Parametric study of a novel asymmetric micro-gripper mechanism

Qingsong XING * and Youhua GE *

* Yancheng Institute of Technology
9 Hope Avenue, Tinghu Region, Yancheng City, Jiangsu Province, 224051, China
E-mail: ycitxqs@126.com

Received 18 May 2015

Abstract

Aiming at the requirements of micro-assembly for the microtubule (diameter of 0-200μm) components, a new type of asymmetric flexible micro-gripper mechanism based on flexure hinges was designed and studied. The asymmetric micro-gripper mechanism was driven by piezoelectric actuator, whose output displacement was amplified and transmitted by flexure hinges. The displacement amplification ratio of the asymmetric flexible micro-gripper mechanism was deduced theoretically, and the key structure parameters were developed by the FEA (Finite Element Analysis) method. The simulation and experiment were both carried out in order to study the displacement amplification ratio in detail. The experiment results show that the displacement amplification ratio of the asymmetric flexible micro-gripper mechanism is 4.16, compared with the FEA result and the theoretical calculation result, the error between them is 1.89% and 5.67%, respectively. The experiment results also show that the step-wise resolution of the micro-gripper is 7.50μm. The asymmetric flexible micro-gripper mechanism is able to perform the micro-assembly tasks for the microtubule parts, and it is helpful to design this type of micro-gripper mechanism.

Key words: Micro gripper, Asymmetric, Parametric study, Flexure hinge, Parallel-four bar

1. Introduction

As the development of Microelectro-mechanical Systems (MEMS), precision machinery processing, and manufacturing technology, more and more micro-components and parts are produced, and these micro-components and parts could only be assembled in micro-assembly system. In micro-assembly system, micro-gripper is the key component to finish the assembly actions, such as pickup, handling, assembly and release. For the fact that most micro-components and parts are small, light, thin and brittle, (Zhang, et al, 2012), the traditional micro-gripper with of large rigidity and uncontrollable clapping force is unable to apply in micro-assembly system directly. The new type of micro-gripper based on flexure hinges, which is driven by piezoelectric actuator, has been obtained the widespread interest and research in recent years, because of the fact that this type of micro-gripper has the distinct advantages, like no mechanical friction, high precision and fast response. Conversely, the flexure hinge's micro-displacement, which is generally between a few microns to tens of microns, (Li, et al, 2004), is realized by making use of the slight elastic deformation and its self-recovery features of the own structural weakness. To satisfy the requirements of micro-assembly system, it is necessary to use flexible amplification mechanism to amplify and transmit the micro-displacement of flexure hinges.

Presently, the commonly used micro-displacement amplification mechanism includes a multi-stage lever amplification mechanism, (Zhang and Bhagat, 2012,2014), a differential lever amplification mechanism, (Choi, et al, 2007), and a bridge-type amplification mechanism, (Meng, et al, 2014). The principle of the lever amplification mechanism is simple and easy to implement, and in theory, the output is a linear amplifier for input, but the amplification ratio of the lever mechanism is highly limited, while error accumulation and oversize would be caused if the multi-stage lever amplification mechanism was used, (Kim, et al, 2012). The amplification ratio could be enlarged distinctly by the differential lever amplification mechanism, the application scope of which is limited for the
complicated analysis of structure, and it is still unable to achieve the compact structure. The bridge-type amplification mechanism, which is designed by the principle of triangular amplification, has a large amplification ratio and a compact structure, but it is difficult to process, (Do, et al, 2014). On the other hand, many have studied micro-gripper mechanism from different aspects. Han et al. (2009), Li et al. (2014), and Hao et al. (2014) designed the symmetrical micro-gripper with flexure hinges, Chen et al. (2013) and Feng et al. (2012) developed a micro-gripper with two stage amplification that was driven by piezoelectric actuator, Eric et al. (2014) studied a magnetostrictive micro-gripper system, and pointed out the test plan, Hamed et al. (2014) proposed a new type of electrostatic micro-gripper by taking use of capacitive touch sensor for applying the biological cell field, El-Sayed et al. (2013) designed a kind of micro-gripper mechanism with piezoelectric bimorph, and Liu et al. (2010) studied the micro-piezoelectric stepping mechanism based on the inverse piezoelectric effect, and a new type of micro-gripper mechanism that was driven by piezoelectric actuator by using cantilever beam.

Summary the studies above, most micro-gripper mechanism used the symmetric structure, which has some advanced features of double amplification of displacement, and they could meet the requirements of clamping and assembling micro-parts with larger geometry. One of the traditional symmetric type of micro-gripper (Bao, et al, 2014) was shown in the Fig.1 as following.

![Fig.1 Schematic diagram of difference between symmetric and asymmetric type of grippers](image)

Fig.1 Schematic diagram of difference between symmetric and asymmetric type of grippers

Apparently, the disadvantage of micro-gripper mechanism with symmetric structure are also obvious, which is that the movement of both sides of the micro-clamps can not be completely synchronous for the inevitable error that existed in the processing of manufacturing and installation. Therefore, the micro-parts could be destroyed easily by the nonuniform force that caused from the inconsistent output displacement of both sides of micro-clamps. On the contrary, if one side of the two micro-clamps is fixed or unmovable and the other side is movable, there would not be out of synchronized phenomenon of the two micro-clamps, and this is the most important advantage of the asymmetric type of micro-gripper. On the other hand, there is also no nonuniform force in the processing of carrying out the micro-parts. Consequently, the micro-parts would not be destroyed by the unilateral force for that there is only one side of micro-clamps that is movable.

Therefore, in order to satisfy the requirements of micro-assembly for the microtubule components (diameter of 0-200μm), a new type of asymmetric flexible micro-gripper mechanism based on flexure hinges would be proposed and studied, and the key structure parameters of the asymmetric micro-gripper mechanism were discussed by FEA (Finite Element Analysis) and experiment. The asymmetric micro-gripper mechanism is driven by piezoelectric actuator. In the processing of micro-assembly for microtubule components, one side of micro-clamp could clamp, hold and move parallel by taking use of the flexible parallel four bar mechanism, while the other side of micro-clamp is unmovable. The asymmetric micro-gripper mechanism could carry out the micro-assembly for the microtubule components without damaging.

2. Design of Asymmetric Micro-Gripper Mechanism
2.1 Structure of asymmetric type of micro-gripper mechanism

The asymmetric type of micro-gripper mechanism is constituted by a displacement input unit, a displacement amplification unit, a flexible parallel four bar unit and a pair (left and right) of micro-clamps. The structure and geometry diagram of the asymmetric type of the micro-gripper mechanism was shown in the Fig.2 as follows. The coordinate system was shown in the Fig.2(b), and its definition was as following: the X axis was defined as the longitudinal direction of the flexible hinge $H_1$, the Y axis was defined as the direction that passed through the notch of the flexible hinge $H_1$ vertically, and the Z axis was defined as the direction that was perpendicular to the plane, which was determined by the X axis and the Y axis.

![Fig.2 Structure of micro-gripper mechanism](image)

The responsibility of the displacement input unit is to transmit the driven force and the deformation that caused by the piezoelectric ceramic actuator. The displacement amplification unit could be used to amplify the input displacement by taking use of a lever. When the microtubule components are clamped, hold or assembled, the left micro-clamp is fixed and unmovable, while the right side of micro-clamp is movable, and the microtubule components could be clamped, hold and assembled by the movement of the right micro-clamp, which is used to output the amplified displacement. In order to guarantee that the microtubule components could not be destroyed by the nonuniform force of the both sides of micro-clamps, the flexible parallel four bar unit is performed to make the movement of the right side of micro-clamp parallel to the left immovable micro-clamp in the processing of clamping, holding or assembling.

In the premise of meeting the demand of clamping or assembling the microtubule parts, it is necessary to ensure the safety of the micro-gripper mechanism, which is to say, the maximum stress of the thinnest thickness of the flexure hinge should not exceed the yield strength ($\delta_s$) of the material. Considering the strength and the flexibility requirements of the micro-gripper mechanism, the device could be fabricated in the processing of WEDM (Wire cut Electrical Discharge Machining), and the machining current must be small in order to avoid the phenomenon of stress concentration. The material was chosen as the NO. 45 steel, and its main performance parameters is as follows:

- Elastic Modulus, $E=210\text{GPa}$;
- Tensile Strength, $\sigma_b=600\text{MPa}$;
- Yield Strength, $\delta_s=355\text{MPa}$;
- Poisson's Ratio, $\mu=0.27$.

2.2 Operation principle of micro-assembly system based on the micro-gripper mechanism

A complete micro-assembly system based on the micro-gripper mechanism mainly consists of a fixed platform, a piezoelectric ceramic actuator, and a asymmetric type of micro-gripper mechanism. The overall structure of the micro-assembly system is shown in Fig.3.
The fixed platform was used to locate and install all components of the micro-assembly system. All driving force for the micro-gripper mechanism is supplied by the piezoelectric ceramic actuator, which is used to generate deformation under the driving power, and the deformation could be regarded as the input displacement for the whole micro-gripper mechanism. The input displacement is amplified and transmitted by the micro-gripper mechanism based on flexure hinges, and the output displacement is formed by the movement of the micro-clamp, so that the microtubule components or parts could be assembled in this micro-assembly system.

2.3 Discussion on features of holding parallel

It is necessary to discuss whether the proposed asymmetric micro-gripper could overcome these disadvantages of the micro-gripper with symmetric structure. Whether the movement of the right micro-clamp is parallel to the left unmovable micro-clamp or not is the most important factor of ensuring that the microtubule components could not be destroyed easily by the nonuniform force, which is generated from the out of sync of the movement of the two micro-clamps. Actually, the movement of both sides of the micro-clamps cannot be completely synchronous, for that there are the inevitable error that existed in the processing of manufacturing and installation. How to make sure that the right micro-clamp is parallel to the left unmovable micro-clamp when holding or clamping the microtubule components? The principle of solution was shown in the Fig.4 as follows.

![Fig.4 Principle diagram of parallel movement](image-url)
The flexible parallel four bar mechanism was introduced and applied in the asymmetric micro-gripper. The flexible parallel four bar mechanism could make the micro-clamp perform the parallel motion instead of rotary motion, and its guidance accuracy is also very high (Wang, et al, 2010). So, the flexible parallel four bar mechanism is suitable for the asymmetric micro-gripper.

3 Parametric study of the structure by FEA
3.1 Calculation of the displacement amplification ratio

Assuming that the output displacement of the piezoelectric ceramic actuator is marked as $D_{\text{out}}$, then the flexure hinge $H_1$ is compressed at the X axial direction, and the amount of compression could be marked as $\Delta_1$. The actual input displacement is $D_1$. Apparently, there is a relationship as follows:

$$D_1 = D_{\text{in}} - \Delta_1 \quad (1)$$

The displacement amplification unit actually is a lever, and the principle diagram of the lever mechanism was shown in the Fig.5 as following.

\[ 
\begin{align*}
\frac{D_{\text{out}}}{D_1} &= \frac{l_2}{l_1} \quad (2) \\
\frac{F}{F_{\text{in}}} &= \frac{l_1}{l_2} \quad (3) 
\end{align*}
\]

The acting force $F_{\text{in}}$, which is caused by the piezoelectric ceramic actuator’s deformation, could be calculated as the following formula:

$$F_{\text{in}} = \frac{\Delta_1}{C_{\lambda_{x,F_1}}} \quad (4)$$

Where, $C_{\lambda_{x,F_1}}$ is the axial compliance coefficient of the axis $X$ of the $H_1$.

According with the related literature, (Lobontiu, 2014), $C_{\lambda_{x,F_1}}$ could be gotten as follows:

$$C_{\lambda_{x,F_1}} = \frac{h_1}{Ebt} \quad (5)$$

Where, $E$ is the modulus of elasticity;
\[ b \] is the width of the flexure hinge;
\( t \) is the minimum cutting thickness of the flexure hinge.

When the microtubule components are operated by the micro-gripper mechanism, the movement of the right micro-clamp must be parallel to left micro-clamp. The microtubule components could not be destroyed by the nonuniform force that caused by the unparalleled movement of the right micro-clamp. Therefore, the flexible parallel four bar mechanism is used to make sure that the movement of the right micro-clamp should be parallel to left micro-clamp in the processing of assembling. The flexible parallel four bar mechanism has been widely used in the precision instruments for its excellent features of guiding accuracy, (Wang, et al, 2010). The flexible parallel four bar mechanism uses flexure hinges instead of the traditional hinges, and it is more suitable to be applied in the asymmetric flexible micro-gripper mechanism.

According with the theory of elastic cantilever beam and the related literature, (Ye, et al, 2010), the output displacement of the flexible parallel four bar mechanism could be calculated as follows:

\[
D_{out} = \frac{F_1}{6EI}(4h_1^3 + 6h_1^2h_2 + 3h_1h_2^2)
\]  

(6)

Where, \( I \) is the moment of inertia, \( I = bt^3/12 \).

Taking the formulas (1)~(5) into the formula (6), and the displacement amplification ratio could be calculated as the following formula:

\[
k = \frac{D_{out}}{D_{in}} = \frac{2ml_1}{2ml_1^2 + l_2^2}
\]  

(7)

Where, \( m = \frac{4h_1^2 + 6h_1h_2 + 3h_2^2}{t^2} \).

3.2 Parametric design by FEA

According with the formula (7), there are 7 parameters could affect the amplification ratio \( k \), and it is a huge work to calculate the \( k \) based on the parameters one by one. Actually, all parameters could be analyzed parallel by means of the FEA software, e.g. Ansys.

(1) Sensitivity analysis of parameters

First of all, the sensitivity of all 7 parameters should be discussed. The three dimensional model of the asymmetric flexible micro-gripper mechanism was built in the Pro/E, and the 7 parameters should be set as the strong size constraints in the Pro/E. Then the model was processed with static simulation by importing the model into the Ansys14.0. The output displacement was set to be the primary objective function, and the maximum stress was set to be the secondary objective function. Specifically, the object of the secondary objective function is to investigate the maximum stress of the mechanism when the input displacement was involved. The stresses at the corners of mechanism may be very large because of the fact of stress concentration. Therefore, it is necessary to set the secondary objective function and to make sure that the maximum stress could not exceed the Allowable Stress. By using the function of multi-parameters analysis of Ansys 14.0, the sensitivity of all 7 parameters to the primary and the secondary objective function was shown in the Fig.6 as follows.
Actually, the magnitudes of the sensitivities of \( b \) and \( w \) to the primary objective function are very small, which resulted that the parameters of \( b \) and \( w \) are not shown in the Fig.6(a).

Considering the primary and the secondary object functions, the main parameters that affect the output displacement and the maximum stress greatly is \( l_1 \), \( t \) and \( l_2 \). Therefore, the three parameters were the main object of study.

(2) Given the range of values for parameters

According with the sensitivity analysis of all parameters, there are only three design parameters \( (l_1, t, \text{ and } l_2) \) could affect the output displacement and the maximum stress greatly. Consequently, for the three design parameters \( (l_1, t, \text{ and } l_2) \), it is necessary to give the range of values, which could be determined according with the design requirements of structure; while other 4 parameters could be set based on the structure size and the experience. The range of values for the three design parameters \( (l_1, t, \text{ and } l_2) \) were as follows:

\[
l_1 \in [5.0, 8.0]; \\
l_2 \in [20.0, 32.0]; \\
t \in [0.4, 1.0];
\]

(3) The process of parametric design by FEA

Firstly, the \( l_1 \) was variable while the \( t \) and the \( l_2 \) was invariable. The output displacement and the maximum stress were simulated when the \( l_1 \) varied within the given range of value, so that the best \( l_1 \) could be found.

Secondly, the \( t \) was variable while the best \( l_1 \) and the \( l_2 \) was invariable. Repeat the simulation when the \( t \) varied within the given range of value, so that the best \( t \) could be found.

Thirdly, the \( l_2 \) was variable while the best \( l_1 \) and the best \( t \) was invariable. Repeat the simulation when the \( l_2 \) varied within the given range of value, so that the best \( l_2 \) could be found.

So far, the best design parameters \( (l_1, t, \text{ and } l_2) \) was determined after several times of FEA simulation.

Fourthly, other 4 parameters could be set based on the structure size and the experience, and they also should meet the output displacement requirement and the maximum stress requirement by FEA simulation.

Finally, all key parameters of the asymmetric flexible micro-gripper mechanism were revised after several times according with the simulation results based on the formula (7), and then the final dimensions of all 7 structure parameters were shown in the Table 1.

| Table 1 Main structure parameters of micro-gripper mechanism |
|-----------------|----------------|
| Parameter  | Value (mm) |
| \( l_1 \)   | 6.9         |
| \( l_2 \)   | 30.5        |
| \( h_1 \)   | 5           |
| \( h_2 \)   | 12          |
| \( t \)     | 0.5         |
4 Verification

4.1 Simulation by FEA

According with the formula (7) and the parameters in the Table 1, the displacement amplification ratio of the asymmetric flexible micro-gripper mechanism could be calculated theoretically, and the theoretical calculation result is that \( k = 4.41 \).

The corresponding model that used the same parameters in the Table 1 was processed by the the Ansys14.0. Assuming that the initial input displacement was 0.01mm, which was acted on the axial direction of the axis \( X \) of the displacement input unit, and the simulation result shows that the final output displacement of the right micro-clamp is 0.042374mm. The FEA simulation result is shown in the Fig.7 as follows.

![Simulation of the micro-gripper mechanism by FEA](image)

The displacement amplification ratio of the FEA simulation result is that \( k = 4.24 \), and the error between the theoretical calculation result and the FEA simulation result is 3.85%. The reasons of the error between the theoretical calculation result and the FEA simulation result mainly include as follows: the theoretical calculation only considered the deformation that occurs in the notch of flexure hinge, while the deformation of other parts was all ignored, and at the same time, the internal stress was also ignored.

The maxim stress of the micro-gripper mechanism is 260MPa, which is less than the Yield Strength \( \delta_s \) (355MPa). Therefore, the micro-gripper mechanism could work safely.

There is another result, which is that the movement of the right micro-clamp is indeed parallel to the left immovable micro-clamp, could also be found easily in the Fig.7.

According with the FEA simulation result \( k = 4.24 \), if the piezoelectric ceramic actuator is suitable, and the output displacement \( D_m \) is in the range of 0-50\( \mu \)m, then the micro-gripper mechanism could carry out the microtubule components that the diameter is in the range of 0-200\( \mu \)m.

4.2 Experiment

(1) Experiment system

In order to verify the performance of the asymmetric flexible micro-gripper mechanism, it is necessary to carry out the experiment for the micro-gripper mechanism. The experiment test system mainly consisted of a driven power, a piezoelectric ceramic actuator, a laser measurement instrument and the asymmetric flexible micro-gripper mechanism.

All details of equipment that in the experiment are as follows:
- HPV-3C of Boshi, Driven power (Model Number HPV-3C, Boshi, China);
- VS12/60 of Boshi, Piezoelectric ceramic actuator (Model Number VS12/60, Boshi, China);
- LK-H020 of KEYENCE, Laser displacement sensor (Model Number LK-H020, KEYENCE, Japan).
The driven power was selected the HPV series, which is suitable for the piezoelectric ceramic actuator. The piezoelectric ceramic actuator was selected the VS12 series, whose specifications is φ12mm×60mm, and its nominal displacement is 60μm when the piezoelectric ceramic actuator is driven by the maxim voltage of 150V. The laser measurement instrument was selected the LK-H020 of KEYENCE, and its precision is 0.02μm. The specimen of the asymmetric type of flexible micro-gripper mechanism was shown in the Fig.8 as follows, and the experiment system of the asymmetric type of micro-gripper mechanism was shown in the Fig.9 as follows.

![Physical diagram of the asymmetric micro-gripper](image1)

**Fig.8 Physical diagram of the asymmetric micro-gripper**

![Experiment system of the asymmetric micro-gripper mechanism](image2)

**Fig.9 Experiment system of the asymmetric micro-gripper mechanism**

1 Signal generator 2 Power amplifier 3 Fixed platform 4 Piezoelectric ceramic stack 5 Specimen 6 Laser displacement sensor 7 Laser displacement monitor

(2) Experiment method

In the processing of the experiment, the driven power was adjusted to output different voltage firstly, then different displacement $D_{in}$ was generated by the piezoelectric ceramic actuator when it was driven by the different voltage, and the movement of the right micro-clamp was formed the output displacement $D_{out}$ after amplifying and transmitting by the asymmetric micro-gripper mechanism. The laser measurement instrument was used to measure the $D_{in}$ and the $D_{out}$.

(3) Experiment results

The laser measurement instrument was used to measure the $D_{in}$ and the $D_{out}$. The experiment made a total of 5 sets of data, and all experiment results are shown in the Table 2 as follows.

<table>
<thead>
<tr>
<th>NO.</th>
<th>Driven Power (V)</th>
<th>$D_{in}$ (μm)</th>
<th>$D_{out}$ (μm)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
From the experiment results shown in the Table 2, the displacement amplification ratio could be calculated by the following formula: $k = \frac{D_{\text{out}}}{D_{\text{in}}}$. The average of the five displacement amplification ratios is that $k = 4.16$. When the piezoelectric ceramic actuator is driven by the maxim power 150V, the output displacement of the asymmetric micro-gripper mechanism is 249.39 μm, which is large enough to perform the micro-assembly task of clamping the microtubule components that the diameter is in the range of 0-200 μm.

In order to investigate the resolution of the micro-gripper, the experiment of the step-wise resolution was necessary to carry out. The experiment instruments were the same as above, and when the piezoelectric ceramic actuator was driven by the voltage of 4.7V, the $D_{\text{in}}$ and the $D_{\text{out}}$ was 1.80 μm and 7.50 μm, respectively. The results show that the step-wise resolution of the micro-gripper is 7.50 μm, and the micro-gripper would not be responded if the driven power is less than 4.7V.

### 4.3 Discussion

 Apparently, the experiment is repeatable. In order to analyze the errors quantitatively, the experiment was repeated three times with the same experiment condition, and the error bars to data series was shown in the Fig.10.

![](Fig.10 Error bars to data series of experiment)

There are some reasons that cause the error as follows:

1. There is a certain degree of deviation between the actual geometry and the design geometry because of the machining error, which results the error between the experiment value, FEA simulation value and the theoretical calculation value, especially that the compliance of the whole micro-gripper mechanism is affect obviously by the minimum cutting thickness $t$ and the notch length $h_1$.

2. The theoretical calculation only considerers the deformation that occurs in the notch of flexure hinge, and regards other part of flexure hinge as a rigid body. Consequently, the deformation of other parts was all ignored, and the internal stress was also ignored at the same time. Actually, there is indeed deformation in other parts of flexure hinge, while the FEA simulation and the experiment include the ignored deformation, that’s why the theoretical calculation value is larger than the FEA simulation value and the experiment value.

3. There is an unavoidable phenomenon of work-harden when the asymmetric micro-gripper mechanism was in the processing of WEDM, and the stiffness of the mechanism increased, which resulted the deformation decreased, that’s why the experiment value is smaller than the FEA simulation value.

### 5 Conclusions

1. Aiming at the requirements of micro-assembly for microtubule (diameter of 0-200 μm), a new type of the
asymmetric micro-gripper mechanism, which was driven by piezoelectric actuator, was proposed, and its structure was studied in detail. The output displacement of the right micro-clamp was amplified and transmitted based on flexure hinges, and the flexible parallel four bar mechanism was used to ensure that the movement of the moveable micro-clamp is parallel to the immovable micro-clamp, so that the microtubule would not be destroyed by the nonuniform force that caused from the inconsistent output displacement of both sides of micro-clamps.

(2) The displacement amplification ratio was discussed theoretically based on the lever principle and the output features of parallel four bar mechanism. The key structure parameters of geometry were pointed out by taking use of the FEA method. The result of FEA simulation shows that the displacement amplification ratio is 4.24, and the error between the theoretical calculation result and the FEA simulation result is 3.85%. Therefore, the asymmetric micro-gripper mechanism could perform the micro-assembly task for the microtubule components that the diameter is in the range of 0-200μm only if the piezoelectric ceramic actuator is suitable.

(3) The actual asymmetric micro-gripper mechanism was processed by line cutting of electric spark, and the measurement experiment of the displacement amplification ratio was carried out. The experiment result shows that the displacement amplification ratio is 4.16. The error between the experiment and the FEA simulation is 1.89%, while the error between the experiment and the theoretical calculation is 5.67%. The three displacement amplification ratios by different methods are very close, which has proved the correctness of the theoretical calculation formula (7). The reasons that may cause the error between different methods were also discussed in detail. On the other hand, the step-wise resolution of the micro-gripper is 7.50μm, and the micro-gripper would not be responded if the driven power is less than 4.7V. The asymmetric flexible micro-gripper mechanism is able to perform the micro-assemble tasks for the microtubule parts, and it is helpful to design this type of micro-gripper mechanism.

References


