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***Abstract*— As no reliable methods is available to manipulate component whose typical size is up to $100\,\mu m$, current industrial assembled products contained only components down to this physical limit. In that scale, micro-assembly requires specific handling strategies to overcome adhesion and high precision robots. This paper deals with an original robotic system able to perform reliable micro-assembly of silicon micro-objects whose sizes are tens of micrometers. Original hybrid handling strategies between gripping and adhesion handling are proposed. An experimental robotic structure composed of micropositionning stages, videomicroscopes, piezogripper, and silicon end-effectors is presented. A modular control architecture is proposed to easily design and modify the robotic structure. Some experimental teleoperated micromanipulations and micro-assemblies have validated the proposed methods and the reliability of the principles. Future works will be focused on micro-assembly automation.**

I. Introduction

Current microfabrication constraints highly reduce the diversity, the functionalities and the shape of Micro Electromechanical Systems (MEMS). In fact, its design are restricted to planar monolithic structures. Innovative ways are required to build new generation of out of plane and/or hybrid microsystems [1], [2].
In the macroworld, building complex and hybrid systems requires assembly to simplify fabrication processes of each product's components. As robotic capabilities were not able to perform reliable assembly of micro-parts, this production means was not consider for MEMS in the first place. The micro-assembly has required study of micromanipulation strategies and robotic design adapted to the microworld and especially to the surface and adhesion forces [3], [4]. In these last five years, micro-assembly's performances has grown and this approach is now consider as a future means of MEMS fabrication.

Serial micro-assembly is thus an innovative way to perform out-of-plane and/or hybrid microsystems and requires a lot of innovative breakthrough. Three major domains are studied to improve micro-assembly: the study of new handling strategies adapted to the specificities of the micro-objects [5], [6]; the study of sensors able to measure position of the micro-object (eg. microvision) [7], and handling microforces [8]; the study of high precision robots able to position micro-objects with sufficient accuracy [9].

This article focuses on two challenges : microhandling and robotic structure. The following section presents the microhandling strategies used to perform reliable microhandling and microassembly tasks. The modular robotic structure will be presented in the section III and the modular control software in section IV. The last section deals with experimental micromanipulations and microassemblies.

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II. Handling Strategies

One of the major stakes in robotic assembly is the ability to grasp, position and release a micro-object (usually defined as 'micromanipulation'). Non contact methods can be considered (laser trapping, DEP, etc.), they are able to position objects without adhesion perturbations [10], [11]. However, they cannot induce large blocking forces and thus cannot be considered in a lot of assembly process (insertion, lock, etc.). In other hand, the contact microhandling can be divided into two groups: (i) the passive grippers and the active grippers. In passive gripping, objects must have a specific imprint to be grasped by the passive gripper, release is obtained by using a specific imprint on the substrate (clip, lock, etc.) [1], [2]. Both substrate and objects must have specific imprints dedicated to grasping and release. The active grippers have one or two fingers, the grasp is thus obtained respectively by adhesion or by clamping. The release is performed using specific repulsive forces (inertial release, DEP release, etc.) [6], [12]. As the trajectory of the object after release cannot be controlled, these strategies are able to grasp a micro-object but cannot position it with a sufficient precision. Moreover, current efficiency of these release strategies stays low. Consequently, the only way able to position micro-objects with a sufficient precision and a large blocking force is currently the passive grippers. However, these methods are not able to manipulate a large type of objects because the design of the object are highly constrained by the imprint required for grasping and release.

We are proposing new reliable methods to manipulate and assemble micro-objects without specific imprint. To guarantee a large blocking force which is required in a lot assembly process, we chose to use a two fingers gripper. Contrary to current works, our proposed release strategies are able to position the micro-object with a good repeatability and reliability. We propose to assemble micro-parts in two steps. The first one consists in positioning the first object and blocking it during assembly. The objective of the second step is to grasp the second object and perform assembly. Both steps require robotic capabilities (Degree of Freedom, repeatability...) presented in the section III and specific strategies adapted to the microworld presented in the following.

A. Micropositioning principle: adapting adhesive effects

To guarantee a reliable release, two ways have been chosen: increase adhesion forces between the substrate and the object and decrease adhesion force between the object and the gripper [13].

We chose to use as substrate a transparent gel film well-known in microelectronics: Gel-Pak. This material is in fact transparent and softly adhesive, it consequently allows accurate pick and place tasks. Moreover, the low mechanical stiffness of this polymer induces natural compliance of the substrate required for micro-assembly. In a second time, efforts have been made on end-effectors shaping. First, surface in contact with the micro-object has been reduced by using end-effectors with a small thickness. In second time, the fabrication process called DRIE have been used to give the gripping surface a specific texture. Etching anisotropy of this process is made by a short succession of isotropic etching/protection cycles. These cycles create a phenomenon called *scalloping* illustrated in figure 1. In this way, contact shape between object and end-effectors is a succession of microscopic contact points. As proved by [14], the roughness induced by DRIE is able to highly reduce pull-off force. Force measurements will be performed in a near future to validate the surface force reduction, and the adhesion of the Gel-Pak.

B. Micro-assembly of Both Objects

The release of the second object requires a specific strategy. Two cases can be considered:

- Both objects have to be locked during assembly. In this case, both objects can be considered as the same object, and the adhesion between the first object and the substrate is sufficiently higher than the adhesion between the second object and the gripper to guarantee the reliable release.
- Both objects do not have to be locked during assembly. It could be the case, in the construction of a larger product, where for example a third object is used to lock the whole assembly. In this case, the previous strategy cannot be used. We are proposing to work on the gripper trajectory to be able to release the second object without adhesion perturbation. An example of trajectory is proposed in figure 2(b).

The experimentation of these strategies are presented in the section V.

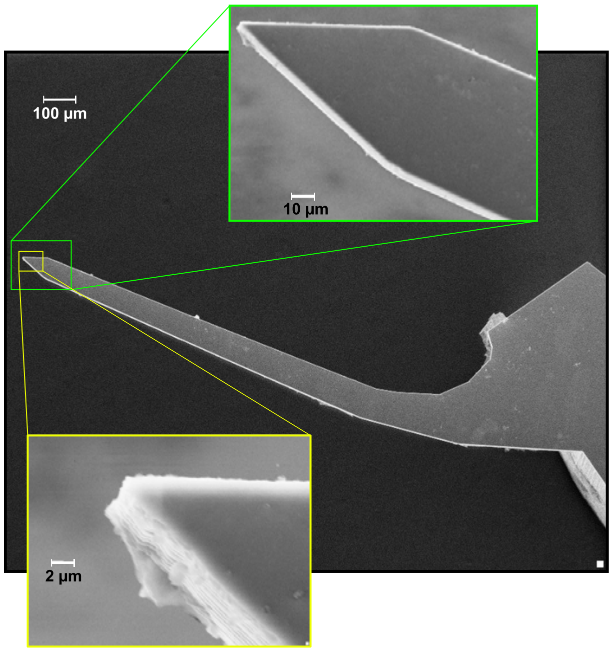
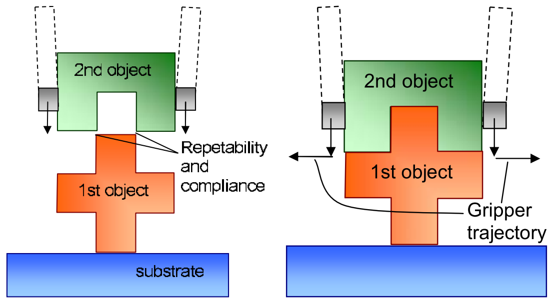


Fig. 1. End-effectors' shape in SEM view. Scalloping is visible in lower picture.



(a) Positioning of the second object before assembly

(b) Release of the second object

Fig. 2. Principle of the Positioning, Assembly and Release of the Second Object

III. Modular Robotic Micro-assembly Device

The assembly of two micro-objects with a gripper needs an adequate robotic device. Three precise cartesian degrees of freedom (DOF) are required to achieve pick and place tasks. Micro-assembly may also require more DOF with micrometric accuracy. We made the choice of a serial robotic structure which is easier to create and use than parallel device. Therefore control system remains complex and a modular concept could improve many parameters like programming time, device customizing and pieces replacement of the robotic structure. Hardware used in our device is presented below.

A. Piezoelectric Microgripper

The MMOC piezomicrogripper[15] used in this robotic structure was developed in our laboratory. It has 2 independent degrees-of-freedom for each fingers, which can perform open-close motion of 320 μm and up-down motion of 200 μm. The resolution of the actuator is close to 1,6 μm/V then submicrometric accurate motions are controllable. Several kind of finger tips can be glued on this piezoelectric actuator. Up-down motion of gripper's actuator is in fact uses to align them before manipulation. The finger tips[16] used for micro-assembly have been designed to handle microscopic objects. They are build in single crystal silicon SOI wafer by a well-known microfabrication process: DRIE. These end-effectors have a long and thin beam (12 μm) designed to handle objects from 5 μm to few hundred micrometers.

B. Robotic structure

Our current robotic micro-assembly device (see in figure 3) is able to realize micro-assembled parts whose size is from 100 μm to few micrometers. Tridimensional micro-assembly are currently done in teleoperation[13] and some automatic pick-and-place operations which use only translation stages are currently available.

Actuation is divided into two groups which has 3 degrees of freedom (DOF). The first one allows displacement of the substrate, where microparts are placed. Two linear and one rotation DOFs are available in the horizontal plane. The second group is the a 'robotic arm', composed of one linear DOF along the vertical axis and two rotation DOFs to ensure pitch and roll rotations of the microgripper. The geometrical modeling of the device is presented in [17].

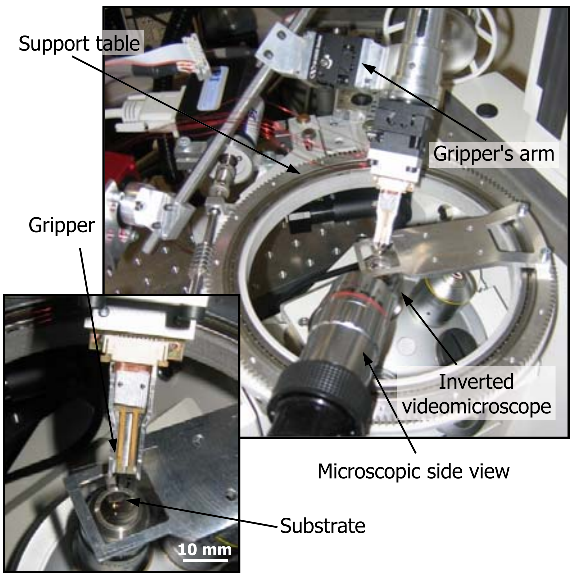


Fig. 3. Microassembly robotic device

In each group (Gripper, table and robotic arm), actuators are constituing modules. These actuating modules have their own control system. Linear stages are actuated by DC motors, including hardware closed loop control with encoders sensor. Positionning defaults due to backlash and non linearity could be partially corrected by a correction in open-loop control [17]. Moreover, robotic substructure resulting of modules' assembly has some defaults. Mechanical assembly causes geometrical error on coplanarity and perpendicularity of DOF. So robotic motion have to be improved with the implementation of a geometrical model in the control.

C. Optical Sensors

Performing serial micro-assembly tasks requires adapted robotic structures, able to position micro-objects with sufficient accuracy and repeatability, typically up to 1 μm for microparts whose typical size is about $10\,\mu m$. These performances are mainly reachable by closed-loop robotic microstages. Nevertheless, in case of complex robotic structure with a gripping device, robotic joint sensors are not sufficient to determine micro-object positioning. Then, using a videomicroscope with a dedicated vision computer is an important way to perform closed-loop control on the entire robotic structure, including the microgripper. Moreover, it allows teleoperated control of the robot by a human operator.

Microscopical vision is provided by two videomicroscopes. As the volume above the micromanipulation plane is dedicated to microgripper movement, an inverted microscope LEICA DM-IRBE is used. It also allows micro-assembly in liquid medium, whose interest is synthesize in [3]. A second view for teleoperated operations is given by a side videomicroscope.

IV. MODULAR CONTROL SYSTEM

As robotic structure is the assembly of actuation and sensor modules, the control system is an assembly of programmed control modules too. All the hardware is connected to regular personal computers. First computer is used for videomicrocope acquisition and computer vision algorithms. The second is used for actuation control and human machine interface (HMI). This section presents modular control architecture, and the quick way to configure and reconfigure it for automated and teleoperated tasks.

A. Programmed Modular Architecture

Robotic micro-assembly could be achieved by many ways. Each way needs a specific control system, including microworld physic properties of grippers (mechanical grip, capillarity, electrostatic, vacuum, etc.). Control system programming and configuration could take time and reconfiguration could be extremely complex. In our case, gripper and vision algorithms could be easily modified when robotic structure remains unchanged. Then, constitution of standard, interchangeable modules improve control system efficiency.

The modular achitecture chosen for our application includes three principles:

- Module frontier is built on hardware limits and also on software control limits (eg. limit between control law and actuator

- Module could have direct communications with a corresponding hardware.
- Modules must exchange information by standard software interface.

A micropositionning linear stage is composed of a DC motor actuation, a mechanical guiding structure and an encoder sensor. This device is controlled by an electronic computer card (PCI bus) which can control four linear stages. The connection between software and the hardware is done via a software module adapted to the control card. In our example, the module can control four linear axis. This module receives and sends information by a standard software interface linked with other modules like HMI control. This standard software interface is called *virtual axis* (figure 4). When the virtual axis received new target position or speed requirement from other modules (automated or HMI control), it sends the command directly to the module in contact with the hardware.

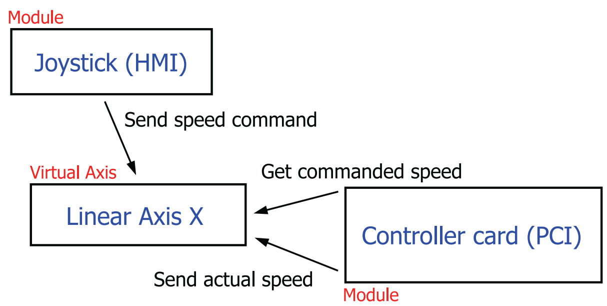


Fig. 4. Communication between two software modules

A virtual axis can receive or send information on robotic axis command (actual position, speed, target position for example). More than one command module can be connected to a virtual axis. In the case of two commands are colliding, the virtual axis chooses which command will be get by the hardware module. Control software users can define links priorities. The virtual axis can be considered as a software model of the real robotic axis.

B. Modular assembly for reconfigurable complex control

Module encapsulation was realized in object programming language C++. Many classes are defined to easily create modules able to communicate in the modular architecture. Moreover, each classe has a graphic interface in a windows environment. Then software users are able to load easily modules and build a control architecture. By using the architecture classes toolbox, it is easy for a programmer to create new modules for specific hardware or specific software control.

As an example, the piezoelectric gripper MMOC is commonly used for teleoperated micromanipulation tasks. Then these tasks only need a HMI module for teleoperation peripheral (eg. joystick) and a hardware module for piezoelectric voltage control. The user of the robotic station can easily

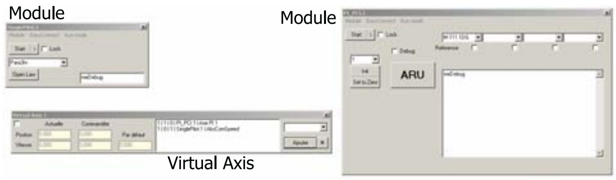


Fig. 5. Graphic interface for two module communication

build a control architecture based on modules to be able to perform teleoperation tasks.

Some more complex tasks (eg. automatic cycle) need a better behaviour of the microgripper. A specific control module is required to drive the piezoelectric actuator with a compensation of the hysteresis. Then a programmer has created a new module to compensate piezoelectric hysteresis. This compensation module can be added easily by the user of the robotic station without specific knowledge. Moreover an other interest of the modular architecture is that module could be used not only for our gripper, but for all piezoelectric actuation with a similar behaviour. Standard classes for modules and virtual axis interfaces allow to easily reuse a module in an other robotic station.

C. Teleoperated Micro-assembly

In section III, the modular robotic device was presented. This device needs commands given by an human operator to perform a micro-assembly. Presented software modular architecture was used for this purpose. Few tenth of software modules was programmed, assembled and configurated to perform this micro-manipulation and micro-assembly tasks presented in next section. Modular architecture massively decrease programming and interfacing time of the control software. Moreover, it allows fast reconfigutration when another hardware device or software control was used to another micro-assembly strategy. Finally, this modular architecture is still used for teleoperated and automated microworld operation and for another experimental devices.

V. Experimental Micro-assembly

Robotic agility of the presented micro-assembly station has been tested to assemble benchmark micro-objects in teleoperation without force feedback.

A. Pick and place

A micro-object is placed on the substrate. First, gripper is moved above and fingers are opened enough to grip the object. Then the object is hold by the end-effectors and gripper is use to separate the object from the substrate. Currently, our gripper has no force sensors and the gripping force is so not controlled yet. The substrate is moved to a new position (target position). Finally, release is performed by moving down the gripper to create a contact between object and adhesive substrate then opening gripper induces the release of the object. All the micromanipulation sequence is shown in figure 6.

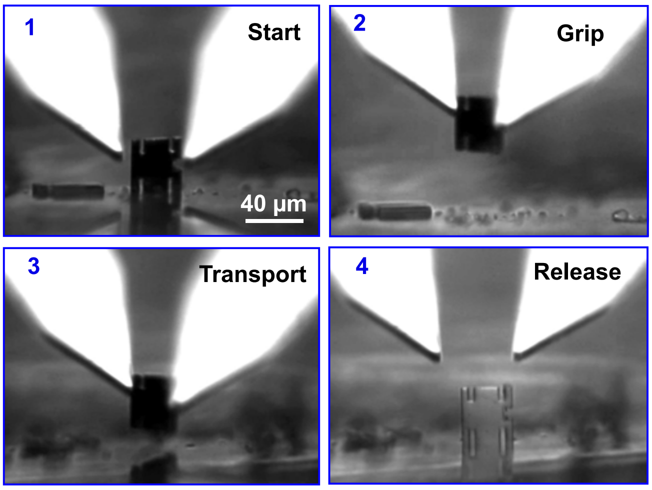


Fig. 6. Pick and place of 40 μm micro-objects.

Without adhesive substrate (eg. on silicon or glass), it is very difficult to release object because during the gripper opening, the micro-object still stick on one of both end-effectors.

B. Insertion

Each puzzle piece has four notches, close to 5 μm width and 10 μm long. As part's thickness is 5 μm, assembly of two pieces requires to insert perpendicularly (figure 7).

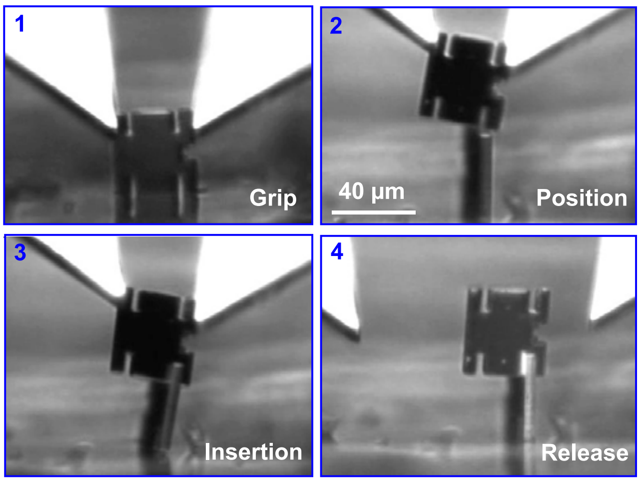


Fig. 7. Insertion assembly.

The first part is gripped and place vertically on the substrate. The second part is taken vertically too perpendiculary to the first one (step 1). Then two puzzle pieces are ready to be assembled. Then the second part is gripped, and is accurately positioned above the first part (step 2). Assembly clearance is very small and evaluated to 200 nm by SEM measurement and accuracy can be made up by substrate compliance. Indeed, compliance of adhesive substrate allows small rotative motion of the first part thus insertion is easily performed without any fine orientation of the gripper (step 3). When insertion is complete, microgripper is opened to release assembled part (step 4). This last operation can failed when adhesive effects between gripper and puzzle piece are stronger than between both puzzle pieces. In fact, the part stay sticked on the end-effector and opening the gripper disassemble the micro-product. Consequently, the trajectory proposed on section II is used to induce a reliable release.

C. Reversible Assembly

The second assembly benchmark requires more steps and more accuracy. Both mechanical parts are different but have the same square shape of 40 μm side. The first part have a small key joint with a T shape on one side. The second part have a T shaped imprint in center of the square (figure 8). To perform assembly, the key must be inserted in the imprint and then a lateral motion of the second part locks the assembly. This benchmark is inspired from Dechev et al [18].

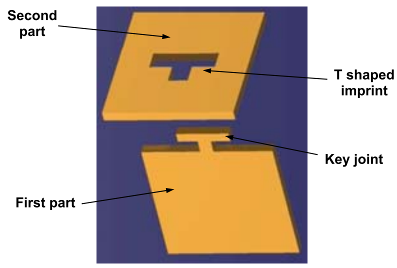


Fig. 8. Lock joint design.

This benchmark has been tested with our robotic structure (figure 9). Parts' orientation is very important, especially for the relative orientation between both micro-objects. The first part is set vertically on the substrate. The gripper is used to grip and align the second part above the key (step 1). When the key is in the imprint (visible on the vertical view), a vertical motion puts the key in the hole (step 2). Finally a lateral motion locks the key and the assembly is performed (step 3).

After locking motion, the 3D microproduct realized can be extracted from the substrate and moved to another place (step 4). Moreover the major interest of this kind of assembly is the possibility to disassemble it. To perform it, motions are repeated on opposite way: a lateral motion to unlock the key (step 5) and a vertical motion to disengage the key from the imprint (step 6). Several cycles of assembly-disassembly have been tested.

D. Analysis of the reliability

In order to show the reliability of our method, numerous pick and place operations have been performed in teleoperation and in an automatic cycle. The tests have been done on a silicon micro-objects whose dimensions are $5 \times 10 \times 20\ \mu m^3$. The objective of the pick and place operation is to grasp the object placed on the substrate, to move it along 100 μm and

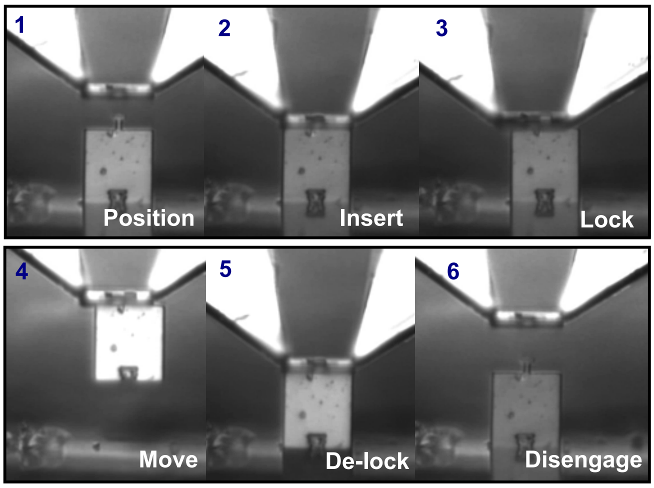


Fig. 9. Reversible assembly.

to release it on the substrate. To evaluate the reliability, the success rate of the pick and place operations and the time cycle have been measured.

First, tests have been done in teleoperation. The operator see the lateral view and the vertical view on two screens. He controls the trajectories and the gripper movements with a joystick without force feedback. 60 operations have been done. The time cycle stays always between 3 and 4 seconds. Secondly, tests have been done in an automatic cycle without force and position feedback. The pick and place trajectory was repeated 60 times and the time cycle was 1.8 seconds.

In both tests, the reliability reaches 100%. As only some articles in the litterature quote the reliability of micromanipulation methods, it is quite difficult to compare this value with other works. However, tests of the reliabilty of microhandling strategies have been presented in [19], [20]. Both tests have been done on polystyrene spheres whose diameter is $50\,\mu m$. The success rate was between 51% and 67% on around 100 tests in [19] and was between 74% and 95% on 60 tests in [20]. Consequently, our method allows a higher reliability on smaller objects which represents a significant contribution.

VI. Conclusion

The robotic assembly is one way to produce new microsystems with improved functionalities. An original hybrid method between adhesion manipulation and standard gripping has been proposed. A complete teleoperated robotic structure included micropositioning stages, vision capabilities, piezogripper with silicon end-effectors, has been presented. The control architecture is based on a modular software which is able to easily add or release technological components on the robot. Some benchmarks of microparts' manipulation and assembly have been tested: pick-and-place operation, insertion of object, and locking of object. These experiments have validated our proposed methods and prove the high reliability of the assembly methods peformed with our device. Future works will focused on the automation of the assembly.

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