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A Robotic Gripper Design and Integrated Solution Towards Tunnel Boring Construction Equipment

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Abstract—**Creative design of grippers on their configurations, mechatronics control system, and multi-component collaborative algorithms is often utilized to realize complex operations in industrial applications, due to the environmental constraints or specific task requirements. Firstly, this paper introduces the background problems. As the main automatic equipment -- the shield machine -- in the field of tunnel boring construction, needs frequent tool (cutter) replacement during underground process, but has no practical automatic method yet, due to heavy payload, complex environment and work procedure. Thus, an integrated solution was proposed by developing a specific gripper and a snake-like manipulator to accomplish tool replacement in a cooperative way. Through simple and unique design of relative components, the solution realizes a fully automatic and precise approach including heavy load tool grasping and regrasping, posture adjustment, unlocking and disassembly, and installation and locking. Finally, this paper also describes the experimental process of tool replacement by the prototype under a real working condition, and discusses the feasibility of putting the scheme into practical application through comparison.**

I. Introduction

Besides the manipulator, robotic grippers also play a very important role and are considered as essential parts for handling objects [1]. Specific attention has been addressed in recent years to grippers' mechanical / mechatronic / sensing / control design with theory, practice, and application. Different from dexterous hands, grippers are used to operate fixed and single objects, with the characteristics of less DOFs (degrees of freedom), simple structure, high rigidity, precise motion etc. For example, the classic pneumatic or electric grippers which are widely used in the industrial applications, either with two or three fingers, accomplish the encirclement motion against the certain and rigid objects by one DOF only (open/close), following the concept of "grasping".

For most cases of mass production in industrial application, the manipulators may employ several simple but different grippers to handle different objects [2] when complicated scenarios are demanded. The research on under-actuation is another branch to operate various objects by utilizing a unique gripper/hand configuration with a mechanical self-adaptive solution. Thierry [3] has developed a three-finger hand (each finger having three DOFs) with only two motors totally, the under-actuation configuration shows an effective performance of grasping various objects with simple mechanism and therefore simple control algorithm. The Robotiq® company [4] has also developed a series of underactuated gripper products with 2 or 3 fingers configuration which have already been applied in practice. Besides using four-bar linkage [5] or similar concept, many researches utilize different mechanism to obtain under-actuation, such as steel cables [6], springs [7], and pneumatics [8]. The motivation of this kind of shape adaptive under-actuation is to use fewer actuators to achieve simple but various grasp by automatically enveloping objects (self-adaptability), and hence, simplify the sequence of grasp and control algorithm.

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G. J. Monkman summarizes a classification [9] of most gripping methods in manufacturing technology according to previous studies into four categories: Impactive, Ingressive, Contigutive, and Astrictive. Hiroyuki Nishimura, et. al, have developed another type of underactuated gripper allowing the mechanism automatically switches its motion from grasp to retraction, when the fingers are in contact with the object [10]. This is a typical prototype representing the concept of functional adaptability rather than shape adaptability, where multiple functions of manipulation are demanded to the gripper besides the grasp.

Besides changing the position and posture, it is often necessary to readjust the grasping mode of the object during the operation due to the environmental constraints or specific task requirements. For example, when an initial placement of the object cannot meet the requirement of assembly task, it needs to regrasp [11], when a single arm cannot complete the relevant work, it needs to cooperate with dual arms [12]. For specific objects and specific tasks, the common research idea is to solve individual problem through unique design of gripper's configuration or mechanism, multi-component collaborative algorithm, and accompany innovation in these processes.

For the similar research motivation, this paper focuses on the development of a unique robotic gripper, its relative solution for tool replacement in the field of tunnel boring construction, and the comparative experiments and verification for the feasibility of practical application. The following chapters are organized as: Chapter II introduces the application background of research and development, Chapter III gives an overall solution and detailed explanation on structure design, Chapter IV presents some relevant experiments and comparative analysis, and finally, Chapter V makes a conclusion.

II. The Background in Tunnel Construction Field

Shield machine is an indispensable automatic equipment in tunnel boring construction field. Influenced by the geological factors and others, the construction period of a single shield machine is usually calculated on a yearly basis [13], with an average tunneling speed about 10 meters per day as a reference. Shield machine uses tools (disc cutters) to cut

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off rocks and soil, which are installed on the front cutter head. Consequently, the wear of the cutters will inevitably result in the need of tool replacement. Up to now, such task still depends on a manual way [14]. Taking the 6.4m-diameter Herrenknecht's shield machine as an example, there are 36 tools installed on the front cutter head with certain alignment. Besides the 150kg heavy self-weight, every cutter is also installed into the relative cutter housing by means of bolt fastening method with accessory parts like washers and nuts. According to the procedure shown in Fig.1, three qualified diving personnel are required to enter the excavation chamber and operate cooperatively, and the time for replacing a disc cutter is about 6 hours.

Figure 1. Manual cutter changing procedure in excavation chamber

Because the tool replacement process directly exposes the personnel to excavation environment, there is high risk during this operation, and casualty accidents are reported constantly [15-16]. In addition, the efficiency of manual tool replacement is extremely low, which greatly affects the whole tunnel boring construction cycle. Therefore, it is imperative to exchange the cutters in an unmanned and automated way, and the task of grasping, disassembly, installation of the disc cutters is the first bottleneck to solve.

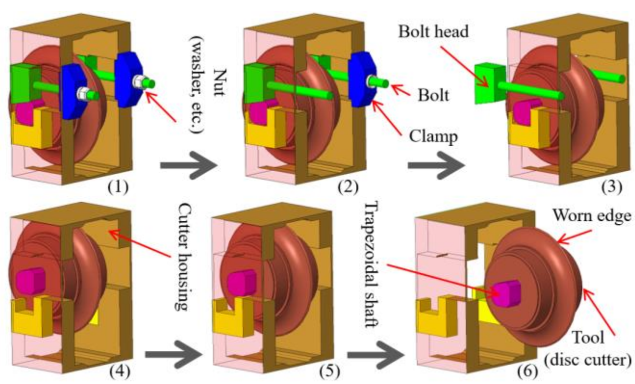

Figure 2. The disc cutter and housing, considered the disassembly

Fig.2 shows the detailed structure of the disc cutter and the cutter housing used in the process of manual tool replacement. The disc cutter is installed into the cutter housing by firmly tightening the nut & bolt, so that the side surface of trapezoidal shaft of the disc cutter is matched with the slope of the bolt head. This is to ensure that the cutting force (generally no less than thousands of Newton) and impact force between the cutter and rock will not cause the cutter to loosen or even fall off during the tunnel boring construction period. The sequence of manually disassembling the cutter is from Fig.2(1) to Fig.2(6): loosen the bolt, remove the nut washer and clamp, push the bolt in (left direction) to expose the trapezoid shaft, and remove the disc cutter out.

The challenge is how to figure out a specific structure to accomplish the automatic tool replacement. Mitsubishi Heavy Industries [17-18] of Japan has developed an overall cutter bit replacement system for large scale shield machines, and IHI Corporation [19] has invented a spherical structure cutter head, which is based on an overall improvement and structural redesign of the main body of the shield machine.

A French team redesigned the structure of cutter housing, and developed a TELEMACH robotic system [20], which was equipped with a Stewart multi-DOF parallel platform and a specific gripper to grasp the disc cutter [21]. In addition, a European consortium including 23 organizations launched a project named NeTTUN, and developed a 5 DOFs heavy duty hydraulic manipulator with a two-fingered gripper. The gripper was equipped with an interchangeable specific fixture, so that it was capable of clamping and locking the disc cutter. The motivation of the robotic approach is to make a reliable and practical design including the gripper and its surroundings, and a reasonable and efficient manipulation strategy to achieve the grasping and disassembly/installation of the tool through a procedure similar to manual operations.

The aforementioned attempts greatly modify the main body of the shield machine to meet the demands of automatic tool replacing operation, or change the structure of cutter housing, the installation method of the cutter, or increase the ability of automatic tool replacement by utilizing a novel robotic gripper and manipulator. However, the large scale transformation of the main structure of the shield machine requires more cost and development cycle. The partial improvement of the structure of cutter housing or installation method also has the disadvantage of poor generality, and may not be applicable to various types of existing shield machines (taking the Chinese market as an example, there are more than 3000 shield machines in service). Therefore, up to now, there is still no practical solution being applied to the actual tunnel boring construction.

In general, the previous challenges and efforts on the tool replacement can be summarized as follows.

1) The manual cutter installation & disassembly method shown in Fig.1 and Fig.2 is not applicable for automatic operation due to complex operations like screwing nut, installing and removing accessory parts (nut, washer, clamp, and so on). It must be simplified, or even avoided through a reasonable way, meanwhile ensuring a firmly installation.

2) It is preferable to minimize the modification to surrounding structures of the disc cutter as less as possible, especially to the main body of the shield machine, in order to save cost and time cycle, and to improve the feasibility to different types of existing shield machines.

3) There is no conventional gripper nor manipulator could be applied directly. The heavy payload, accuracy, installation complexity, and environmental constraints, all multiply the challenges for implementation. A novel and concise design of the gripper with its surrounding structure and an overall

manipulation strategy are expected firstly, by considering the essential functions of grasp, disassembly, installation, and fastening. Meanwhile, the efficiency, robustness and reliability of cutter replacement are also important towards partial structured environment.

III. Mechanical Design of Gripper and Surroundings

A. Brief Proposal

The primary goal of the automatic solution, including the structural design of the gripper, is to be simple, practical and reliable. Therefore, the essential functions of tool replacement operation can be divided into two categories: (a) grasping and holding, which can be realized by opening/closing the gripper; (b) installation/disassembly and fastening/release, which can be realized by other accessories or strategies cooperatively.

Fig.3 shows a schematic diagram of the principle of installation and tightening of the disc cutter into the cutter housing without using bolt and nut. Among them, Fig.3(1) shows the cutter housing, with the upper opening, where the disc cutter is installed or removed from. The inside structure is designed with a perfect circular hole, and the center of which is O_1. Fig.3(2) is a schematic diagram of a rotating block, which is composed of two perfect circular structures with a small gap between their centers, wherein the smaller circular center is O_2 and the larger circular center is O_3. The rotating block is installed into the cutter housing while the center O_2 coincides with O_1, so that the rotating block can be rotated with the O_2-O_1 axis. Fig.3(3) is a schematic diagram of the opening of the rotating block. It is to further explain that the trapezoidal shaft of the disc cutter can be put into the rotating block through this opening. After the installation of disc cutter, the rotating block can be rotated from a released state in Fig.3(4), through Fig.3(5), and then to a tightened state in Fig.3(6) by 180 degrees' rotation. A 180 degrees' rotation can generate the largest eccentric displacement on the locking zone. It can be seen in Fig.3(1) that there is a small plane structure at the bottom of the circular hole. When the rotating block reaches the position in Fig.3(6), it is tightened by the contacting pressure. Fig.3(4) ~ (6) explains the process from installation to fastening, while the inverse turn shows the process from releasing to disassembly.

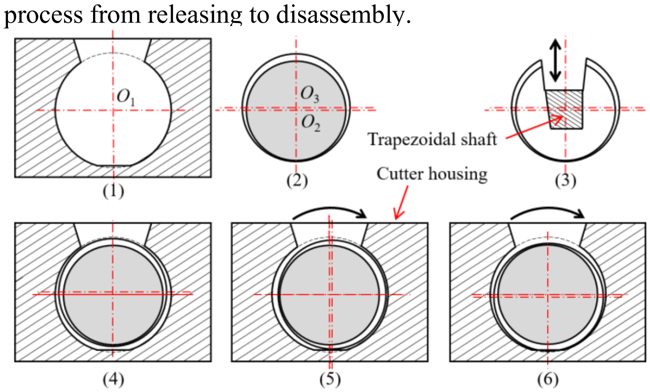

Figure 3. The proposal of installation and fastening

Although Fig.3 shows an integrated solution connecting installation and tightening, it needs a mechanism to perform the rotating action. In fact, this is essentially the adjustment of the object's posture. Therefore, we schedule a strategy using the motion ability of manipulator and the regrasping ability of gripper to perform the rotation cooperatively.

Referring to the traditional grab structure during manual tool replacement, the gripper is preferably an arc-shaped two-finger structure with a simple opening/closing function driven by one motor. In addition, according to the weight, shape, and installation method of the disc cutter, the gripper must grasp the cutter from its two sides respectively. As shown in Fig.4, the gripper is preferably designed with a symmetrical structure having four fingers, which can realize opening and closing synchronously by mechanism or control approach.

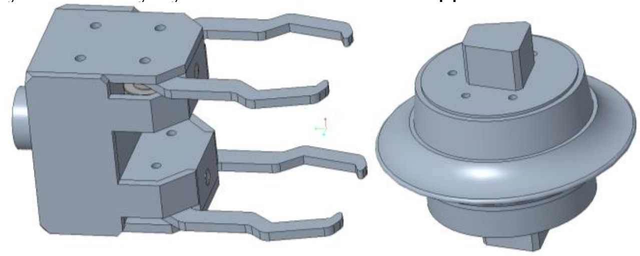

Figure 4. The proposal of gripper

B. Detailed Gripper Design

The appearances of the designed gripper and disc cutter are shown in Fig.5. The central part of palm is designed with a hollow structure to accommodate disc cutter. The 4 fingers of gripper are designed with an internal teethed structure. The both sides of the disc cutter are minimally redesigned with addition of side gear plates, in Fig.5(2). So that it can realize arbitrary posture grasping & holding through the meshing of teethed fingers and side gear plates, in Fig.5(3) and (4).

The front cameras and locating teeth are attached on both sides of the gripper. The cameras are to monitor the locating teeth and feedback the visual information during the grasping process. When the gripper approaches and grasps the cutter, the locating teeth will first get meshing with the side gear plate, so that the information is helpful to get a judgement by the control algorithm: need a further adjustment of the gripper's position and posture, or be sufficient to execute the grasping operation. The side cameras are used to get auxiliary visual information for the control algorithm to do further judgement.

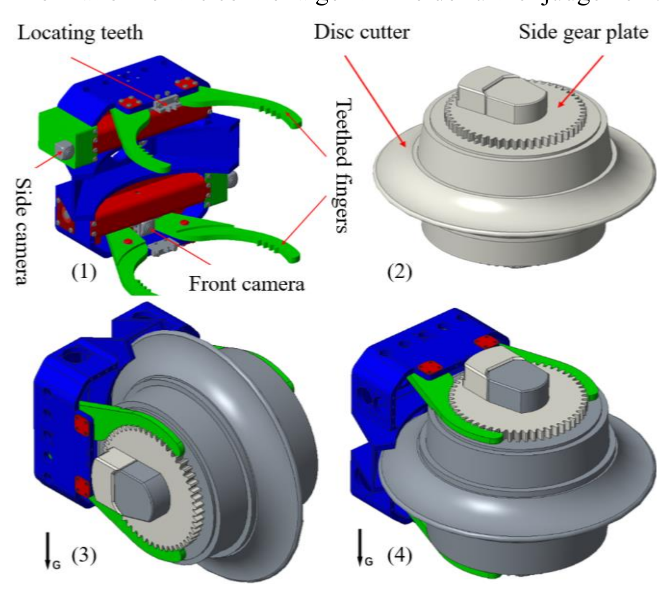

Figure 5. The 3D models of gripper and redesigned disc cutter

Four teethed fingers are divided into two pairs, each driven by a motor. The detailed design of each pair of fingers is shown in Fig.6. The motor power is transmitted through the gear train, which drives a left and right trapezoidal screw rod to rotate, so that the two screw nuts synchronously translate in an opposite inside or outside direction. Therefore, the joint ***A*** of a four-bar linkage mechanism ***A-B-C*** is driven to move oppositely, and finally the fingers in a pair will open or close synchronously.

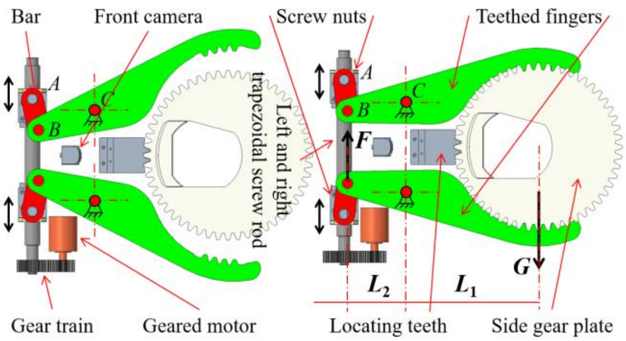

Figure 6. The detailed design of gripper

When the gripper is in the state as shown on the right side of Fig.6, that is, when the shaft of the disc cutter is held horizontally while the gripper is also in a horizontal posture, the gripper mechanism is in the state of stress limit. Consider the cutter is supported by the two lower fingers on both sides, the force ***F*** to every screw rod is calculated as Equation (1), where ***G*** represents the gravity of the cutter, ***L*₁** and ***L*₂** are the distances of the relative forces to the supporting joint ***C***.

$$F = 0.5G\frac{L_1}{L_2} \tag{1}$$

Considering a 150kg weight of the cutter and a sufficient design safety ratio, the parameters of the trapezoidal screw rod are finally designed with 20mm diameter and 4mm lead, and the two motors are selected each with 24V voltage and 100W power. The design enables a mechanical self-locking ability to ensure power failure safety due to the trapezoidal screw rod.

It is important to check the strength of gripper, especially check the postures shown in Fig.5(3) and (4). Fig.7 shows the simulation result with extreme situation. In design, the material of gripper's main framework is 7-series aluminum alloy, while teethed fingers and revolution joints are 45# steel.

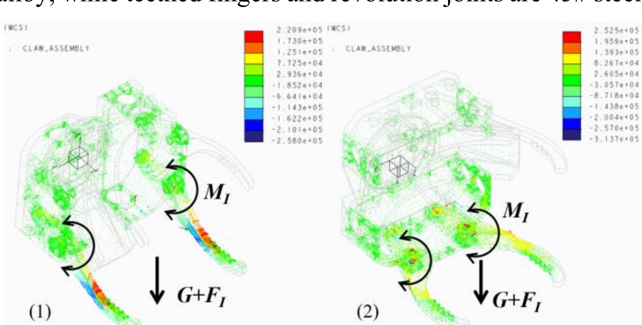

Figure 7. Stress simulation of the gripper with load

For the posture shown in Fig.5(3), the extreme load distribution is set as: the gravity force G=1500N, a same direction and same level impact force F_I=1500N with a bending moment M_I=200Nm in case of an unexpected collision, and assuming all the forces are received by the two lower fingers. This assumption is based on the motion speed of the gripper or manipulator is very low (several mm/s level), so that if a great quantity of impact force is generated, there is sufficient time to judge and stop the motion in the control algorithm. As shown in Fig.7(1), the simulation result shows that an extreme maximum value of the stress is no greater than 259Mpa.

For the posture shown in Fig.5(4), the extreme load distribution is set similar: the gravity force G=1500N, a same direction and same level impact force F_I=1500N with a bending moment M_I=200Nm in case of an unexpected collision, and assuming all the forces are received by the two lower fingers. As shown in Fig.7(2), the simulation result shows that an extreme maximum value of the stress is no greater than 314Mpa.

In summary, the maximum stress of the gripper's fingers is about 300Mpa level in each case, therefore, the design of using 7-series aluminum alloy is feasible, whose yield strength is greater than 500Mpa. The 45# steel is also sufficient as the material of fingers, revolution joints, and even the main framework since its yield strength is greater than 355Mpa. In the actual manipulation, the upper two fingers are also stressed, which will greatly reduce the stress concentration and improve the safety.

C. Cutter and Cutter Housing Design

Next, based on the analysis of Fig.3, the mechanical design of disc cutter and cutter housing is further refined. Although Fig.3 explains the principle of an unified tool installation and fastening process, there are still three problems: (a) how to solve the contradiction between the opening structure of the rotating block for tool installation and fastening while rotating; (b) how to ensure that the tool can be rotated 180 degrees in the predetermined direction and then be stopped; (c) how to ensure that the tool in the tightened state (Fig.3(6)) does not loosen due to the impact of external forces during excavation.

First of all, Fig.8 shows the detailed design of both sides of the disc cutter. In addition to refining the two perfect circular structures described in Fig.3, an auxiliary block is added at the shaft end, and, both the side gear plate and the auxiliary block are fixed onto the side of the disc cutter. After the cutter is installed into the rotating block, the cylindrical surfaces of the auxiliary block and the rotating block combine two perfect circular surfaces but with a small gap between their centers, realizing the fastening principle shown in Fig.3.

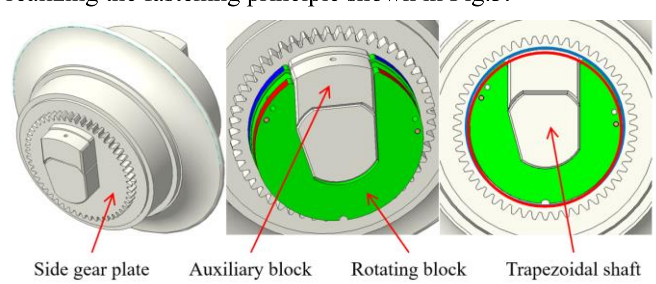

Figure 8. The detailed design of side structure of disc cutter

Fig.9 illustrates a solution for the aforementioned second problem. A clamp is used to help the installation of the rotating block. A stopper is designed on the inner surface of the clamp, and pins are installed on the rotating block (Fig.9(2) and (3)). When the cutter is installed, the rotating block can only be rotated in a clockwise direction shown in Fig.9(1), and will be stopped by the stopper after 180 degrees' rotation. At this state, a pressing force will generate between the tightening zone on the clamp and the auxiliary block to complete the tightening. The locating observers can be monitored by the front cameras, so as to confirm the tightened state in the control algorithm.

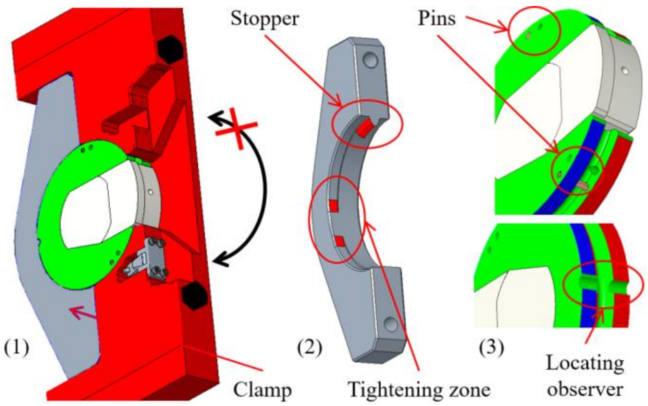

Figure 9. One-way rotation and stopper

The last, a locking mechanism shown in Fig.10 enables to limit the rotation of disc cutter. When the fingers of gripper are inserted into the cutter housing to grasp the cutter, the locking mechanism will be squeezed by the fingers and separated from the teeth of the side gear plates, meanwhile, the cutter can be rotated freely. But, after the fingers are away, the locking mechanism pops out under the action of springs, and snaps onto the teeth, so as to achieve the locking.

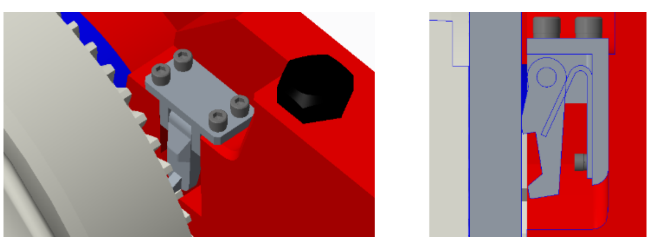
Figure 10. The locking mechanism

IV. Experiments, Algorithm, and Analyses

A. Basic Tests of grasping

It took 3 years for the whole project to develop a prototype of disc cutter changing robot. Fig.11 shows the newly developed gripper, the minimally modified existing disc cutter, and a temporary cutter housing for basic tests in the lab.


Figure 11. The developed gripper, disc cutter, and housing

Fig.12 shows some basic tests on the specification for the gripper, in which the manipulator carries the gripper at different posture for testing measurements. The stroke, payload, accuracy, meshing performance, and other related parameters of the gripper are checked and listed in Table 1. The verified payload ability is much greater than the mass of disc cutter, by considering an external impact force.


Figure 12. The verification of basic requirement for mamipulation

TABLE I. Specification of Gripper

Mass	21.5Kg	Payload	250Kg
Dimension	280×320×320mm	Stroke	200~265mm
Fingertip speed	8mm/s	Accuracy	1mm/s

Next, the performance of the locking mechanism is also confirmed. As shown in Fig.13, when the finger leaves, the locking mechanism pops up and snaps onto the gear teeth, thus preventing the cutter from rotating. After the finger is inserted, the locking mechanism is pressed in, so that the cutter rotates under the action of the gripper.

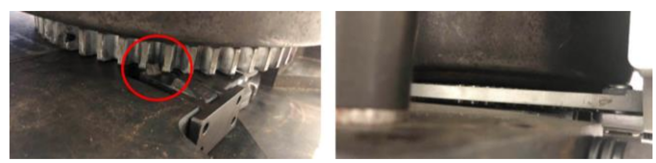
Figure 13. The verification of locking mechanism

B. Rotating, Regrasping and Posture Adjustment

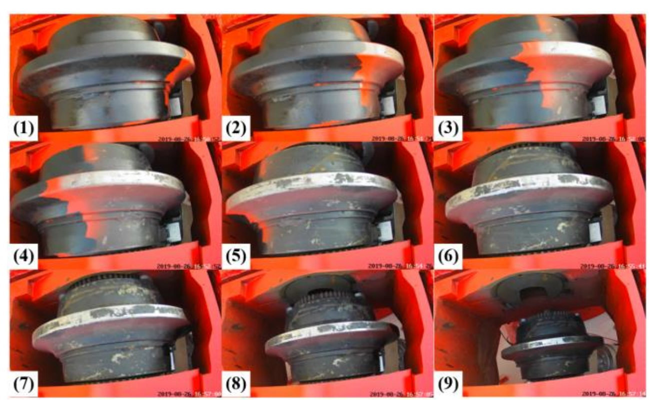

Figure 14. The rotating, regrasping and posture adjusting

The position and posture of housing and cutter are structural parameters, which can be obtained in advance but not accurate. Therefore, after the gripper is near to the relative cutter, precise positioning is achieved by the algorithm with the help of light and cameras. After confirming that the locating teeth on both sides of the gripper are meshed well with the relative side gear plates, the program will record this accurate grasping position and figure out the spatial coordinates of the cutter's rotation axis. The subsequent rotating and regrasping are based on this global coordinates, no need a further relocation.

Constrained by the structure of housing, each rotation can only be carried out in a relatively small angle range. Fig.14(1) ~(9) shows the video screenshot of disassembly of disc cutter. Starting from the initial grasping, it takes 9 times of regrasping for the whole 180 degrees' rotation, since every time can only complete an angle about ±10 degrees. The posture adjustment of the regrasping process is cooperatively executed by the inverse kinematics algorithm of the manipulator. The whole process takes about 7 minutes, of course, the regrasping during the installation process will take a considerable time.

C. Integrated Experiment with Shield Machine

The whole cutter changing robot was docked into the shield machine for an integrated experiment from April 2019. The experimental video and progress are released in September in same year. According to the order from Fig.15(1)~(9), the robot completes the whole process of disc cutter changing: moving out → adjusting posture → gripper meshing with the cutter →rotating, regrasping & loosening the cutter → removal the worn cutter & returning back → and inversely.

The whole process of replacing one disc cutter by robot is completed in 24 minutes. Compared with traditional manual cutter changing, which takes about 6 hours, the efficiency and safety have been greatly improved. The period of robot cutter changing can still be further improved by future optimization.

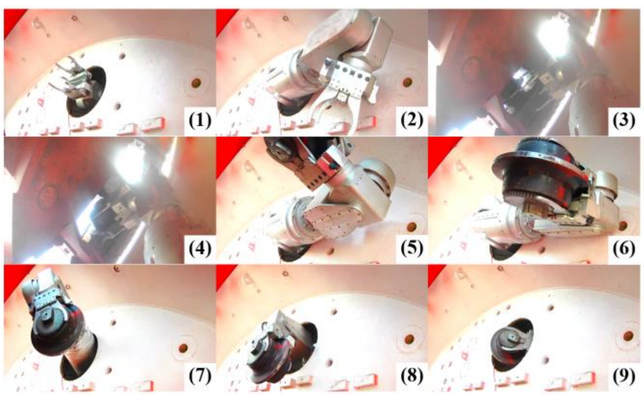

Figure 15. An integrated cutter changing experiment with shield machine

V. CONCLUSIONS

This paper discusses the issues of manual tool replacement faced by shield machine in tunnel construction, and introduces the current research regarding to the issues. It points out that the first goal to tackle them is to focus on simple, practical and reliable grippers, and a minimum modification of the housing structure and surroundings. The tool replacement task should be accomplished through a cooperative approach by flexibly operating the manipulator.

With this motivation, this paper presents a new gripper design and relative control strategy. The gripper is simple and compact, with a four teethed-finger synchronous opening and closing structure driven by two motors. It describes the unique solution of grasping, holding, rotating, fastening and locking by meshing the teethed fingers and the side gear plates. It also explains in detail the minimum modifications of the disc cutter and housing.

This is the first prototype of tool changing robot for tunnel construction developed in China. Through a large number of experiments, the performance of the gripper is validated in terms the payload, accuracy, locating, rotating, disassembly, and locking mechanism. Moreover, through the experiment of tool replacement in the actual shield machine, the efficiency and safety are confirmed.

To expand this work, the authors will further solve the generality problem, form the design criterion and quantifiable parameter index, and make the cutter changing robot of shield machine enter the standardization stage, in order to be applied in the industry as soon as possible.

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