displacement \(\delta_x\) consists of both movements of the rotational prism \(\delta_{x(t)}\) and the translational prism \(\delta_{x(r)}\). Because serial springs withstand identical force, those individual displacements can be easily determined as follows:
\[
\delta_{x(r)} = C_{x(r)} F_x = \frac{2F_x}{K_x}
\]  
(16.a)
\[
\delta_{x(t)} = C_{x(t)} F_x = \frac{2F_x}{K_y}
\]  
(16.b)

Similarly, corresponding displacements for the \(y\) direction are
\[
\delta_{y(r)} = C_{y(r)} F_y = \frac{2F_y}{K_y}
\]  
(17.a)
\[
\delta_{y(t)} = C_{y(t)} F_y = \frac{2F_y}{K_x}
\]  
(17.b)

4. Stability Analysis

Assume a polygonal object is supported by springs in space as shown in Fig. 6. For the sake of simplicity, assumptions of rigid body and frictionless joints are made. Besides, without loss of generality, original lengths of all springs are also presumed to be zeros. Consider that the object initially stays at an equilibrium state and is disturbed by an external force. Two end points of the \(i\)-th spring, \(P_i\) and \(Q_i\), therefore moves to different locations, \(P'_i\) and \(Q'_i\), respectively. The following expression can be easily established by the vector analysis technique.
\[
a_i + L'_i = L_i + R_i
\]  
(18)

where
\[
a_i = Q_i - Q_i
\]
\[
R_i = P_i - P_i
\]
\[
L_i = P_i - Q_i
\]
\[
L'_i = P'_i - Q'_i
\]

Since this system is in static equilibrium at the beginning, summation of all spring forces should be equal to zero, i.e.,
\[
\sum k_i L_i = 0
\]  
(19)

where \(k_i\) denotes the spring constant of the \(i\)-th linear spring.
\[ \theta_i \text{ and } \beta_j \text{ represent the angle displacements of the } j-\text{th spring before and after accepting the external disturbance. The angle variations of two ends of the torsional spring are denoted by } \alpha_i \text{ and } \beta_i, \text{ respectively, as illustrated in Fig. 7. An equivalent angle displacement } \delta \theta_i \text{ that produces identical energy storage can therefore be found and should satisfy} \]
\[ \delta \theta_i^2 = (\theta_i + \alpha_i - \beta_i)^2 - \theta_i^2 \]

If the body is supported by a number of springs and the gravitational potential energy can be neglected, the total potential energy \( V \) should be equal to the sum of the elastic potential energy of all the springs, i.e.,
\[ V(R_i, a_i, \alpha_i, \beta_i) = \frac{1}{2} \sum_i k_i \delta \theta_i^2 + \frac{1}{2} \sum_j k_j \delta \theta_j^2 \quad (23) \]

The object will be in static equilibrium if and only if the total forces and moments are zeros. It also implied that all the first partial derivatives of the potential energy function \( V(R_i, a_i, \alpha_i, \beta_i) \) should be zero.
\[ \left. \frac{\partial V}{\partial R_i} \right|_{(0,0,0)} = \sum_i k_i \delta \theta_i = 0 \]
\[ \left. \frac{\partial V}{\partial a_i} \right|_{(0,0,0)} = \sum_i k_i \delta \theta_i = 0 \]
\[ \left. \frac{\partial V}{\partial \alpha_i} \right|_{(0,0,0)} = \sum_i k_i \delta \theta_i = 0 \]
\[ \left. \frac{\partial V}{\partial \beta_i} \right|_{(0,0,0)} = \sum_i k_i \delta \theta_i = 0 \]

The above equations indicate that the spring-supported system is at equilibrium state as long as both the total force generated by linear springs and the total moment produced by torsional springs are zero. In other words, linear springs and torsional springs only contribute linear forces and moments respectively.

Furthermore, a point at the potential field with the property of strictly local minimum is stable equilibrium. Therefore, if the equilibrium state is stable, the Hessian matrix \( H \) of the potential energy function \( V \) with respect to the equilibrium state needs to be positive definite.
\[
\begin{bmatrix}
\sum k_i & 0 & 0 & -\sum k_i & 0 & 0 & 0 & 0 \\
0 & \sum k_i & 0 & 0 & -\sum k_i & 0 & 0 & 0 \\
0 & 0 & \sum k_i & 0 & 0 & -\sum k_i & 0 & 0 \\
-\sum k_i & 0 & 0 & \sum k_i & 0 & 0 & 0 & 0 \\
0 & -\sum k_i & 0 & 0 & \sum k_i & 0 & 0 & 0 \\
0 & 0 & -\sum k_i & 0 & 0 & \sum k_i & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \sum k_0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\sum k_0 \\
\end{bmatrix}
\]
\tag{24}

If all the Hessian matrix's principal minors are strictly greater than zero then it is positive definite. But all the principal minors of the above matrix are

\[\det H_1 = \sum k_i > 0\]
\[\det H_2 = \left(\sum k_i\right)^3 > 0\]
\[\det H_3 = \left(\sum k_i\right)^5 > 0\]
\[\det H_4 = 0, \quad 3 < k \leq 8\]

So the system is not positive definite but semi-positive definite. Higher order terms then must be included to decide whether the system is stable or not. Because all third partial derivatives of the potential energy function \(V(x)\) at the equilibrium state reduce to zeros, it can be concluded that the system is neutral equilibrium at this specific state.

Since the MRCC device is supported by springs, its stability problem can be analyzed by the above similar process. Because the housing of the translational prism is fastened at the end effector, springs in charge of translation motion can be considered as one end fixed. However, the springs attached at the rotational prism are components with two free ends. Therefore, the total potential energy of the MRCC mechanism can be expressed by

\[
V(R_i, R_o, a_i) = \frac{1}{2} \sum K_\delta_i^2 + \frac{1}{2} \sum K_\delta_i^2
\tag{25}
\]

where
\[
\delta_i^2 = |R_i|^2 + 2L_i \cdot R_i - a_i
\]
\[
\delta_i^2 = (R_i - a_i) \cdot (R_i - a_i + 2L_i)
\]

In addition, the translational prism is positioned by springs with \(K\) and \(K_o\). The relation of \(R_i = a_i\) can therefore be concluded. The above energy equation reduces to

\[
V(R_i, a_o) = \frac{1}{2} \sum K(|a_i|^2 + 2L_i \cdot a_i) + \frac{1}{2} \sum K_o (R_i - a_i) \cdot (R_i - a_i + 2L_i)
\tag{26}
\]

The first derivatives of \(V\) can be solved as:

\[
\frac{\partial V}{\partial R_i} \bigg|_{a_o} = \sum K_\delta_i = 0
\]
\[
\frac{\partial V}{\partial a_i} \bigg|_{a_o} = \sum KL_i - \sum K_\delta_i = 0
\]

Besides, the corresponding Hessian matrix \(H_o\) is

\[
H_o = \begin{bmatrix}
4K_\delta & 0 & 0 & -4K_\delta & 0 & 0 \\
0 & 4K_\delta & 0 & 0 & -4K_\delta & 0 \\
0 & 0 & 4K_\delta & 0 & 0 & -4K_\delta \\
-4K_\delta & 0 & 0 & 4(K + K_o) & 0 & 0 \\
0 & -4K_\delta & 0 & 0 & 4(K + K_o) & 0 \\
0 & 0 & -4K_\delta & 0 & 0 & 4(K + K_o)
\end{bmatrix}
\tag{27}
\]

It appears that
\[\det H_o = 4096KK_o(2K_\delta^2 + 2K_\delta K + K^2) > 0\]

Consequently, the MRCC system at the equilibrium point \((0, 0)\) is stable.

5. Experiments and Discussions

In order to verify the assembly capability of the
errors. This phase ends till the peg touches the chamfer with the condition of one-point contact.

One-point contact

As the square peg reaches a point $Z_0$ on chamfer surface $E_1$ depicted in Fig. 9, a reaction force $F$, and a moment $r \times F$, are exerted on the peg. Assume the axial moment is too small to overcome the friction constraint on the chamfer surface. The peg can only slide on chamfer with little adjustment on pitch and yaw angles. Therefore, the peg tends to move along the unit planer vector $n_1$, which points toward center of the hole and perpendicular with its edge, on the corresponding chamfer surface. This path is illustrated as $S_1$ in Fig. 10.

Two-point contact

Similarly, two reaction forces, $F_1$ and $F_2$, exist, while two-point contact occurs. A reasonable assumption that the inserting force $F$ is evenly distributed at these two points is made. Those two reaction forces can therefore be approximately equal to each other. $S_2$ in Fig. 10 demonstrates the trajectory on the chamfer surface for two-point contact. Note that $S_2$ is almost parallel to the direction of chamfer corner intersected by chamfer surfaces with $n_2$ and $n_5$. As a result, the peg will follow the tendency determined by correspondingly adjacent planar vectors $n_1$ and $n_5$, i.e.,

$$ n_1 + n_5 = \begin{pmatrix} 0 \\ 0 \\ (0, 0, 1) \cdot n_1 \end{pmatrix}, $$

which is equivalent to the line direction of the corner between the chamfer planes 1 and 2. It should be noted that the last term of Eq.(28) is equal to $\sin \gamma$, where $\gamma$ denotes the chamfer angle.

Three-points contact and four-point contact

Based on the similar reason, the peg experiences through stages of three-point and four-point contacts. When the four-point contact occurs, the peg is almost clamped by the chamfer and is not able to translate any more.

Rotation

If further insertion is desired, the push force exerted on the peg should be increased. When two pairs of force couple generated by reaction forces are large enough to overcome friction constraint for rotation, the peg starts to rotate till the peg’s orientation coincides with the hole. In this phase, both the rotational prism and the translational prism rotate at the same time. At one-point contact through three-point contact on chamfer, the translational prism supplies the lateral compliance. At four-point contact, both the translational and rotational blocks provide the orientational compliance.

MRCC device, we install it on a Mitsubishi RV-MI robotic arm as shown in Fig. 8. The experiments include both up-down and horizontal insertions. The followings describe typical stages for the assembly of a square peg and a hole with chamfer using the proposed mechanism.

**Approach**

The peg moves slowly toward the hole along the azimuth direction with possibly lateral and tilted
Fig. 11 Coordinate frame applied in experiments

**Departure from chamfer crossing**

The zero orientation error still cannot guarantee successful assembly for polygonal insertion. The peg may be tilted. As long as the wedging can be avoided, the tilted angle will be automatically compensated by the compliance of rotational prism.

**Insertion**

To avoid jamming is the main subject in this stage. In other words, the applied force and moment should be managed in appropriate ratios. The MRCC owns compliance in all directions and is able to self-adjust to its proper arrangement for accomplishment of insertion assembly.

Finally, actual insertion tests of using the novel MRCC device were extensively examined. In order to judge the assembly in different directions, both horizontal and standard top-down assemblies were conducted. In addition to the traditional cylinder peg, a variety of polygonal pegs, including square, rectangular, triangular, pentagonal, and hexagonal shapes, were applied. The material for the cylinder, square, and rectangular pegs was steel. But the triangular, pentagonal and hexagonal pegs were made of copper. All the holes were made of steel with chamfer width about 4.55 mm. The clearance between the peg and the hole was approximate 0.1 mm. Figure 11 illustrates coordinate definitions used in the experiments. The MRCC successfully completes a variety insertion tasks, as shown in Table 1. Compared to other passive compliant devices, the MRCC was capable of performing polygonal assembly with lateral and/or angular errors. Insertions with relatively large deviations could also be effectively managed. Above all, the MRCC could execute horizontal insertions, which were not easily to be achieved by using other passive compliant mechanisms.

<table>
<thead>
<tr>
<th>assembly direction</th>
<th>Geometry</th>
<th>Dimension (mm)</th>
<th>Lateral errors (mm)</th>
<th>Angular errors (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Edge length</td>
<td>$e_x$</td>
<td>$e_y$</td>
</tr>
<tr>
<td>Up to down</td>
<td>Cylinder</td>
<td>20.7</td>
<td>4.5</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Square</td>
<td>20.20</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>Rectangular</td>
<td>30.20x20.2</td>
<td>4.7</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Triangular</td>
<td>23.12</td>
<td>4.2</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Pentagon</td>
<td>15.90</td>
<td>4.5</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Hexagon</td>
<td>14.28</td>
<td>4.2</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Cylinder</td>
<td>20.7</td>
<td>4.1</td>
<td>4.1</td>
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<tr>
<td></td>
<td>Square</td>
<td>20.20</td>
<td>4.1</td>
<td>4.3</td>
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<tr>
<td></td>
<td>Hexagon</td>
<td>14.28</td>
<td>4.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

* Diameter of the cylindrical peg
** $P_x$: positive pitch angle, $P_y$: negative pitch angle, $R_x$: positive roll angle, and $R_y$: negative roll angle

**6. Conclusions**

This paper presents a novel passive compliance device, the Multiple Remote Compliance Center (MRCC), for polygonal assembly, which extends the capability of a traditional RCC. Besides the compliance of the conventional RCC mechanism, the MRCC owns an additionally azimuthal compliance, which is able to provide the orientation adaptability for polygonal insertions. Furthermore, a special function of adjustable compliance that can overcome the gravitational effect is also designed. Actual insertion experiments were extensively conducted on a variety of polygonal assembly tasks. Experimental results demonstrate encouraging insertion performance for lateral and orientational errors. The assembly capability for horizontal directions is almost identical with the performance for traditional top-down insertions.

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References


