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GUIDE

Team O2AS' Approach for the Task-board Task of the World Robot Challenge 2018

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In this paper, we describe the approach of Team O2AS to complete the task-board task of the World Robot Challenge 2018, held in Tokyo. We use a custom gripper and graspable tools with inbuilt compliance to work with various kinds of parts, increase robustness against uncertainties, and to avoid complicated control strategies. The robots are able to finish all the sub-tasks without the need to exchange grippers. The main idea is to use mechanical compliance and self-centering mechanisms to deal with uncertainty. This is achieved by aligning the objects using either the gripper and tools, or by the design of the robot motions.

Keywords: gripper design; tool design; robotic assembly; task-board; alignment; screw arrangement; picking

1. Introduction

In the near future, especially developed countries like Japan are expected to face increasing labor shortage and labor cost. While automated machine assembly is expected to alleviate this problem, it stills requires very high setup costs, due to the use of specialized jigs and grippers, expensive sensors and complicated control strategies.

This leads to a lack of flexibility of the robot system, and large difficulties when trying to adapt to high-mix low-volume series which is the current manufacturing trend.

The World Robot Challenge (WRC) 2018 aims to realize the future of industrial robotics by building agile and lean production systems that can respond to changing manufacturing requirements with minimal down-time.

This paper focuses on the approach Team O2AS used for the task-board task of the WRC 2018. In the task-board task, the parts laid out on the placement mat are to be assembled onto the desired locations of the task-board.

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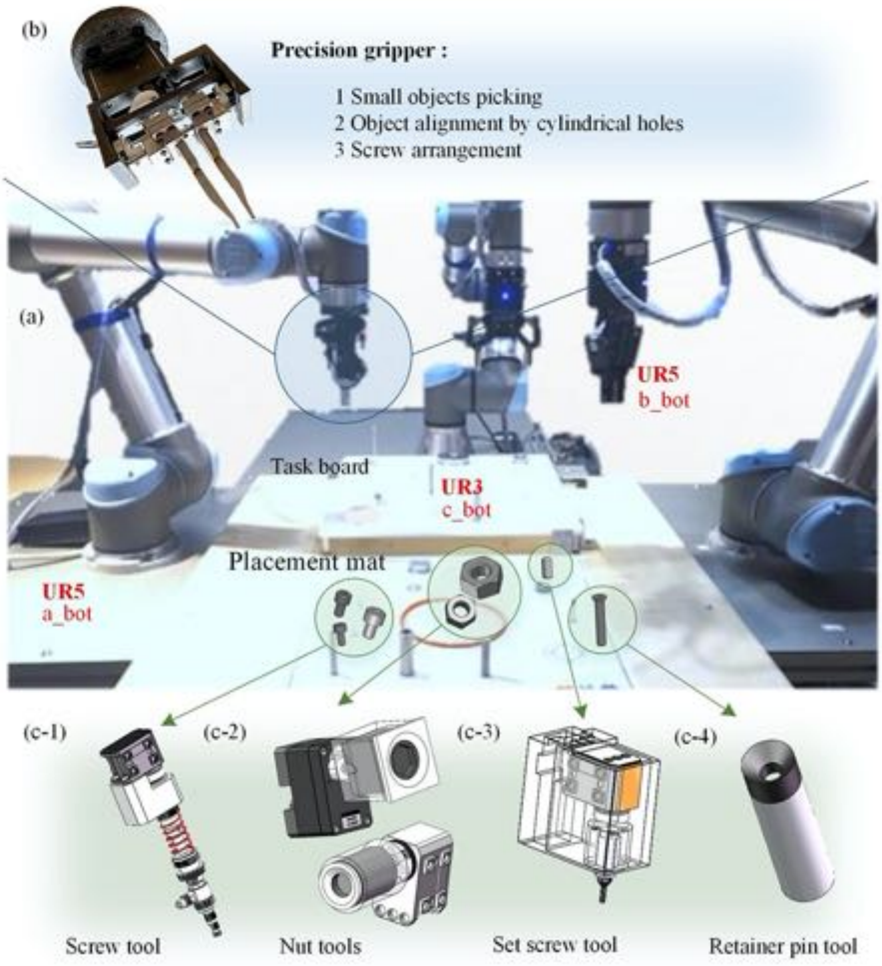


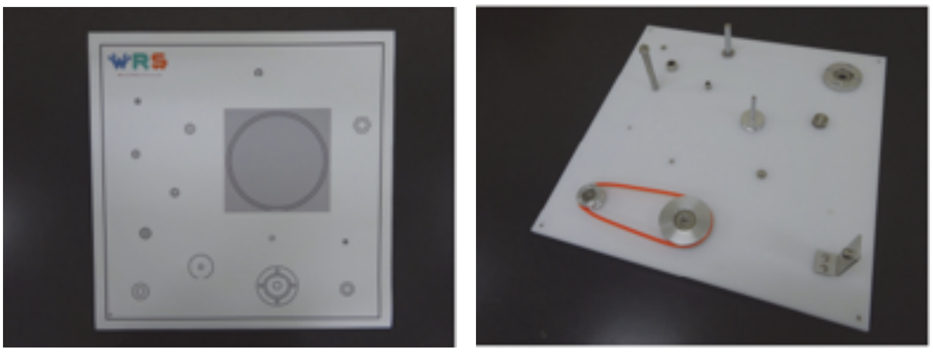
Figure 1. (a)A Schematic of the task-board task setting. (b)The design and features of the precision gripper. (c)Designed tools.

The schematic view of the robot system setting is shown in Fig.1(a). Three UR robot arms(Fig.1(b)) including two UR5 robot arms and one UR3 robot arm are used. A customized gripper is installed on one of the UR5 robot arms(a_bot). The Robotiq 2-Finger 85 grippers, ("Robotiq gripper") are installed on b_bot and c_bot. Several tools presented in Fig.1(c) are also used in the task. Instead of changing grippers, the designed tools are used by the robots during the task and the noises in pose are eliminated with the help of the gripper, the tools as well as the robot motions. As a result, the system is robust and versatile, aiming to replicate the conditions of an industrial scene.

The organization of the paper is as follows. Rule specification is introduced in Section 2. Section 3 and 4 presents the designs of the gripper and tools used in the task-board task. The system setting is shown in Section 5. The strategies are explained in Section 6. Finally, discussions and conclusions are given in Section 7.

2. Rule Specification and Strategies

Parts are initially laid out on a placement mat in an orientation defined in the rule book. The position of each part on the placement mat differed between trials, and was unknown until the start of the Preparation Phase. Each team was required to assemble the parts to designated locations on the task-board. The task-board and a placement mat used in the competition are



(a) Placement mat(Mat size: 400mm x 400mm) (b) task-board when assembly was completed

Figure 2. An example of the task-board and placement mat used in the competition.

shown in Fig.5(a)(b).

The specification of the tasks and parts is explained in the Fig.3(a)(b). In order to deal with different parts including picking, alignments of the objects and the requirements of the tasks , the precision gripper and special tools are designed to meet various needs. By analyzing and classifying the requirements of each of the task, the tasks can be divided into 3 categories:

- `Need for special tools` – The tasks include screwing and aligning objects without a hole.
- `Need for precision gripper` – These include tasks involving parts which require the precision gripper for picking, alignment or arrangement.
- `Need for handovers` – These include tasks involving parts which need to be turned over, for which we use a handover between the robots.

The sequence of the tasks is shown in Fig.3(c). It is mainly decided based on how stable the objects on the placement mat are and the difficulties involved in the assembly process. The two general difficulties of the task-board tasks are the unknown initial layouts of the placement mat, the large variety of the parts involved and the types of assembly.

In order to overcome these difficulties, the precision gripper and special tools are designed for the purposes of picking and aligning different objects. Fig.3(c) shows which parts are grasped by the precision gripper, and which are handled with special tools. Further details are given in section 5.

3. End Effector Design

This section elaborates the design of the precision gripper and other specially designed tools, and how they meet the needs of different parts in various tasks. The sub-tasks of the task-board task can be mainly divided into three categories, which are (1)Picking up small objects; (2)Screwing; (3)Insertion. The proposed gripper and special tools are used to deal with these tasks. The details are mentioned below.

3.1 *Gripper design*

The overview of the proposed gripper (called precision gripper) is shown in Fig.1(b). The gripper is supposed to have the functions of aligning objects and be able to pick up small objects like washers and screws.

For the work with similar goals, Chen et al. [6] designed a gripper using the combination of linear motors and rotational motors to twist and re-positioning objects. Nishimura et al. [7]designed a gripper which is able to position objects using a chuck clamping mechanism with

(a)

No.	Part name	Task	Require
1	Bearings with Hosting	Insertion into a hole	Precision gripper
2	6mm Bearing retainer pin	Insertion into a hole	Retainer pin tool
3	17mm Spacer for bearings	Insertion into a hole	Precision gripper
4	9mm Spacer for bearings	Insertion into a hole	Precision gripper
6	4mm Round belt	Looping over pullies	Precision gripper
7	M6 Nut & Bolt	Fasten a nut and bolt	Precision gripper & Nut tool
8	M12 Nut	Conjunction with a bolt	Nut tool
9	6mm Washer	Placing onto a shaft	Precision gripper
10	10mm Washer	Placing onto a shaft	Precision gripper
11	M3 Setscrew	Screwing into a tapped hole	Set screw tool
12	M3 Bolt	Screwing into a tapped hole	Precision gripper & Screw tool
13	M4 Bolt	Screwing into a tapped hole	Precision gripper & Screw tool
14	Pulley	Placing onto a shaft	Precision gripper
15	10mm End cap	Placing onto a shaft	Precision gripper & Hand over

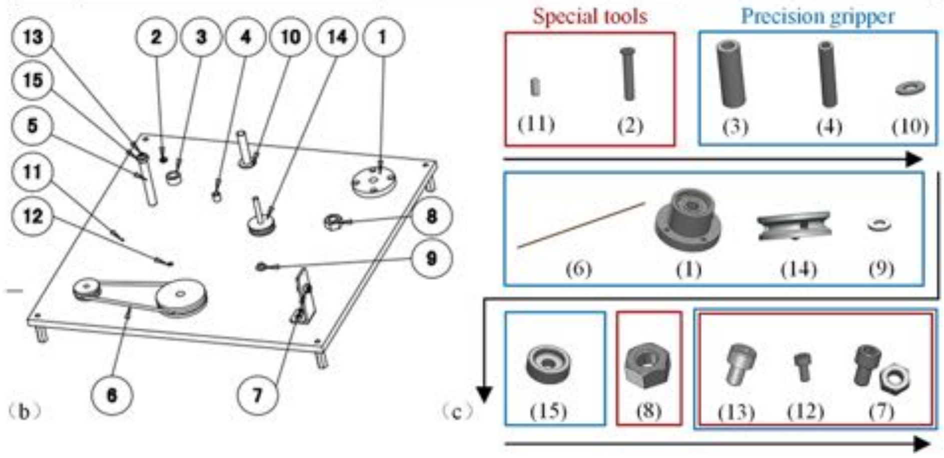


Figure 3. (a)The specification of the parts and tasks (b)The layout of the task-board. (c)The black arrow indicates the proposed task sequence. (Blue: tasks that need special tools, Red: tasks that need the precision gripper.)

special design surfaces of the finger tips. Hirata et al. [8] presented a design of fingertips that could cage, align, and firmly pick up small circular parts like bearings, washers, and gears. A parallel mounted self-locking underactuated mechanism designed by Hsu et al.[9] could self-lock automatically when the desired grasp is achieved in order to realize the goal of firm grasping. Harada et al.[10] proposed a gripper design that uses multiple fingers to align and adapt objects as well as a granular jamming gripper to firmly hold objects with different shapes. Bunis et al. [11] designed a three-finger gripper that can cage grasp with noisy poses and grasp it to a precise goal position. Goldberg [12] used a gripper with flat finger pads as well as some designed work strategies to align objects. Zhang et al. [13] designed a gripper to align objects with reconfigurable jaw tips and a sequencer.

Our proposed gripper follows the previous works and relies on the geometric constraints of the design and simple work strategies to realize the goal of object alignment. The working strategies for the gripper to eliminate position errors and arrange screws are implemented by taking advantages of the geometric constraints of finger shapes and gravity.

The structure of the gripper is compact so that it can pick up objects in narrow spaces. Fig.4 shows the mechanism of the precision gripper. Two fingers are driven by a single motor through a slider-crank mechanism, which connects two links that turn the rotational motion to the linear motion. The fingers are guided by a linear rail and connected to the motor via two links.

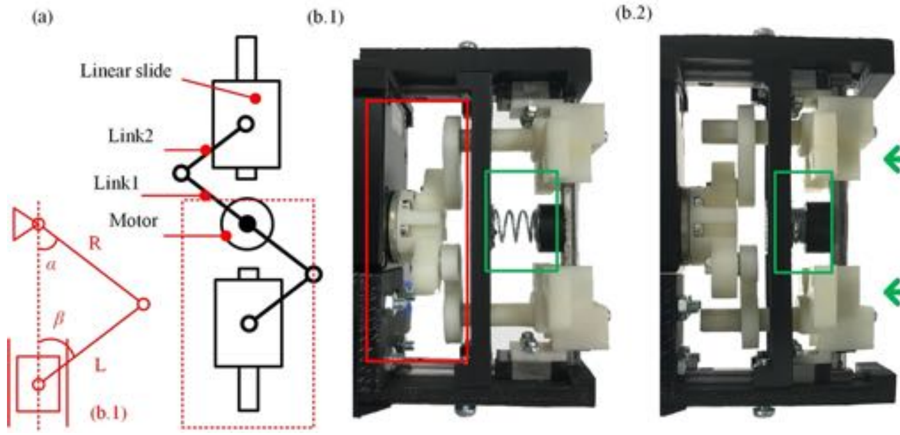
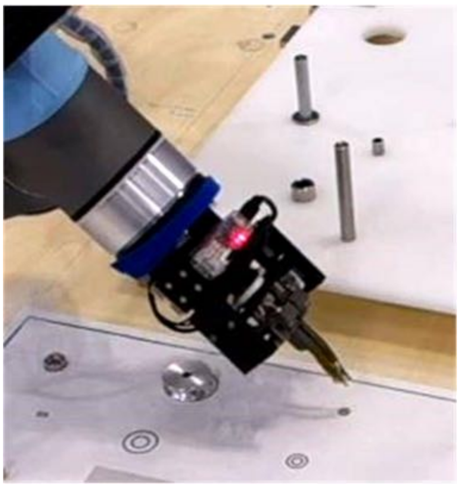


Figure 4. (a.1)The mechanism of the precision gripper. Two fingers, each connected through the links to the motor, are guided by a linear slide. The links convert the rotational motion of the motor to a linear finger motion. (b.1)A zoomed up view of the compliant mechanism. When external forces are exerted at the fingertips, the fingers will retract along the linear slide B, and the spring is compressed (see (b.2)). When the external forces disappear, the spring extends and moves the fingers back to their initial position.



(a) screw picking

(b) washer picking

Figure 5. Examples of picking up a small object using the precision gripper. (a)The precision gripper can pick up a screw by holding the thread of the screw. (b)The fingertips of the precision gripper can be inserted into the hole of a washer to grasp the washer from the inner side.

3.1.1 Small object picking

There are several kind of small objects such as screws and washers in the task-board tasks. It is difficult to use conventional grippers to pick up the aforementioned small objects. The precision gripper, on the other hand, can be used to pick up these small objects due to its pointed fingertips.

Fig.5 shows two examples of a robot arm picking up small objects using the precision gripper. (a)The precision gripper is tilted in order to pick up a screw that stands on the placement mat by grasping its thread. (b)First, the robot inserts the closed fingers of the precision gripper, which are compliant so that they make contact with the surface, into the hole of a washer. Then, the fingers are opened to pick up the washer from the inside. The pointed fingertips are designed such that they can be inserted into small holes to pick up objects.

3.1.2 Objects alignment

The precision gripper can be used to align cylindrical objects that have a hole in the middle. The working strategy is shown in Fig.6. First, the closed fingers are inserted into the hole of the object. Then the gripper opens and grasps the part from the inside, automatically centering it. At the beginning of the centering process, one finger touches the object first(Fig.6(b.2)), the object moves with this touching finger until the other finger touches the object. Then the object is pushed from the inside of the hole by both fingers(Fig.6(b.3)). Finally, the object is aligned to the center of the precision gripper(Fig.6(b.4)).

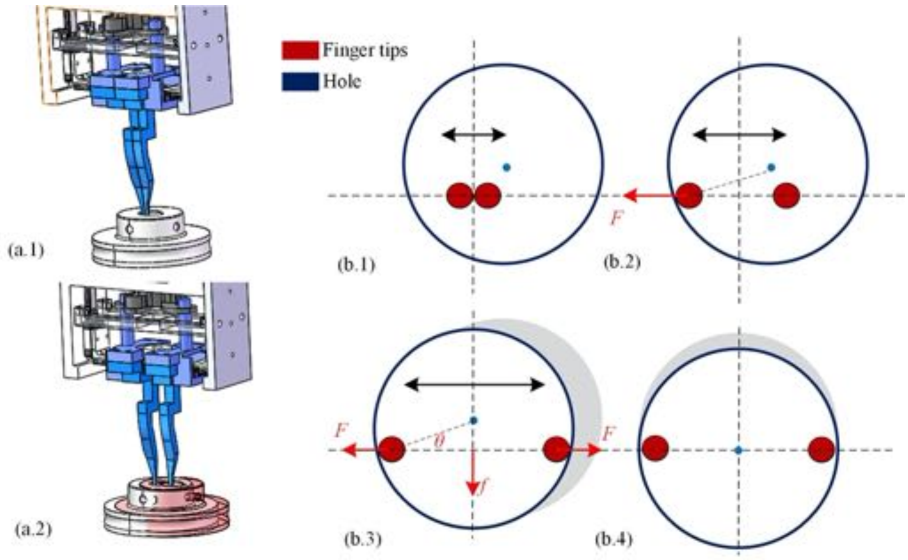


Figure 6. (a.1)The precision gripper fingers are inserted into the hole. (a.2)The precision gripper align the object by pushing outward to the edges using the fingers from inside of the hole.(b.1)-(b.4) show the flow of the alignment function. F is the force that the fingers give to the object. f is the friction. θ is the angle between the horizontal line of the gripper. (a.2)The precision gripper aligns the object by pushing outward to the edges using the fingers from inside of the hole.(b.1)-(b.4) show the flow of the alignment function. F is the force that the fingers apply to the object. f is the friction force. θ is the angle between the horizontal line of the gripper and the line which connects the finger and the center of the object

One thing to note is that the fingers pushing outward to the edges from inside of the hole to eliminate the initial errors. However, the object can be stuck at some points before the alignment is fully completed. In other words, θ will be gradually reduced but it may not be able to reach 0 at the end of the adjustment process because of friction. We call this point the locking point, as shown in Fig.7.

The locking point changes depending on the opening speed of the fingers of the precision gripper and the friction between the objects and the placement mat as well as the friction between the objects and the fingers of the precision gripper. In the case of task-board tasks, the target objects are light and the placement mat has a low friction coefficient, so the friction force can be neglected.

Fig.7(a) shows the locking point. The red curve indicates the force applied to the object while the blue curve indicates the friction between the object and the fingers of the precision gripper. As θ gets smaller, the two curves may intersect at an angle we call "locking angle". At this angle, the driven force exerted by the fingers is equal to the resistance force, and the fingers are stuck by the object. However, before getting stuck, the object is moving at a varying acceleration motion. It has an initial speed, allowing the object to avoid being stuck. The object will be finally aligned as long as the initial speed is large enough.

Although not explicitly shown, the influence of the friction coefficient μ between the object and the fingers and F can be analyzed graphically using Fig.7. The changes of the locking angles and the varying forces exerted by the fingers with respect to different μ and F are shown in Fig.7(b) and (c). In Fig.7(b), F is fixed to a constant. The locking angles shift to the left as μ becomes smaller. In 7(c), μ is fixed to a constant, more force is exerted to the object before the locking angle and the object has a larger initial speed. For a specific object, μ is fixed, the best way to perform a successful alignment is to enlarge the force exerted by the fingers. When the force is increased, the two curves are scaled up vertically like 7(c). The object gets a larger

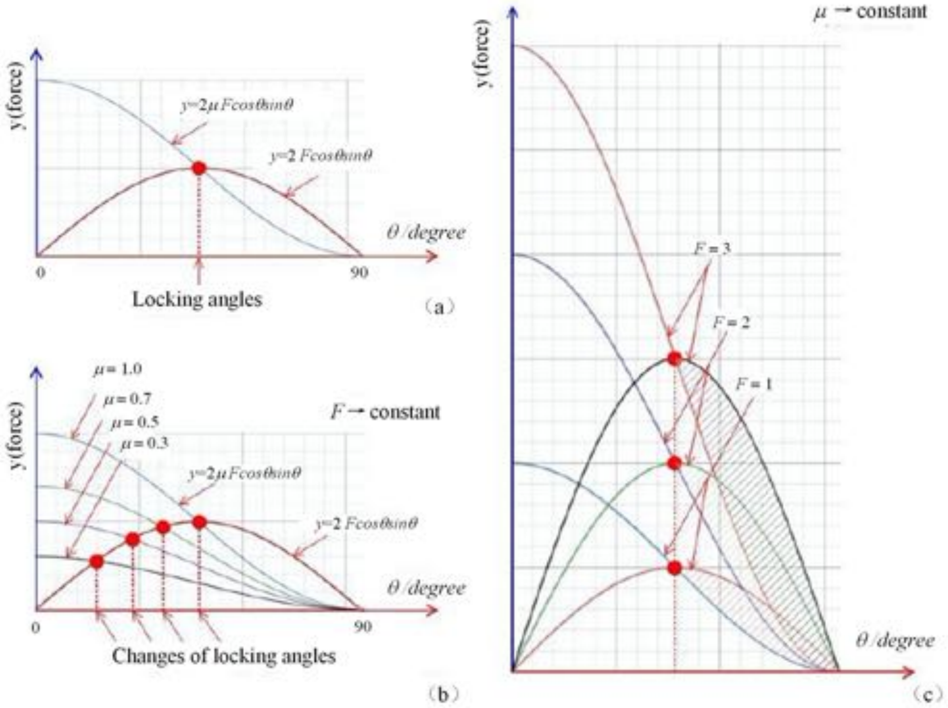


Figure 7. (a)The locking point.(b)The lock point gets smaller with smaller . (c)Increase of force does not affect the lock point, but it will result in more energy being passed to the objects.

initial speed at the locking angle and will move past the locking angle.

More detail of the validation for the alignment function is given in [2].

3.1.3 Screw arrangement

In the section 3.1.1, the ability of the precision gripper to pick up screws is explained. However, the pose uncertainties of the screws pose a challenge. In order to finish the assembly tasks successfully and smoothly, we use the precision gripper directly to arrange the screws to a certain position after picking.

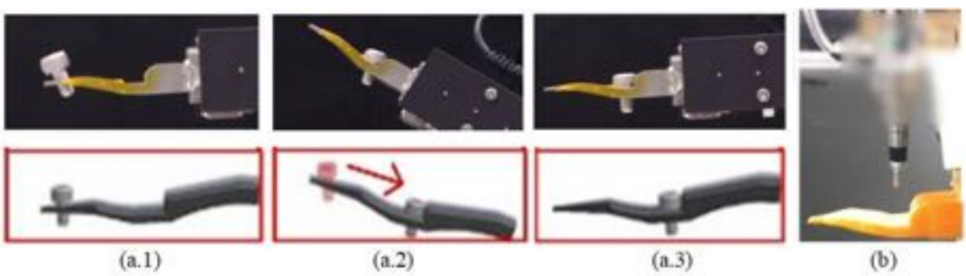


Figure 8. (a.1)-(a.3)The flow of arranging a screw. (b)The screw tool picks up the screw.

Our strategy is shown in Fig.8. First, the precision gripper picks up the screws using its narrow fingertips (Fig.8(a.1)). Then the gripper tilts up and slightly opens the fingers so that the screw will slide along the fingers until it reaches the corner of the fingers.(Fig.8(a.2)(a.2)). After the arrangement, the screw tool is used to pick up the screw and finish the screwing task.(Fig.8(a.3))

3.2 *Tool designs*

Current robot arms can exchange their grippers to expand their capability. One problem with is that tool exchange process is inefficient. Our approach is to let the robots manipulate tools in order to deal with various needs for different tasks. The tools are shown in Fig.1(c) for the screws, the nuts, the set screw and, the bearing retainer pin respectively. The tools are designed for picking as well as aligning.

3.2.1 The set screw tool

Fig.9(a) shows the design of the set screw tool. The set screw is very small and hard to be picked up and arranged. A torx bit socket is used to hold the set screw and a motor connected to the torx bit socket is used to finish the screwing task. A holder is installed as a cover so that the tool can be easily held by the Robotiq gripper. Inside the holder, the space is filled with a silicon sponge acting as a compliant spring in all directions. At the same time, the compressed silicon sponge gives the resistant force which can push the torx bit socket back to its initial pose after usage. By taking advantages of the compliance and a spiral pushing motion of the robot, even though there is a small misalignment between the hole and the set screw, successful assembly can be performed. When it finds the hole, the set screw will be pushed into the hole by the force that the silicon sponge gives and be screwed into the task-board. Fig.9(b) shows a example in the real world.

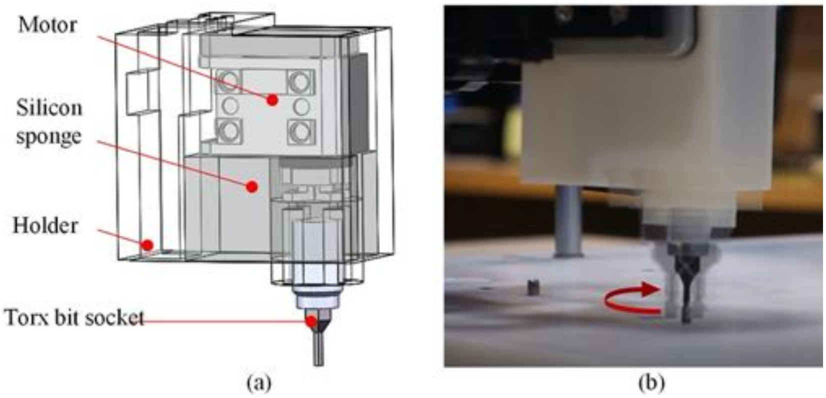


Figure 9. (a)The design of the screw tool. (b)Using the torx bit to screw the set screw. The Robotiq gripper holding the tool performs a spiral motion to search the hole while pushing the set screw onto the task-board.

3.2.2 The retainer pin tool

The retainer pin tool is composed of a funnel cap and a spacer, as shown in Fig. 10(a). As small positioning uncertainties when grasping the retainer pin result in relatively large errors at the tip, we designed the tool to orient and insert the pin by dropping it into the tool. Fig.10(b.1)-(b.2) shows how a bearing retainer pin with uncertainties in pose can be arranged to a certain pose. A spiral motion is then performed with the tool, which causes the pin to fall into its hole by gravity. We lift the tool by a few mm before performing the spiral motion, so that the cap of the pin does not collide with the tool after the pin has dropped into the hole.

3.2.3 The nut tools

The nut screw tools are designed to fasten the 8 mm and 6 mm nut shown in Fig.11(a). Each tool comprises a silicone sponge, a 3D printed cover, and a Dynamixel XM430-350R motor. The sponge is inserted into the 3D printed cover, and the Dynamixel motor is used to rotate the cover. A hole to hold the nut is cut into the sponge, and a conic surface attached to the outside of the sponge to guide the nut into the center when it is being picked up, as shown in (Fig. 11(b.1)). After the robot pushes the tool onto the nut, it is squeezed into and held by the silicone sponge as shown in Fig.11(b.2).

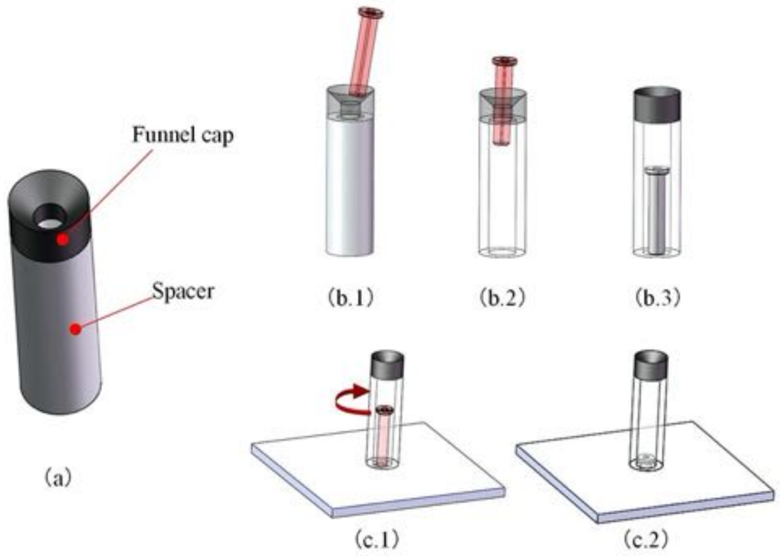


Figure 10. (a)The design of the retainer pin tool. (b.1)The initial pose of the bearing retainer pin with uncertainties.(b.2)The bearing retainer pin slides into the spacer through the funnel cap.(b.3)The bearing retainer pin is arranged to a certain pose. (c.1)(c.2)Spiral motion is used to move the bearing retainer pin around the hole. Once the bearing retainer pin and the hole are aligned, the pin drops into the hole by gravity.

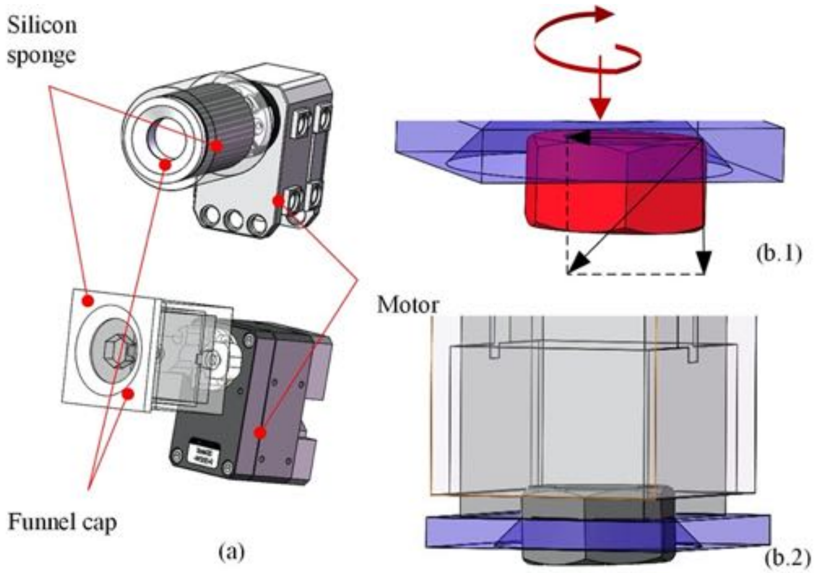


Figure 11. (a)The designs of the nut tools. (b.1)To pick up the nut, the nut tool is pushed downwards while it is being moved along a spiral path. (b.2)The nut slides to the center of the nut tool and is inserted into the silicone sponge. The nut tool holds the nut by the friction between the silicone sponge and the nut.

3.2.4 The screw tool

The screw tools [1] shown in Fig. 1(c-1) consist of three parts: a motor, a tool bit and the joint between the motor and the tool bit. They are used to pick up screws from the screw feeders or the precision gripper. The tool has a hex bit inside to turn the screw, as well as a suction cup pad to pick up screws by suction. A barometric pressure sensor is used to detect whether the screw was picked up successfully or not. The tip of the tool is compliant and spring-loaded along one axis, so it can easily pick up screws and apply force when fastening them. The suction pad is separately spring-loaded. The compliance not only protects the tool but is also useful to realize

[1] The screw tools were designed by F. von Drigalski(OMRON SINIC X), C. Nakashima(OMRON) and SAWA LTD

the alignment mentioned below. We prepared 3 screw tools for M3, M4, M6 screws respectively.

4. Motion Designs

The motion designs mentioned in this section are used to deal with the pose uncertainties of the parts as well as the task-board.

4.1 *Spiral motion*

Spiral motion is designed to deal with the position errors of the task-board. It takes advantages of the compliance in z-direction. Here, we take peg-in-hole task as an example. If there is a misalignment between the peg and the hole, the peg will not be inserted into the hole. Instead, the tool(gripper) used to hold the peg will retreat due to the compliance and the force that the peg gives. At the same time, the tool(gripper) will also give a resistance force to the peg against the ground. At this point, a spiral motion is performed by the tool(gripper) to search the hole. When the peg and the hole is aligned. the peg will be pushed into the hole due to the force given by the compliance mechanism. This strategy is frequently used in the task-board tasks.

4.2 *Aligning by regrasp*

Regrasp is designed to deal with the uncertainties associated with cylindrical parts. To perform a regrasp, the Robotiq 2-Finger 85 grippers of b_bot and c_bot are used. The purpose of regrasp is to eliminate the initial uncertainties of the part.

Fig.12 shows an example. First, b_bot holds the peg and c_bot aligns the peg in one direction by grasping the peg. Then b_bot releases the peg (Fig.12(1)(2)). After this motion the uncertainties in one direction is eliminated. In the same way, b_bot closes to hold the peg and c_bot releases the peg to let b_bot turn 90 degrees (Fig.12(3)). Then c_bot grasp the peg while b_bot releases the peg (Fig.12(4)). At this point, the uncertainties of the peg has been eliminated. Finally, b_bot closes the gripper to hold the peg and c_bot releases the peg (Fig.12(5)). b_bot continues to perform the following task with the aligned peg (Fig.12(6)).

5. Task details

In this section, the strategies for each task are introduced, following the sequence shown in Fig.3(c). The work place environment is shown in Fig.13. The screw tools and the M6 nut tool are hung on the side of the work table. The M12 nut tool and the retainer pin tool are put on the work table. There are two screws feeders for M3 and M4 bolts are placed on the left side of a_bot.

5.1 *Preparation phase*

The layout of the task-board is known in advance. The problem is that the layout of the placement mat is unknown until ten minutes before the task-board task starts. Our strategy is to use a generator (a python script). We use during the ten minutes of Preparation Phase to manually measure the layout of the placement mat using a large transparent plastic board with grids. The measurement data of the layout is used to update the robot scene simulator using a generator module. In this way, all the motions for each tasks can be generated automatically.

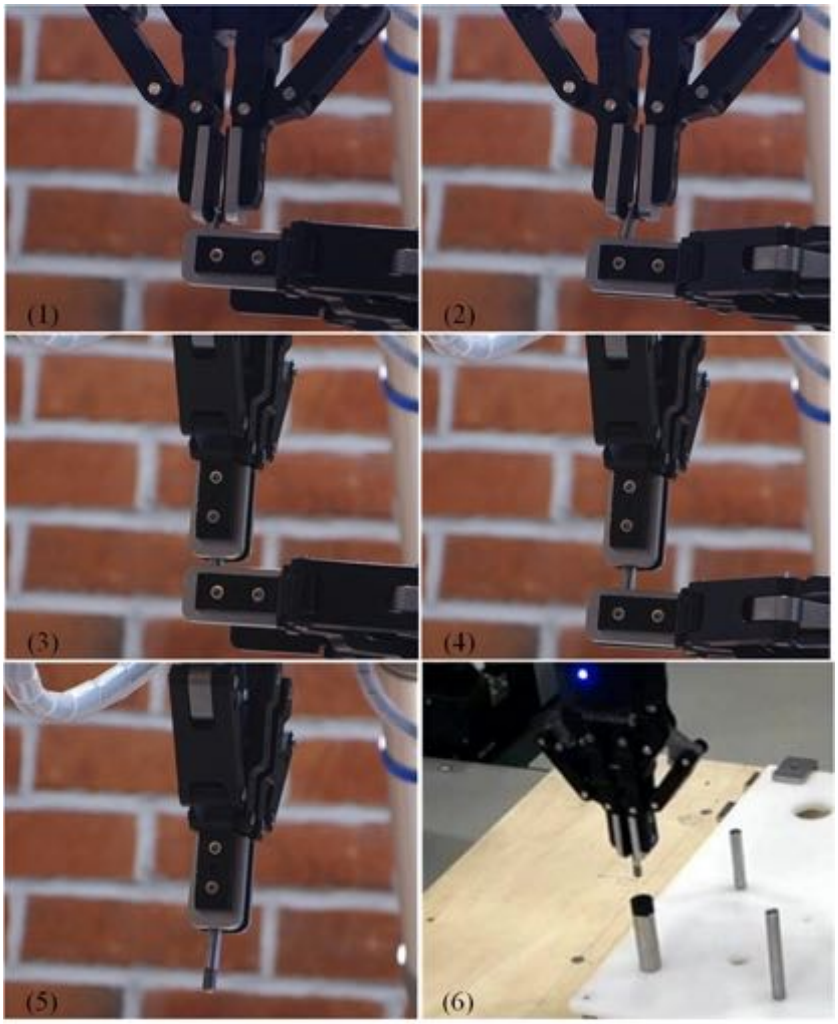


Figure 12. (1)b_bot holds the peg and c_bot closes the gripper to align the peg in one direction by grasping. (2)b_bot releases the peg and grasps it again. (3)c_bot releases the peg and b_bot turns the gripper 90 degrees around z axis. (4)c_bot grasps the peg to align the other direction and b_bot releases the peg. (5)b_bot grasps the peg and c_bot releases the peg. The alignment is finished. (6)After the alignment, b_bot, which holds the aligned peg, continues to perform the rest of the task.

5.2 *Part11: M3 set screw*

- **Difficulties**
  The alignment between the set screw and the set screw tool.
- **Requirements**
  - The set screw tool
  - The initial set up
  - b_bot equipped with the Robotiq gripper
  - c_bot equipped with the Robotiq gripper

The set screw is set on the task-board initially. The goal is to screw the set screw fully into the task-board. It is very hard to insert the bit into the set screw because of its very small size and the positioning tolerances of the robot and the tool. The rule of the task-board tasks does not limit the initial poses of the robots as long as they are not touching the task-board and the objects. We thus positioned the set screw tool perfectly above the set screw at the start of the round, so that the robot only has to move downwards to fasten it.

Step 1: b_bot holds the set screw tool and the pose of the set screw tool is manually set initially to be right above the set screw (Fig.14(1)).

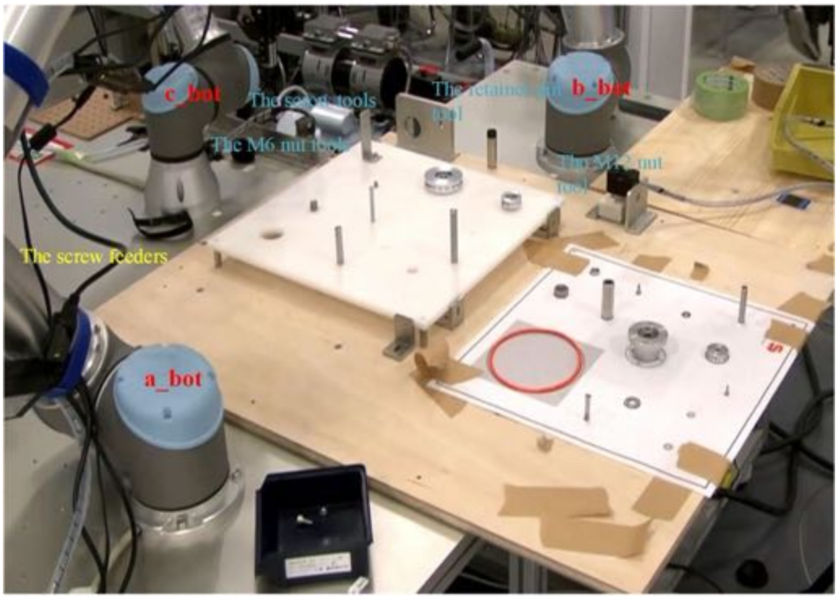


Figure 13. The work space.

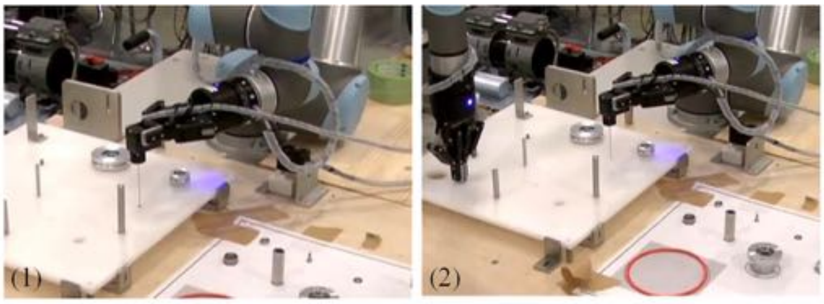


Figure 14. (1)The initial set up of the set screw task. (2)After the set screw is fully screwed in, c_bot holds down the task-board while b_bot returns the set screw tool.

Step 2: When the task begins, b_bot goes down to insert the tip of set screw tool into the set screw. After that, the set screw tool starts to screw the set screw into the task-board.

Step 3: When the screwing is finished, b_bot lifts the set screw tool and returns it. The tool may be stuck to the set screw after fastening. Hence, the task-board may be lifted up, and shifted while removing the tool from the set crew. c_bot is used to pushes the task-board to prevent the task-board from being lifted up. (Fig.14(2)).

5.3 *Part2: 6 mm Bearing retainer pin*

- **Difficulties**
  The retainer pin falls down easily and is hard to grasph. The alignment between the retainer pin and the hole.
- **Requirements**
  - The retainer pin tool
  - Regrasp
  - b_bot equipped with the Robotiq gripper

The bearing retainer pin may accidentally fall down while other tasks are being done. This the reason why it is set to the second task. The other challenge is that because the bearing retainer pin is picked up by the screw tools, it is difficult to deal with the position uncertainties of the retainer pin. A regrasp is used to solve this problems. In order to align the bearing retainer pin

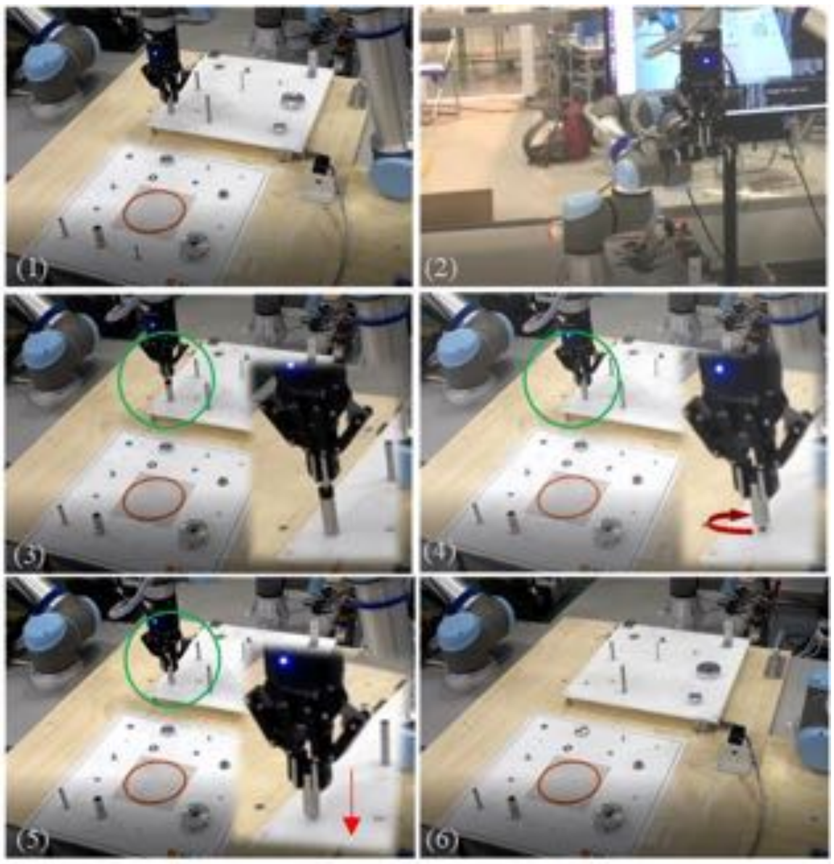


Figure 15. (1)b_bot picks up the retainer pin tool and puts it onto the hole. (2)b_bot picks up the bearing retainer pin and uses regrasp to align the bearing retainer pin. (3)b_bot drops the bearing retainer pin into the retainer pin tool. (4)b_bot lifts the the bearing retainer pin above the hole and performs a spiral motion. (5)b_bot uses the retainer pin tool to push the bearing retainer pin. (6)b_bot finishes task and returns the tool.

and the hole, the retainer pin tool is used.

Step 1: b_bot picks up the bearing retainer pin tool and put it onto the hole where the bearing retainer pin should be inserted (Fig.15(1)).
Step 2: Then b_bot picks up the bearing retainer pin and performs a regrasp between b_bot and a_bot to eliminate the initial position error of the bearing retainer pin (Fig.15(1)).
Step 3: After that, b_bot drops the bearing retainer pin into the bearing retainer pin tool (Fig.15(3)). At this stage, if the bearing retainer pin and the hole is well aligned, the retainer pin tool will guide the bearing retainer pin to the hole. Otherwise, the bearing retainer pin will stand on the task-board due to misalignment.
Step 4: In order to ensure the assembly is finished successfully, b_bot lifts up the retainer pin tool a little and performs an additional spiral motion to search the hole (Fig.15(4)). The reason why the retainer pin tool is lifted before the spiral motion is to avoid the collision between the retainer pin tool and the cap of the bearing retainer pin during the spiral motion in case of the bearing retainer pin has dropped into the hole before the spiral motion.
Step 5: b_bot uses the retainer pin tool to push the bearing retainer pin again to ensure the bearing retainer pin is fully inserted into the hole and return the tool to finish the task.(Fig.15(4)(5))

5.4 *Part3,4: 17mm/9mm spacer for bearings*

- **Difficulties**
  The alignment between the hole and the spacer.

- **Requirements**
  - a_bot with the precision gripper

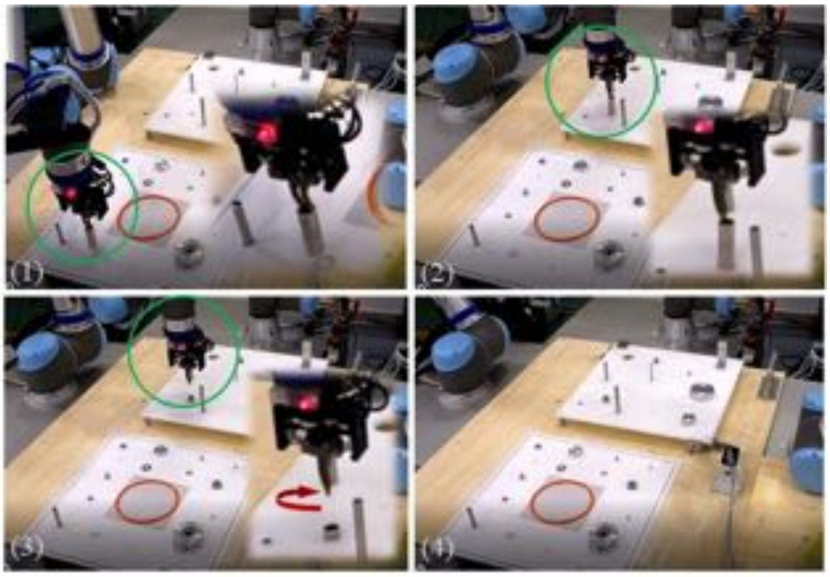


Figure 16. (1)a_bot picks up the spacer from the inner side. (2)a_bot releases the spacer just above the hole. (3)a_bot performs a spiral motion since the spacer may not inserted fully, and goes back to the initial pose. (4)the task is finished.

In this task, the compliance of the precision gripper is used to deal with the uncertainties between the hole and the spacer. The same strategy is used for 9mm and 17mm spacer. Here we take the task of 17mm spacer as a example.

Step 1: a_bot aligns and picks up the spacer by pushing outward to the edges using the fingers from inside of the hole (Fig.16(1)).Then a_bot transfers the spacer to the hole and inserts it (Fig.16(1)).

Step 2: After this motion, the spacer is released by closing the fingers of the precision gripper. If the spacer is well aligned to the hole, the spacer will drop into the hole directly. Otherwise, the spring of the precision gripper will be compressed due to the force the spacer gives. To ensure the insertion is finished successfully, a bot is set to perform a spiral motion after the insertion (Fig.16(3)).

Step 3: The small fingers of the precision gripper drives the spacer move around until it finds the hole. The spacer will drop into the hole due to its own gravity (Fig.16(4)).

5.5 *Part9,10: 6mm/10mm washer*

- **Difficulties**
  The washer is hard to be picked up. The alignment between washer and the peg.
- **Requirements**
  - a_bot with the precision gripper

Because of the thickness and shape of the washers, it may be very hard to use conventional grippers as well as suction cups to pick them up. The precision gripper, with its pointed finger tips, is designed to pick up these washers. The alignment between the pegs and washers is by the spiral motion. The same strategy is used for 6mm and 10mm washer. the task of 10mm washer is taken as an example here in this paper.

Step 1: First, the fingers of the precision gripper are inserted into the hole. By opening the fingers and hence pushing outward to the edges using the fingers from inside of the hole, the washer can be picked up an aligned. (Fig.17(1)).

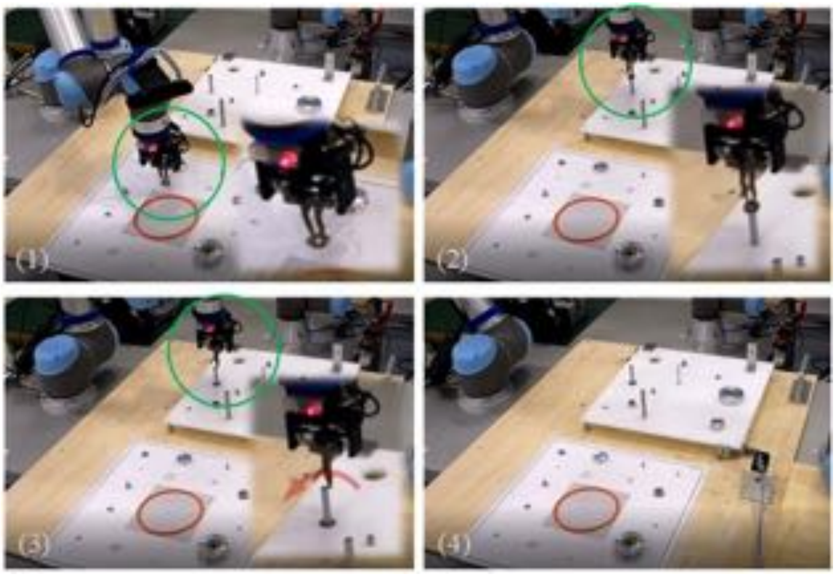


Figure 17. (1)a_bot aligns and picks up the washer from the inner side. (2)a_bot puts the washer onto the peg. (3)a_bot performs a spiral motion and goes back to the initial pose. (4)The assembly is completed.

Step 2: a_bot moves the washer on top of the peg and releases the washer by closing the fingers (Fig.17(2)). The washer should be placed just on top of the peg such that the washer will drop to the bottom if the washer is in the right position.

Step 3: A spiral motion is performed after closing the fingers in order to ensure the washer has dropped to the bottom of the peg (Fig.17(2)). One thing to mention is that the diameter of the spiral motion should be as same as or slightly larger compared to the diameter of the peg. If the finger tips of the precision gripper goes beyond the peg too far, the washer might drop outside which leads to a failure of the task. On the other side, if the spiral motion is too small, the washer might be stuck on the top of the peg instead of dropping to the bottom.

5.6 *Pulley*

- **Difficulties**
  The alignment between the peg and the hole of the pulley. The pulley might stuck midway instead of dropping to the bottom.
- **Requirements**
  - b_bot with the Robotiq 2-Finger 85 gripper
  - a_bot with the precision gripper

The strategy for the pulley is similar with to the one for washers. The precision gripper is used to pick up and align the pulley from the inner side of the hole. And the spiral motion is performed to deal with the misalignment between the peg and the pulley. Different from the washers, the pulley might be stuck at the top part of the peg. Another step is added to ensure the pulley has dropped to the bottom by having b_bot push the pulley.

Step 1: First, the precision gripper inserts the fingers into the hole of the pulley. Then open the fingers to align and pick up the pulley from the inner side of the hole (Fig.18(1)).

Step 2: Then, a_bot transfer the pulley to the peg (Fig.18(2)).

Step 3: At last, a_bot performs a spiral motion to adjust the position of the pulley (Fig.18(3)).

Step 4: After the spiral motion, b_bot is used to push the pulley again in order to ensure that the pulley is fully inserted (Fig.18(4)(5)). Before pushing, the gripper of b_bot is opened to a certain range, between the diameter of the peg and the diameter of the pulley, so that the

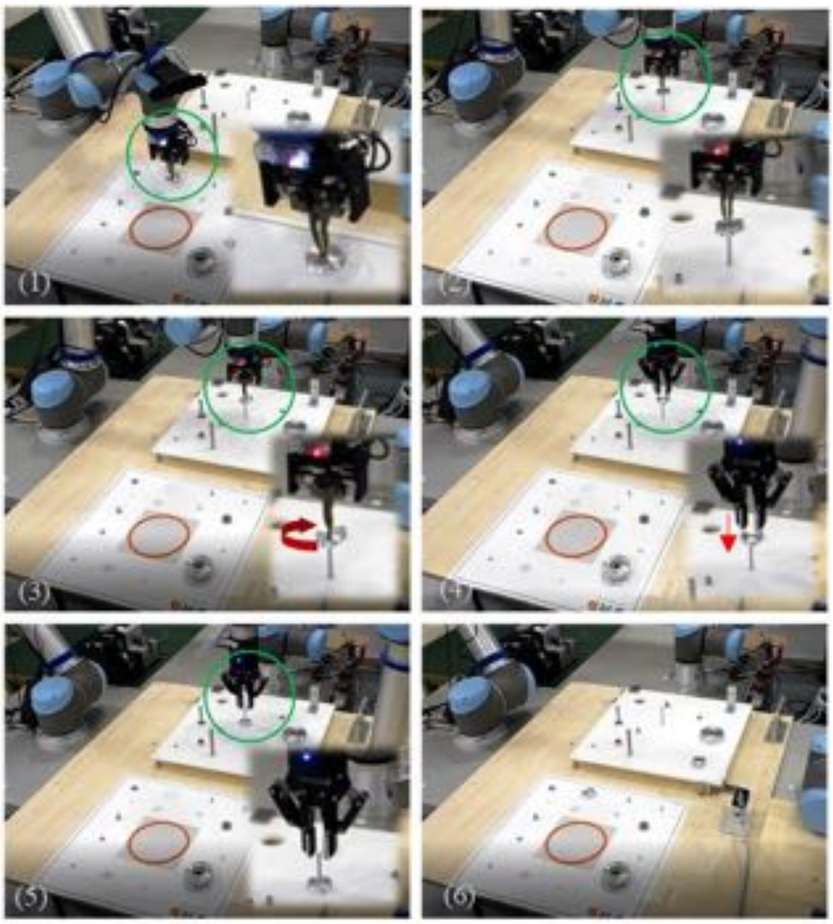


Figure 18. (1)a_bot picks up the pulley from the inner side. (2)a_bot puts the pulley onto the peg. (3)a_bot performs a spiral motion. (4)(5)The Robotiq 2-Finger 85 gripper of b_bot opens to a certain range and pushes the pulley. (6)The task is finished.

Robotiq 2-Finger 85 gripper is able to push the pulley without hitting the peg.

5.7 *Part1: Bearing with hosting*

- **Difficulties**
  The weight of the bearing is too heavy for the precision gripper to pick. The alignment between the hole and the bearings.
- **Requirements**
  - b_bot with the Robotiq gripper
  - a_bot with the precision gripper

This part is too heavy to be picked up by the precision gripper from the inner side of the hole. In this task, our strategy is to use the fingers of the precision gripper to lead the bearings to the hole, followed by the use of spiral motion and pushing by b_bot to ensure successful completion of the task.

Step 1: Part 1 is picked up by the Robotiq gripper of b_bot and placed to a certain position on the task-board (Fig.19(1)(2)).

Step 2: After placing the bearings, the robot regrasps the part by closing and opening the fingers again with a lower speed and force in order to ensure the bearings are in the center of the gripper (Fig.19(3)).

Step 3: The fingers of the precision gripper are inserted into the hole of Part 1. The robot slides Part 1 towards the hole (Fig.19(4)). The slide motion should be fast enough so that the

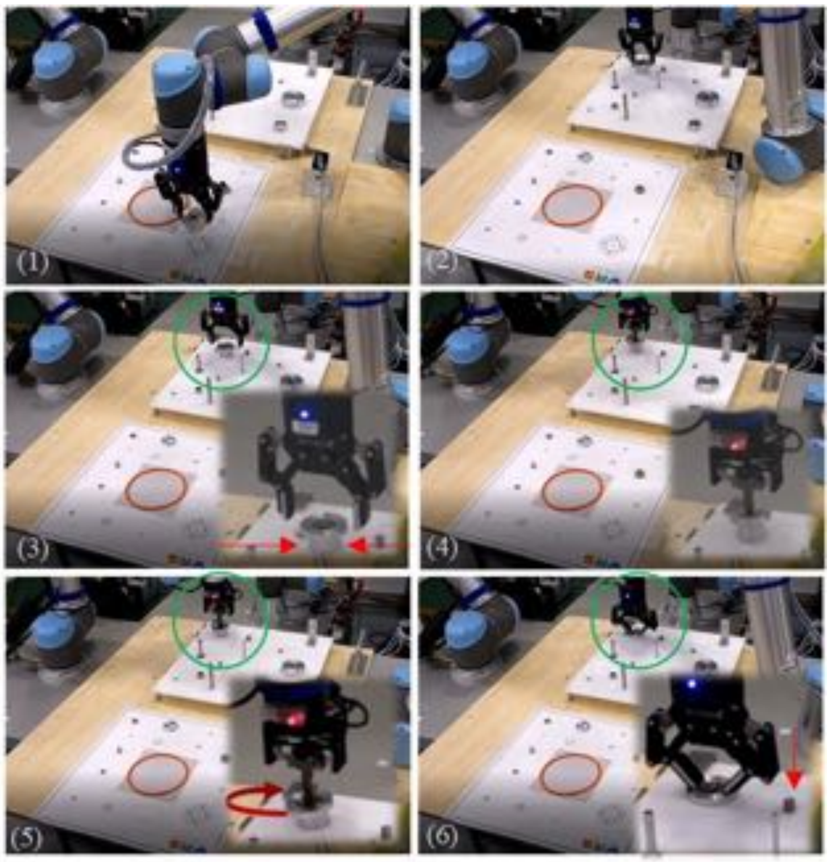


Figure 19. (1)b_bot picks up the bearing. (2)b_bot places the bearing on the task-board. (3)b_bot closes the gripper with a low speed to push the bearing to the center and releases the bearing again. (4)a_bot inserts the fingers into the hole of the bearing and slides the bearing to the hole. (5)a_bot performs a spiral motion to ensure the bearing drops into the hole. (6)The gripper of b_bot gripper to a certain range and pushes the bearing.

bearings would drop into the hole instead of falling aside when it reaches the hole.

Step 4: The Robotiq gripper opens to a certain range and push the object in order to make sure Part 1 is fully inserted into the hole instead of stuck in the midway (Fig.19(6)).

5.8 *Part 6: 4mm round belt*

- **Difficulties**
  The uncertainties of the belt. The looping task.
- **Requirements**
  - b_bot with the Robotiq gripper
  - a_bot with the precision gripper

The belt is soft. It has a lot uncertainties especially when force is applied. To solve this problem, a metal plate is used to limits the position of the belt. The belt should be looped between two pulleys, called the big pulley and the small pulley, which are initially assembled on to the task-board. The looping is very tight, the precision gripper is used here to loop the belt on the pulley by dragging and leading the belt from the inner side.

Step 1: b_bot picks up and put the plate next to the small pulley on the task-board. Here b_bot holds the plate with a certain force(5N) moving towards the small pulley until it touches the pulley and is stopped by the small pulley to ensure the plate is in right position (Fig.20(1)). The shape of the belt has uncertainties, the plate is used to limit the position of the belt to ensure the small belt is inside the belt when the belt is put. Also the plate makes the position of the belt higher to fit the height of the small pulley.

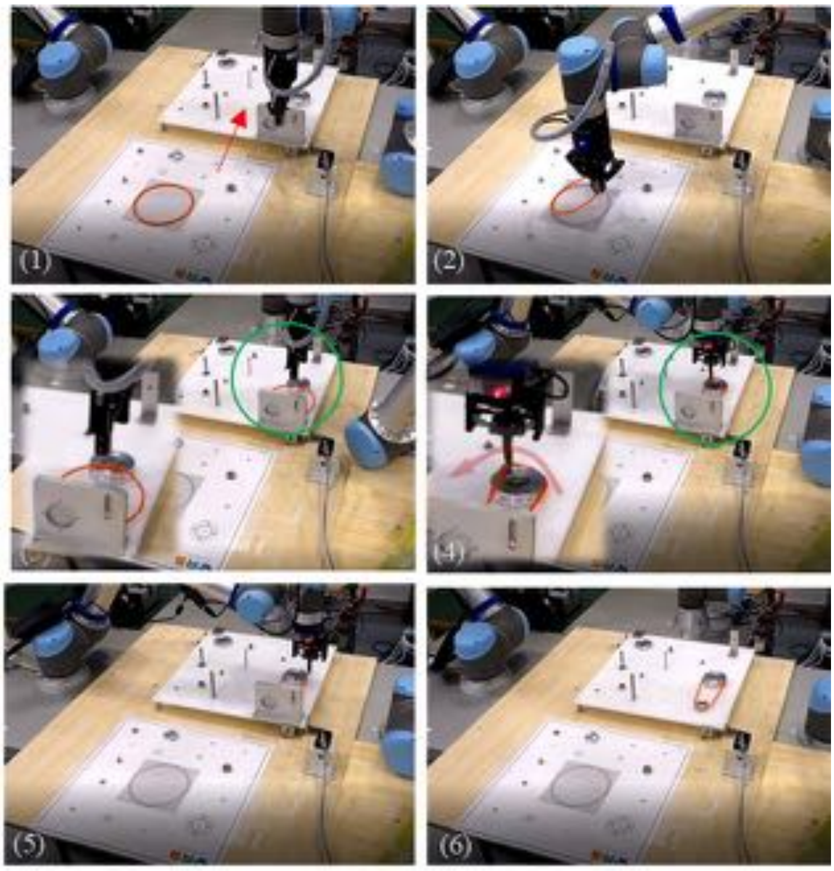


Figure 20. (1)b_bot picks the plate and moves the plate next to the small pulley assembled on the task-board. (2)(3)b_bot picks up the belt and put the belt one side on the plate, the other side on the other large pulley assembled on the task-board. (4)Insert the fingers of the precision gripper in the round belt and loop the belt by moving the fingers around the large pulley. (5)a_bot moves the fingers around the large pulley again to ensure the looping is completed successfully. (6)Return the plate and the task is completed.

Step 2: b_bot picks up the belt and places it on the pulley. b_bot first moves above the large pulley, then move towards the plate. The plate will give a resistance force when the belt touches it. At last, b_bot moves down and drops one side of the belt on the large pulley. The other side of the belt should be on the bottom of the plate. At this time, the small pulley should be inside the belt (Fig.20(2)(3)). Without the plate, the belt might goes under the pulley when the looping task begins.

Step 3: The precision gripper is moved around the pulley. The finger tips of the precision gripper will stretch the belt and hang it on to the pulley that the fingers are moved around. The circle motion of the precision gripper will repeat twice to ensure the looping has been finished successfully.(Fig.20(4)(5))

5.9 *Part 15: 10mm end cap*

- **Difficulties**
  The alignment between the end cap and the peg.
- **Requirements**
  - b_bot with the Robotiq gripper
  - a_bot with the precision gripper
  - Hand over between a_bot and b_bot

The end cap is small and light-weighted. It is hard for the precision gripper to insert the fingers into the hole. And if we use the spiral motion to search the hole, the end cap will also

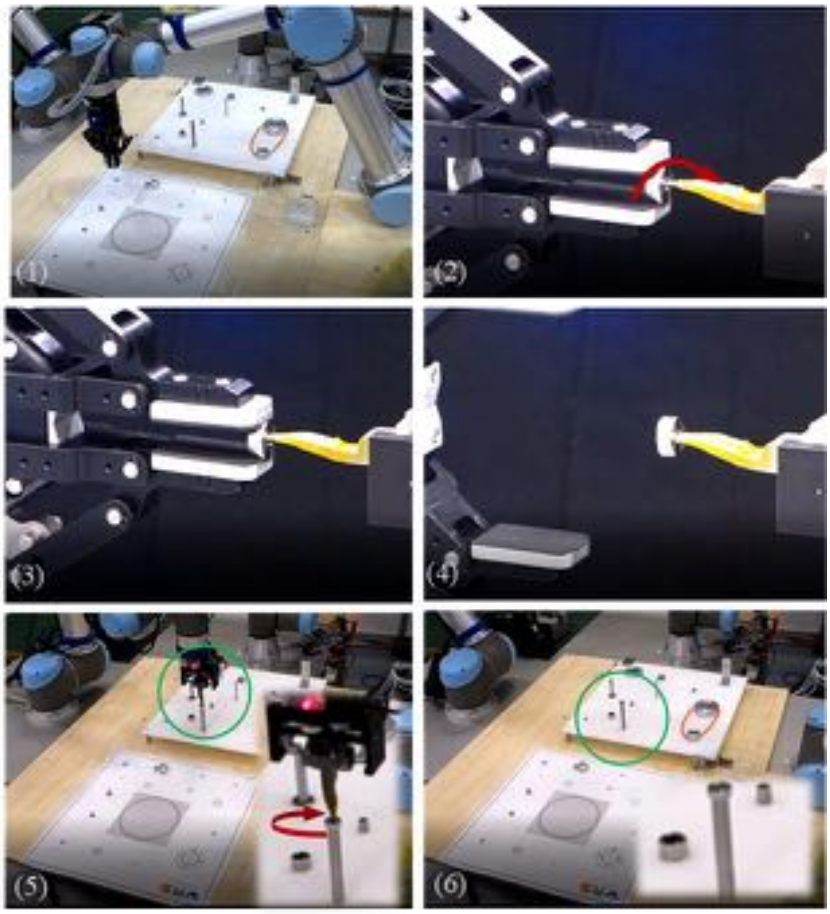


Figure 21. (1)b_bot picks up the end cap. (2)(3)(4)A handover is performed between a_bot and b_bot. In (3), the precision gripper performs a spiral motion to search the hole of the end cap. (5)a_bot places the end cap on the peg and performs a spiral motion. (6)The task is finished.

move around because of its light weight. As a result, the end cap is difficult to be aligned by the precision gripper only. For the task, a handover between a_bot and b_bot is used. Use b_bot to hold the end cap, then insert the small fingers into the hole.

Step 1: b_bot picks up the end cap (Fig.21(1)).
Step 2: The precision gripper inserts the fingers into the end cap. Here a spiral motion is performed to search the hole (Fig.21(2)(3)).
Step 3: The fingers of the precision gripper open to hold the end cap and then the Robotiq gripper release the end cap to finish the handover (Fig.21(4)).
Step 4: The precision gripper put the end cap on the peg and performs a spiral motion to ensure the end cap sits on the peg fully.

5.10 *Part 8: M12 nut*

- **Difficulties**
  The alignment and the screwing task of the nut.
- **Requirements**
  - b_bot with the Robotiq gripper
  - The nut tool for M12 nut

The difficulty of the task is how to screw the nut. If grippers are used, it is difficult to align the nut and the screwing process takes plenty of time because of the joint limits of the robot. Here, the nut tool is designed to solve these problems.

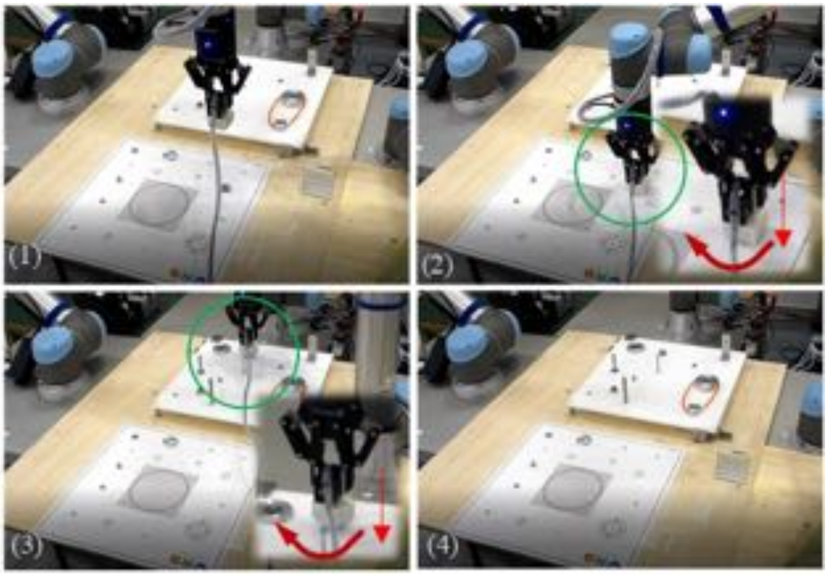


Figure 22. (1)b_bot picks up the M12 nut tool. (2)Pick up the nut by the nut tool. (3)Screw the nut onto the task-board. (4)Return the nut tool and the task is finished.

Step 1: b_bot picks up the M12 nut tool (Fig.22(1)). And the nut tool starts to rotate.

Step 2: b_bot pushes the rotating nut tool against the M12 nut While performing a spiral motion to ensure the nut has slid to the center of the nut tool and held by the silicon sponge (Fig.22(2)).

Step 3: b_bot transfers the nut to the stud where it should be screwed on. Firstly, b_bot slightly push the nut on the stud while performing a spiral motion to let the nut find the right position. Then b_bot pushes the nut tool hard against the task-board to use the compliance of the silicon sponge and the friction to screw the nut fully to the bottom of the stud (Fig.22(3)).

5.11 *Part 12,13: M3/M4 bolt*

- **Difficulties**
  The picking and the arrangement of the bolt. The screwing as well as the alignment.
- **Requirements**
  - b_bot with the Robotiq gripper
  - The screw feeder for M3 bolts
  - a_bot with the precision gripper
  - The M3 screw tool

For the M3 and M4 bolt, the screw feeders are used to arrange the bolt to save time. The bolts are picked up by the precision gripper and be threw into the feeder in advance so that the feed could have time to arrange the bolt. The M3 and M4 bolt share the similar strategy. The M3 bolt is screwed into the task-board and the M4 bolt is screwed into the shaft. Below, we describe the procedure for the M4 bolt:

Step 1: The precision gripper picks up the bolt by the finger tips and throws it into the M3 feeder (Fig.23(1)(2)).

Step 2: c_bot picks up the M3 screw tool and uses the rotating screw tool to pick up the arranged bolt from the feeder. Here the screw tool also performs a spiral search if the picking fails. The spiral search here is different from the spiral motion mentioned before. After the screw tool fails, it will move to another position and try to pick the bolt again. The trajectory of the positions is spiral (Fig.23(3).

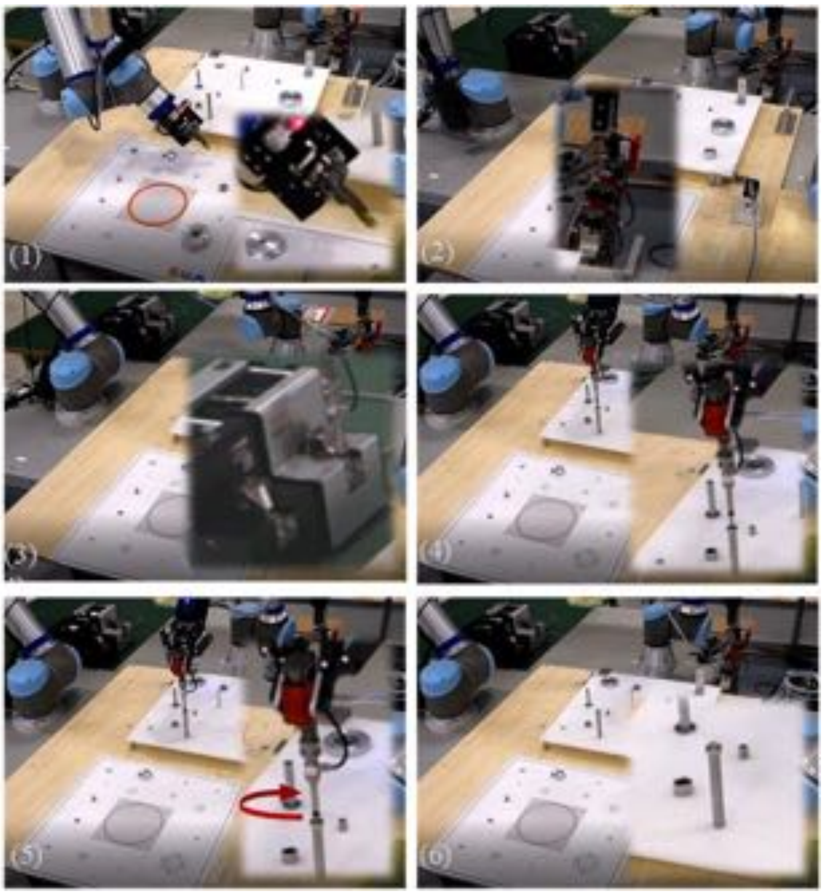


Figure 23. (1)a_bot picks up the M4 bolt by the precision gripper and drops the bolt into the screw feeder. (2)(3)c_bot picks up the screw tool and uses the screw tool to pick up the bolt from the feeder. (4)(5)Screw the bolt on the end cap which is assembled in the previous task. A spiral motion is performed to search the hole of the end cap as (5) shows. (6)The task is finished.

Step 3: The screw tool carries the bolt to the screw hole and pushes the bolt onto the task-board. At the same time c_bot performs a spiral motion to search the screw hole. When the bolt finds the hole, it will be screwed into the hole by the force that the screw tool gives (Fig.23(4)(5).

5.12 *M6 nut & bolt*

- **Difficulties**
  The picking, arrangement and alignment of the M6 bolt and nut. The screwing task between the nut and the bolt.
- **Requirements**
  - b_bot with the Robotiq gripper
  - c_bot with the Robotiq gripper
  - a_bot with the precision gripper
  - The M6 screw tool
  - The M6 nut tool

We consider part 7 to be the most difficult sub-task of the task-board tasks and we set it the last task as a challenge. It has two parts to be assembled together and requires two robots at the same time to finish the assemble. c_bot is not able to reach the M6 nut, but only c_bot is able to pick the M6 nut tool. In this situation, the precision gripper is used to transfer the M6 nut to another position where it can be picked up byc_bot with the nut tool. Since we do not have an M6 screw feeder, the precision gripper is used to arrange the M6 bolt.

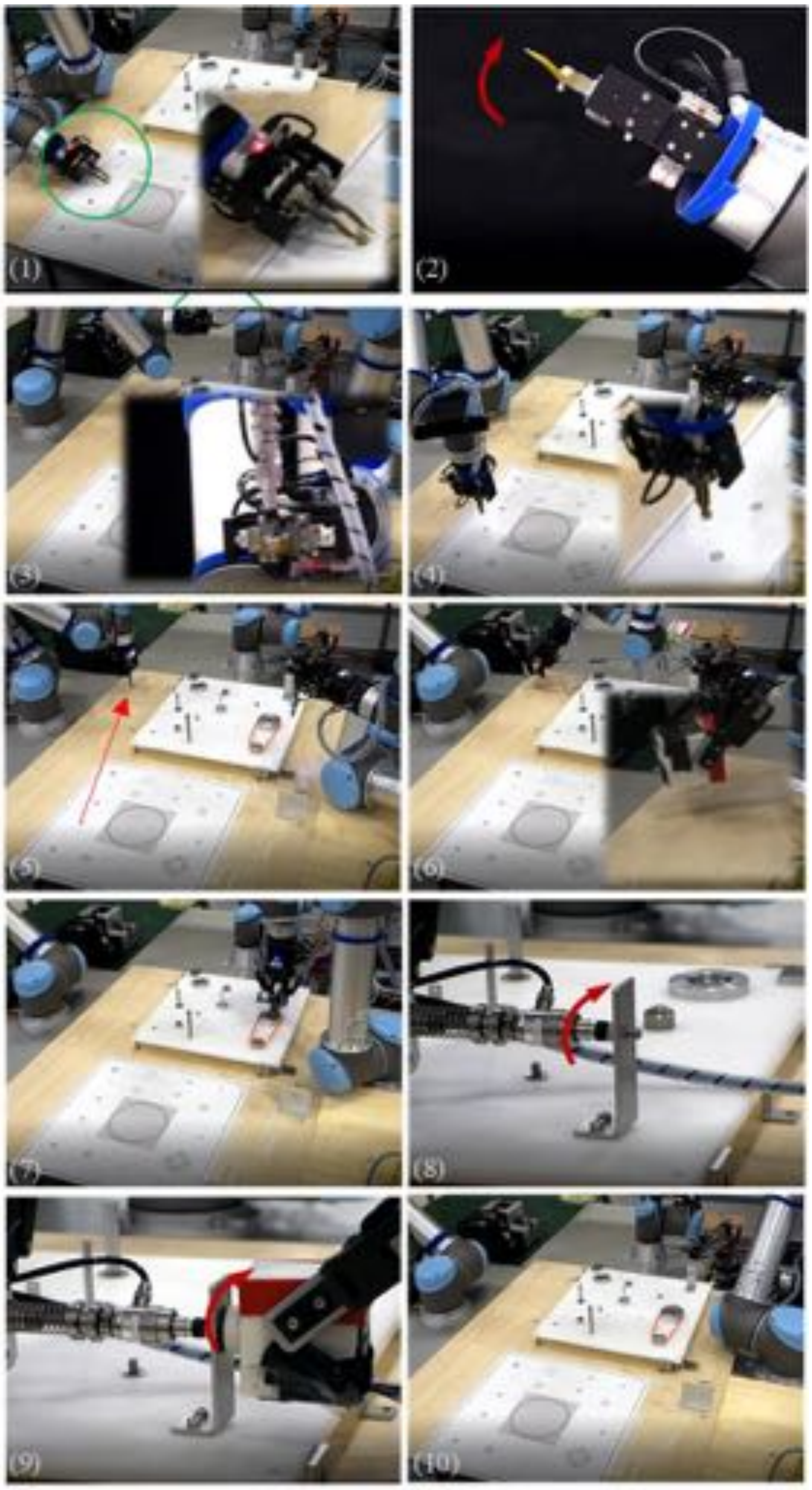


Figure 24. (1)a_bot picks M6 bolt by the precision gripper. (2)Arrange the bolt by the precision gripper. (3)b_bot picks up the screw tool and uses the tool to pick up the screw from the precision gripper. (4)a_bot picks up the M6 nut from the inner side. (5)a_bot transfer the nut to a position that c_bot could reach. (6)c_bot pick up the M6 nut tool and picks up the nut by using it. (7)(8)Move the screw tool to the assemble pose and perform a spiral motion to search the hole. (9)Move the nut tool to the position and perform a spiral motion to finish the screwing task. (10)Return all the tools and the task is finished.

Step 1: The precision gripper picks up the M6 screw and arrange the bolt. The tilting motion is performed twice in order to ensure the bolt has been arranged successfully (Fig.24(1)(2).
Step 2: The bot_c picks up the M6 screw tool and use it to pick up the arranged bolt from the precision gripper. The screw tool will do a spiral search if the picking fails (Fig.24(3).
Step 3: Pick up the nut by using the precision gripper and put it in a position that bot_c could reach (Fig.24(4)(5).
Step 4: c_bot picks up the nut tool and use the nut tool to pick up the nut on the working place. The picking strategy is as same as it for M12 nut in the previous task (Fig.24(6).
Step 5: Transfer the nut tool and the screw tool to the both sides of the plate where the parts should be assembled to prepare for the screwing task. First, b_bot holding the screw tool performs a spiral motion to search the hole on the plate and inserts the bolt into the hole (Fig.24(7)(8).
Step 6: After the bolt is in position, c_bot holding the nut tool will push the nut tool onto the plate to screw the nut onto the bolt that is held by b_bot.
Step 7: Return the nut tool and the screw tool. The task is finished.

6. Discussion and Conclusion

Our solution placed 5th among 16 teams in the task-board part with 36 points, using a custom, compliant gripper and a series of specialized tools. While the performance of the system was good, it was not robust enough to score highly during the trials. Below, we explain some failures we have encountered.

(1) For the set screw task, a torx bit can reliably hold a set screw if it is pressed lightly into the bit, because the inside of the screw slightly deforms around the edges of the torx bit. However, when fastening the screw, this deformation can grow so large that it becomes hard to remove the bit from the set screw. During the competition, this force caused an emergency stop in our robot.
(2) The M17 spacer was dropped several times due to the weight of the spacer, the acceleration of the robot motion, and low friction on the precision gripper's fingertips.
(3) The holes of the pulley, 6 mm washer and 9 mm spacer are small, so the precision gripper sometimes failed to insert its fingers into the hole.
(4) The task-board configuration was sightly different from the design. The height is not well adjusted. In case of the 6 mm washer task, the finger tips of the precision gripper became higher than the peg. That made the spiral motion failed and the washer did not drop to the bottom. The failure highlights the insufficiency of the robustness of the robot system in task-board tasks.
(5) Large forces and subtask failures sometimes caused emergency stops on the robots, requiring a full reset.
(6) Because there was little feedback to detect failures, tasks that failed mid-task were carried out until the end, wasting time.
(7) The gripper was 3D printed, so it was not as precise after long use, and sometimes dropped parts.

The importance of a robust system is highlighted by the fact that in the last full test before our last trial, the system scored over 70 points. During the subsequent trial, however, small problems caused a loss of over half the points.

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