Design and analysis of a flexure based passive gripper

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ABSTRACT

This paper investigates a compliant 5-DOF flexure based passive gripper for pick-and-place and insertion task. The proposed design eliminates the use of actuators and sensors to achieve proper alignment during insertion. The gripper consists of picking, aligning and releasing mechanisms. The maximum load capacity of the picking mechanism and compliance matrix of the releasing and alignment mechanism is determined analytically. Further, the formulations are validated using flexible multibody modelling software. A candidate gripper was designed and fabricated, and experiments were performed using an industrial robot. The gripper is capable of picking 1.5 kg rectangular object and handling 2 mm linear and 5° rotational misalignments. The gripper can be customized for various geometric shapes, sizes and alignment requirements depending on the application.

1. Introduction

Robotic grippers are widely used in assembly processes where parts have to be picked and placed or inserted into a hole or tube [1,2]. These grippers have many moving parts and joints. They are actuated electrically, pneumatically or hydraulically. Sensors are used to detect the error in position and orientation of the gripper and then corrected for misalignment. The use of sensors and actuators increases the overall cost considerably [3]. A passive device using shear pad based remote centre compliance is an alternate solution [4]. These devices eliminate the use of any sensor, but they are expensive and bulky.

Several researchers have developed different types of grippers using smart materials and analysed the peg-in-hole assembly problem with different approaches. Various concepts of peg-in-hole assembly like a square peg into a square hole and a round peg into a round hole were analysed by Arni and Makino [5]. A general method was introduced to make three-dimensional static models, and different kinds of errors were studied. A chamfer-less peg-in-hole assembly, by showing the geometrical, dynamical conditions for a successful assembly operation was provided by Haskiya et al. [6]. An emphasis on an image-based effector for handling an under servoing process of perception-action cycles with continual visual feedback was given by Pauli et al. [7]. A new passive compliant centre device for assembly tasks that can effectively compensate the pegs orientation and deviation for polygonal insertions was developed by Cheng et al. [8]. An active zooming control method that enables dynamic adjustment of the DOF according to the position was presented by Tao et al. [9]. The method was based on an artificial potential field method. Several contact phases in the square peg in hole process are proposed and analysed using Force/Torque (FT) sensor by Park et al. [10]. A compliant ionic polymer metal composite (IPMC) microgripper for selective compliant assembly robot arm (SCARA) was designed by Jain et al. [11]. A microgripper with flexure hinges and piezoelectric actuator was developed by Qiao et al. [12]. A mobile micro manipulation system for a robotic micro assembly using a compliant piezoelectric actuator based micro gripper was designed by Jain et al. [13] for handling the miniature parts and compensation of misalignment during peg-in-hole assembly.

Contact models and various positioning stages for peg-in-hole insertion were proposed and developed by various researchers. A contact model in peg-in-hole assembly and the alignment motion for arbitrarily large errors between the axes of peg and hole were discussed by Bruyninckx et al. [14]. Analytical, simulation and experimental results from a study of compliant insertion tasks in the micro assembly were presented by Lee et al. [15] where a comb structure was integrated into the gripper to calculate insertion force by measuring the deflection of a gripper. A novel compliant flexure based micro-parallel positioning stage for micro active vibration isolation application was designed by Xiao et al. [16]. A new model of 6-DOF 8-PSS/SPS compliant dual redundant parallel robot with wide-range flexure hinges was proposed by Yun et al. [17]. A macro parallel robot in which conventional bearings are replaced by pseudo-elastic flexure hinges was developed by Hesselbach et al. [18]. The robot consists of a spatial parallel structure with three translational degrees of freedom and is driven by three linear direct drives. A compliant micro gripper using bimorph piezoelectric
Pneumatic, electromagnetic and piezoelectric actuators are often used as grippers in the most of pick and place applications. These actuators are expensive, bulky and energy consuming. Further, force and proximity sensors are used for positioning of the gripper. Some of these sensors are eliminated by adding compliance to the grippers with help of smart materials and flexures. We, therefore, propose a flexure based passive gripper that accomplishes gripping without any actuator. Further, the design eliminates use of sensors by incorporating a 5-DOF mechanism for alignment.

In this paper, the problem of picking a cuboidal object and inserting it into a thin walled square hole is addressed (Fig. 1). A passive flexure based gripper, capable of handling limited misalignment, is proposed. The complete operation is divided into three processes - picking, alignment during insertion and releasing. For each process, a mechanism based on flexures is designed. Mathematical model is developed and stiffness values are calculated for each mechanism. An FEM model is developed to verify the analytical results. Experiments were conducted on a scaled version of the alignment mechanism made of stainless steel (SS) to validate the design. A candidate gripper was realized using 3-D printing for testing, using PA (polyamide) material for picking an object, cuboid in shape (20 mm × 20 mm x 40 mm) and inserting into a hole of similar dimensions of wall thickness 2 mm (Fig. 1).

This paper is organized as follows. In Section 2, design of the proposed gripper is discussed. Mathematical model and validation of the design using kinematic principles are presented in Section 3. Simulation in SPACAR and experiment details are covered in Sections 4 and 5, respectively. Experimental results and discussions are included in Section 5. Conclusion is presented in Section 6.

2. Design of passive gripper

The design of the gripper includes gripper base, picking mechanism, alignment mechanism and releasing mechanism (Fig. 2). These mechanisms are responsible for specific tasks, namely picking, alignment and releasing. The sequence of operations is illustrated in Fig. 3.

2.1. Picking mechanism

Picking is achieved by using sheet flexure as a cantilever beam as shown in Fig. 4. The mechanism is attached to the gripper base (Fig. 5). Gap between the two beams is smaller than size of the object to be picked so that each beam overhangs by a small amount as shown in Fig. 5. When the gripper is pushed towards the object, both the sheet flexures deflect upward making way for the object to get in place as shown in Fig. 6. Due to this deflection, bending moments are produced in the flexure which in turn apply normal reaction forces to the object. Owing to this normal force, friction force between the beams and object counteracts the gravity preventing the object from falling. A friction pad is attached to the free end of each beam to increase friction.

2.2. Alignment mechanism

During insertion, alignment mechanism compensates for error in position and orientation which are present in the system due to backlash in drive-train, flexibility of robot links, least count of sensors, etc.
For successful insertion, the gripper should have higher stiffness in the translational direction perpendicular to the plane of object as compared to other two translational and three rotational directions. Therefore, a 5-DOF alignment mechanism with decoupled rotation and translation (i.e., motion in one direction should not have a large effect on the motion in other directions) is required.

A flexure stage using folded sheet flexures as alignment mechanism is proposed and designed. A single folded sheet flexure provides one degree of freedom constraint along the fold line as shown in the Fig. 8 [30]. In the present embodiment, upper and lower part of the alignment mechanism is connected through an intermediate link using sets of two folded sheet flexures. Upper part is connected to the intermediate body with two folded sheet flexures in such a way that the two fold lines are parallel to the constraint direction. The intermediate body is further connected to the lower part with another set of two folded sheet flexures in a similar fashion but the plane containing two fold lines are orthogonal to the previous one. This arrangement results into 5-DOF flexure stage as shown in Fig. 7. The constraint direction is along the intersection of two planes containing the sets of two fold lines of the folded sheet flexures. Upper part is attached to the robotic manipulator and lower part to the gripper base. The mechanism has high stiffness along the z-axis and comparatively lower stiffness in other five degrees of freedom.

As the gripper base comes in contact with the object, appropriate element in the mechanism will deform and compensates for the translational and rotational misalignment between the object and gripper base. The maximum allowable misalignments (both rotational and translational) depend on the dimensions and material properties of each single folded sheet flexure. A candidate mechanism was fabricated using 3-D printing. It was designed to compensate for 2 mm linear and 5° rotational misalignments. The design was validated using finite element method and tested for performance. A prototype of the alignment mechanism was manufactured using stainless steel material.

### 2.3. Releasing mechanism

After alignment, the next task is to insert or release the object into the hole or tube. A passive mechanism is designed to release the object from picking mechanism (Fig. 9).

The releasing mechanism is a compliance structure, containing two identical folded sheet flexures, and two rigid intermediate bodies. The two folded sheet flexures are placed opposite to each other. The gap between two folded sheet flexures is such that it will only allow the object to pass through it but not the hole. The releasing mechanism is placed between the picking mechanism and the gripper base as shown in Fig. 10.

During the releasing process, as the gripper lowers on the hole, wall of the hole comes in contact with the intermediate body of the releasing mechanism. The folded sheet flexures deflect and push the sheet flexures of the picking mechanism. As the object looses contact with the sheet flexures, it falls inside the hole (Fig. 10).

### 3. Calculation and model validation

#### 3.1. Picking mechanism

The picking mechanism consists of two identical sheet flexures, one
end of each flexure is fixed at the base, and another end is free where a normal and frictional forces are acting as shown in Fig. 11.

If the normal force on the beams exceeds the critical force, then the beams will buckle. Therefore, the gripping capacity of the mechanism is limited by the critical load. The critical load for buckling is given by Ref. [31].

\[ P_{cr} = \frac{\pi^2 EI}{4L^2} \]
where \( P_c \) is the critical load for buckling, \( L \) is the length of the beam, \( E \) is Young's modulus, and \( I \) is the area moment of inertia of the beam.

The loading capacity of the gripper is given by

\[
W = n P_c
\]

(2)

\( F_r = \mu N \)

(3)

where \( W \) is the maximum weight that can be lifted by the gripper, \( F_r \) is friction force, \( N \) is the normal force, \( \mu \) is the coefficient of friction between the object and the picking mechanism and \( n \) is the number of sheet flexures.

For prototype fabrication, the dimensions of flexure are 20 mm in length, 16 mm in breadth and 0.6 mm in thickness. The coefficient of friction between the object and picking mechanism is 0.5. The material used for 3-D printing is PA3200 (polyamide) which has Young's modulus of 2.6 GPa. The maximum lifting capacity of the gripper, thus calculated, is 2.17 kg.

### 3.2. Releasing mechanism

As the hole comes in contact with the intermediate body of the releasing mechanism, the latter experiences a vertical force which causes the bending of two flexures as shown in the Fig. 12.

Consider a single folded sheet flexure \( e \), it is loaded at the sheet-end by planar forces \( F_{xe} \) and \( F_{ye} \), and an in-plane moment \( M_{xe} \). Assuming small elastic deformations, the displacement at the sheet-end \( (u_{xe}, u_{ye}, \theta_{x}, \theta_{y}) \) due to these forces are given by Ref. [30].

\[
U_e = C_r F_r
\]

(4)

where

\[
C_r = \begin{bmatrix}
\frac{1}{EI} & \frac{1}{EI} & 0 & 0 \\
\frac{1}{EI} & \frac{1}{EI} & 0 & 0 \\
0 & 0 & \frac{-E}{GJ} & \frac{-E}{GJ} \\
0 & 0 & \frac{-E}{GJ} & \frac{-E}{GJ}
\end{bmatrix}
\]

\[
F_r = \begin{bmatrix}
F_{xe} \\
F_{ye} \\
M_{xe}
\end{bmatrix}
\]

\[
U_e = \begin{bmatrix}
u_{xe} \\
u_{ye} \\
\theta_{x} \\
\theta_{y}
\end{bmatrix}
\]

here, \( U_e \) is the displacement vector at the sheet-end and \( C_r \) is the compliance matrix. Lengths of horizontal and vertical part of the folded sheet flexure are \( a \) and \( b \) respectively. Since both the sheet flexures are attached to the bottom rigid intermediate part, the displacement along \( x \) axis \( (u_{xe}) \) and angular displacement along \( x \) axis \( (\theta_{x}) \) are zero.

Therefore, the displacement at sheet-end of flexure \( e \) is given by

\[
U_e = \begin{bmatrix}
u_{xe} \\
u_{ye} \\
\theta_{y}
\end{bmatrix}
\]

(5)

Also, the forces acting at sheet-end of flexure \( e \) is

\[
F_{xe} = \frac{F_{yo}}{2}.
\]

(6)

Therefore, displacement of the intermediate body is given by

\[
\begin{bmatrix}
0 \\
F_{yo} \\
0
\end{bmatrix}
\]

(7)

Hence, the compliance along \( y \)-axis is

\[
C_y = \begin{bmatrix}
\frac{1}{EI} & \frac{1}{EI} & 0 \\
\frac{1}{EI} & \frac{1}{EI} & 0 \\
0 & 0 & \frac{-E}{GJ}
\end{bmatrix}
\]

(8)

The material used for 3-D printing fabrication of the prototype is PA3200 (polyamide). The values of \( a, b, \) width and thickness of the flexure are 19.6 mm, 10.2 mm, 16 mm, and 0.6 mm. The value of \( C_y \), thus calculated, is \( 5.60 \times 10^{-4} \text{ m/N} \) for the fabricated prototype.

### 3.3. Alignment mechanism

The relation between force applied and displacement for a single folded sheet flexure can be written as

\[
U = CF
\]

(9)

where \( U \) is the displacement vector and \( F \) is the force vector. Both \( U \) and \( F \) are written as a screw vector. Displacement vector \( U \) contains both linear and angular displacements. Similarly, the force and torque applied are assembled into a screw \( F \) (called a wrench) [32]. The compliance matrix \( C \) of the folded sheet flexure with equal horizontal and vertical length, displacement vector \( U \) and force vector \( F \) are given by (refer Appendix A).

\[
C = \begin{bmatrix}
u_x^2 & \nu_y^2 & 0 & 0 & 0 & \nu_z^2 \\
\nu_x^2 & \nu_y^2 & 0 & 0 & 0 & \nu_z^2 \\
0 & 0 & \frac{-l^2}{l^2} & \frac{-l^2}{l^2} & 0 & 0 \\
0 & 0 & \frac{-l^2}{l^2} & \frac{-l^2}{l^2} & 0 & 0 \\
\nu_z^2 & \nu_z^2 & 0 & 0 & 0 & \frac{-l^2}{l^2}
\end{bmatrix}
\]

\[
U = \begin{bmatrix}
u_x \\
u_y \\
u_z \\
\theta_x \\
\theta_y \\
\theta_z
\end{bmatrix}, \quad F = \begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_x \\
M_y \\
M_z
\end{bmatrix}
\]

where \( u_x, u_y, u_z \) are the linear displacements, \( \theta_x, \theta_y, \theta_z \) are the angular displacements, \( F_x, F_y, F_z \) are the forces applied and \( M_x, M_y, M_z \) are the torque applied along three axes. \( L, E, G, I \) and \( J \) are the length of single flexure, Young's modulus of elasticity, modulus of rigidity, area moment of inertia and torsion constant respectively [31].

The construction of 5-DOF flexure stage as alignment mechanism is shown in Fig. 13.

Diagonally opposite flexures \( a \) and \( c \) are connected to the robotic arm and the other two flexures \( b \) and \( d \) are attached to gripper mechanism via attachments H1 and H2. The coordinate system \( O \) is fixed to robotic arm and \( O' \) is fixed to the gripper. Let there be a displacement \( U_{oc} \) occurred at the centre \( O' \) due to the application of force \( F_{j} \). For calculation, \( O_{x}, O_{y}, O_{z} \) and \( O_{t} \) ends are taken as the free end of each folded sheet flexure \( a, b, c \) and \( d \) respectively. The corresponding displacement \( U_{oc} \) of flexure at \( O_{t} \) (for \( i = a, b, c, d \)) is calculated with the help of coordinate transformation in screw theory [32] and is given by

\[
U_{oc} = \begin{bmatrix}
R & 0 & 0 \\
\frac{1}{R} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

(10)

\[
D = (R, \theta_t)
\]

(11)
Another 12 equations are obtained from Eq. (9) for two flexures a and c.

\[ U_a = C_a F_a \]  \hspace{1cm} (15)

\[ U_c = C_c F_c \]  \hspace{1cm} (16)

Let \( U_{ac}^O \) represents the displacement \( U_O \) when only the flexures a and c are considered. The displacements \( U_a \) and \( U_c \) in Eq. (15) and Eq. (16) are written in terms of \( U_O \) (here \( U_{ac}^O \)) using Eq. (10). Therefore, by solving resulting 18 equations, the displacement \( U_{ac}^O \) is calculated.

\[
U_{ac}^O = \begin{bmatrix}
\frac{S_{32} F_{32}^2}{4EI} & \frac{S_{32} F_{32} F_{33}^2}{4EI} & \frac{S_{33} F_{33}^2}{4EI} \\
0 & \frac{2 S_{32} F_{32}^2}{4EI} & \frac{S_{33} F_{33}^2}{4EI} \\
0 & 0 & \frac{4 S_{33} F_{33}^2}{4EI}
\end{bmatrix}
\]

(17)

Similarly, the displacement \( U_{bd}^O \) from the other two flexures b and d is also calculated.

\[
U_{bd}^O = \begin{bmatrix}
\frac{S_{32} F_{32}^2}{4EI} & \frac{S_{32} F_{32} F_{33}^2}{4EI} & \frac{S_{33} F_{33}^2}{4EI} \\
0 & \frac{2 S_{32} F_{32}^2}{4EI} & \frac{S_{33} F_{33}^2}{4EI} \\
0 & 0 & \frac{4 S_{33} F_{33}^2}{4EI}
\end{bmatrix}
\]

(18)

Since, these two pairs of flexures are in series configuration, the total displacement of centre \( O' \) will be the sum of these two displacements.

\[
U' = U_{ac}^O + U_{bd}^O = \begin{bmatrix}
\frac{S_{32} F_{32}^2}{4EI} & \frac{S_{32} F_{32} F_{33}^2}{4EI} & \frac{S_{33} F_{33}^2}{4EI} \\
\frac{2 S_{32} F_{32}^2}{4EI} & \frac{2 S_{33} F_{33}^2}{4EI} \\
\frac{4 S_{33} F_{33}^2}{4EI}
\end{bmatrix}
\]

(19)

The corresponding compliance matrix for the mechanism is, therefore, given by

\[
C = \begin{bmatrix}
\frac{4 S_{33} L^3}{24EI} & 0 & 0 & 0 & 0 \\
0 & \frac{2 S_{32} L^3}{24EI} & 0 & 0 & 0 \\
0 & 0 & \frac{2 S_{32} L^3}{24EI} & 0 & 0 \\
0 & 0 & 0 & \frac{2 S_{33} L^3}{24EI} & 0 \\
0 & 0 & 0 & 0 & \frac{2L J}{3EI}
\end{bmatrix}
\]

(20)

The obtained compliance matrix is a diagonal matrix. This indicates that the displacement (or angular displacement) along any direction is depended only on the force (or torque) along that direction. Moreover, the compliance value for displacement along the Z direction is zero, which implies that the mechanism is rigid along the Z direction. Therefore, this mechanism provides decoupled 5-DOF flexure stage to facilitate alignment during insertion.

Stainless steel (SS) was used for the fabrication of prototype. A scaled-up version was proposed to achieve large deflection range. The dimensions (length \( L \), width \( w \), and thickness \( t \) ) of single flexure were 30 mm, 10 mm and 0.5 mm respectively. Corresponding values of area moment of inertia \( I \) and torsion constant \( J \), thus calculated, are
1.04 \times 10^{-13} \, \text{m}^4 \text{ and } 4.04 \times 10^{-13} \, \text{m}^4. \text{ The value of Young's modulus } E \text{ and modulus of rigidity } G \text{ for SS are 200 GPa and 76.92 GPa respectively } [31]. \text{ The compliance matrix, thus obtained, is given by (translational stiffness in m/N and rotational stiffness in rad/Nm)}

\[
C = \begin{bmatrix}
2.7 \times 10^{-4} & 0 & 0 & 0 & 0 & 0 \\
0 & 2.7 \times 10^{-4} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.48 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.093 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.48 \\
0 & 0 & 0 & 0 & 0 & 0.093
\end{bmatrix}
\]

4. Simulation in SPACAR

A flexible multibody model was built to validate the analytical results using SPACAR which is a modelling and simulation tool based on finite element method (FEM) for multibody dynamic analysis of planar and spatial mechanisms and manipulators with flexible links [34].

4.1. Releasing mechanism

The SPACAR model of releasing mechanism consists of two folded sheet flexures \(a\) and \(b\) and two rigid beams \(c\) and \(d\) as shown in Fig. 14. Beams \(c\) and \(d\) are joined together with a node. Force in \(y\)-direction was applied at the bottom-mid point of the model and deflection of the node was observed. Deformation of the releasing mechanism due to the applied force is shown in Fig. 15. Dimensions and the material property are same as of the prototype. Compliance in \(y\)-direction \(C_y\), thus obtained, is \(5.7 \times 10^{-4} \, \text{m/N}\).

4.2. Alignment mechanism

The SPACAR model of alignment mechanism consists of 4 folded sheet flexures \(a, b, c\) and \(d\) (each flexure has two sections, and each section has five beam elements) and six rigid beams \(e, f, g, h, i\) and \(j\) as shown in Fig. 16. Beams \(g\) and \(h\) are joined at the centre of the model with node 1 whereas beam \(e, f, i\) and \(j\) are joined at the same location with different node 2.

To obtain the compliance matrix for this model, a range of forces and moments for all the directions were selected within the limit of tensile strength (for stainless steel) of the model, e.g., \(F_x\) from 0 to 15 N, \(F_y\) from 0 to 15 N, \(M_x\) from 0 to 0.4 Nm, \(M_y\) from 0 to 0.4 Nm and \(M_z\) from 0 to 2 Nm. Forces or moments were applied on node 1 and displacement or rotation of the node was calculated for each direction. Deformations in each of the five directions are shown in Fig. 16.

Compliance in each five DOF was obtained from the simulation results. Table 1 shows the values of compliance in five DOFs. The variation in compliance values are also given. Off-diagonal elements of the compliance matrix were also calculated. However, their values were negligible as compared to diagonal elements. Hence, it is verified that displacement or rotation of the mechanism in any direction is dependent on force or moment applied in that direction.

5. Experiment

Experiments were conducted to validate the analytical and simulation results of the compliance matrix for alignment mechanism.

5.1. Experimental setup

Experiments were carried on KUKA KR-5 sixx R850 robot [35]. ATI Force/Torque Gamma sensor [36] was used to measure forces and torques which was mounted on the end effector of the robot. The alignment mechanism was mounted on the end effector of the robot with help of a flexure mounting as shown in Fig. 17. The flexure components of the alignment mechanism were fabricated using wire EDM method from a stainless steel monolithic block as shown in Fig. 18.

5.2. Experiment

The end effector was moved along the \(X\) direction to create known deflection in flexure stage, and corresponding forces and torques in all three directions were recorded. For each 0.2 mm displacement, readings were noted. Experiments were repeated for \(Y\) and \(Z\) direction. The experiment was conducted in both negative and positive directions. Similarly, for known angular displacement of flexure stage, the corresponding forces and torques were recorded in all three directions for each 0.5° displacement.

5.3. Results

Compliance is calculated for each direction and plotted with respect to the deflection. Linear fit was used and it was observed that the values are constant in the deflection range. Experimental values of compliance, thus obtained, are 0.291 mm/N for \(C_x\), 0.293 mm/N for \(C_y\), 28.31°/Nm for \(C_{0x}\), 28.50°/Nm for \(C_{0y}\) and 5.86°/Nm for \(C_{0z}\). Experimental results were compared with analytical and simulation results for compliance in translation and rotation in all five DOFs and shown in 19–23.

6. Discussion

The diagonal elements of the compliance matrix of the alignment mechanism were calculated by analytical, simulation and experimental methods. Analytical and simulation values are same for all directions. Experimental values are greater than analytical and simulation values as shown in Figs. 19–23. The causes of these variations could be the difference between actual and theoretical dimensions, and material properties, stresses due to mounting of the mechanism and non-rigidity of the intermediate bodies used for mounting the mechanism.

The performance of gripper was tested with the help of KUKA KR-5 robot by gripping and placing an object which is cuboid in shape and size of (20 mm × 20 mm × 40 mm) as shown in Fig. 24. The maximum weight of the object that can be lifted by the gripper is determined by the critical load for buckling of picking mechanism, which is found to be 2.17 kg. However, the gripper was tested for picking the mass of 1.8 kg as a precaution. The gripper was tested using KUKA robot for misalignment of 2 mm in translation and 5° in rotation during the insertion process. The object was inserted in the hole with the help of releasing mechanism.
7. Conclusion

A passive gripper based on flexure mechanism is conceptualized and analysed in this paper, which consists of picking, alignment and releasing mechanisms. Design and working principle of each mechanism is discussed in detail. The maximum load capacity of the gripper is calculated by considering the buckling effect of picking mechanism. Equations for compliance of alignment and releasing mechanisms are formulated as a function of flexure dimensions and material properties. The obtained equations are validated using a flexible multibody model in SPACAR. Prototypes were fabricated and tested for performance using KUKA KR-5 robot. Experimental results were in agreement with the analytical and simulation results.

The gripper is able to pick and insert an object without any extra
electrical or pneumatic actuators. Use of the flexure mechanism enables the gripper to handle small misalignment between object and hole. The gripper is designed for cuboidal object, however it can be adapted for different geometric shapes and sizes. The designed gripper, because of its compact size, light weight, and capability of handling misalignments, makes it suitable for pick and place or insert application over a traditional gripper.

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Appendix A. Calculation of Compliance matrix of Folded Sheet Flexure

Consider a single folded sheet flexure as shown in the Fig. 8. It is loaded at the sheet-end by three forces \( F_x, F_y, F_z \) and three moments \( M_x, M_y, M_z \). Corresponding linear and angular displacements along three axes are \( u_x, u_y, u_z \) and \( \theta_x, \theta_y, \theta_z \) respectively. Consider the effect of one force or moment at a time. Beam theory [31] is used for the calculation of displacements at the sheet-end of flexure. Only small elastic deflections are assumed. The flexure has constant thickness \( t \), length \( L \), area moment of inertia \( I \), and torsion constant \( J \). The material has Young’s modulus of elasticity \( E \) and modulus of rigidity \( G \).

Application of \( F_x \)

\[
u_x = \frac{4L^3}{3EI} F_x
\]

(A.1a)
\[ u_y = \frac{L^3}{2EI} F_z \]  
\[ u_z = 0 \]  
\[ \theta_x = 0 \]  
\[ \theta_y = 0 \]  
\[ \theta_z = \frac{3L^2}{2EI} F_z \]  
(A.1f)

Application of \( F_y \)

\[ u_x = \frac{L^3}{2EI} F_y \]  
\[ u_y = \frac{L^3}{3EI} F_y \]  
\[ u_z = 0 \]  
\[ \theta_x = 0 \]  
\[ \theta_y = 0 \]  
\[ \theta_z = \frac{L^2}{2EI} F_y \]  
(A.2f)

Application of \( F_z \)

\[ u_x = 0 \]  
\[ u_y = 0 \]  
\[ u_z = \frac{L^3}{GJ} F_z \]  
\[ \theta_x = -\frac{L^2}{GJ} F_z \]  
\[ \theta_y = 0 \]  
\[ \theta_z = 0 \]  
(A.3f)

Application of \( M_x \)

\[ u_x = 0 \]  
\[ u_y = 0 \]  
\[ u_z = -\frac{L^2}{GJ} M_x \]  
\[ \theta_x = \frac{L}{GJ} M_x \]  
\[ \theta_y = 0 \]  
\[ \theta_z = 0 \]  
(A.4f)

Application of \( M_y \)

\[ u_x = 0 \]  
\[ u_y = 0 \]  
\[ u_z = 0 \]  
\[ \theta_x = 0 \]  
\[ \theta_y = \frac{L}{GJ} M_y \]  
\[ \theta_z = 0 \]  
(A.5f)

Application of \( M_z \)

\[ u_x = \frac{3L^2}{2EI} M_z \]  
(A.6a)
\[ u_y = \frac{L^2}{2EI} M_x \]  \hspace{1cm} (A.6b)

\[ u_z = 0 \]  \hspace{1cm} (A.6c)

\[ \theta_y = 0 \]  \hspace{1cm} (A.6d)

\[ \theta_z = 0 \]  \hspace{1cm} (A.6e)

\[ \delta_z = \frac{2L}{EI} M_x \]  \hspace{1cm} (A.6f)

Overall displacement at the sheet-end is, therefore, written as

\[ u_x = 4\frac{L^3}{3EI} F_x + \frac{L^3}{3EI} F_y + \frac{3L^2}{2EI} M_x \]  \hspace{1cm} (A.7a)

\[ u_y = \frac{L^3}{2EI} F_x + \frac{L^3}{3EI} F_y + \frac{L^2}{2EI} M_x \]  \hspace{1cm} (A.7b)

\[ u_z = \frac{L^3}{EI} F_x - \frac{L^2}{EI} M_y \]  \hspace{1cm} (A.7c)

\[ \delta_x = \frac{L^2}{GJ} M_y \]  \hspace{1cm} (A.7d)

\[ \delta_y = \frac{L}{GJ} M_y \]  \hspace{1cm} (A.7e)

\[ \delta_z = \frac{3L^2}{GJ} F_x + \frac{L^2}{2EI} F_y + \frac{2L}{EI} M_x \]  \hspace{1cm} (A.7f)

It can be further expressed in matrix form as

\[ U = CF \]  \hspace{1cm} (A.8)

where \( U \) and \( F \) are the displacement and force vectors respectively. \( C \) is the compliance matrix of the folded sheet flexure.

References


