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Design and Implementation of Disc Cutter Changing Robot for Tunnel Boring Machine (TBM)

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***Abstract* — Although Tunnel Boring Machine (TBM) is a well-developed semi-automated equipment for infrastructure construction, it still needs manual operation such as disc cutter changing task. There is still no practical solution answering the arising accident reports of injury or death during the manually underground cutter changing process around the world. In this paper, we first analysis the current situation and key problems preventing the implementation of automatic cutter changing operation. Then, describe a proposal with detailed consideration solving several main challenges, such as a narrow but long path versus large working space and large payload in the existing TBM, complicated environmental information that is difficult to obtain, such as dark, high pressure, mud and rust. In the finally part an implementation, test, and discussion are carried out to verify the feasibility of this first prototype.**

Index Terms – TBM, robot, cutter changing, shield machine, tunnel construction

I. INTRODUCTION

THE TBM has already developed more than 60 years [1]. It is a typical semi-automated equipment that plays a very important and indispensable role for tunnel infrastructure construction. As one of the key components, the disc cutters (tools) get inevitable wear during continuous cutting process directly with soil or rocks [2]. Associated with the wear, inspection, maintenance, and changing processes take up more than one third time of whole construction, the cost also exceeds one third from the total [3]. More seriously, most of the inspection and changing tasks must be carried out manually underground, where the operators have to suffer the problems of high pressure, under water, mud, dangerous gas, boring face collapse, etc. Many accidents have been reported either physically injury or even death in the world [4, 5].

Many companies and scholars have already devoted to the research of decreasing tool wear, maintenance time and cost [6-8]. In addition, some have announced and discussed great trials that using automatic or robotic approaches to inspect even change the disc cutters. KAJIMA Corporation [9] gave a survey of cutter changing situation and reported that automatic approach is an inevitable direction in near future. Mitsubishi Heavy Industries [10] redesigned the TBM in large scale, and invented a cutter bit replacement system naming *Trail Method* [11]. IHI Corporation [12] invented a bit replacing technique by utilizing spherical structure bit head. Instead of seeking structural improvement of cutter bit or cutter head, the research institutes in Europe and America have been focusing on the cutter changing technologies by introducing advanced equipment or robotics [13]. Scholars in France proposed a scheme by using tele-operated articulated manipulator, and suggested that the manipulator should have 5 degrees of freedom with 2m reach and 300kg payload ability at least [14]. Telemach system [15] gave a cutter changing demonstration by using KUKA's industrial manipulator with a special designed end effector, and confirmed the process in an open environment but not underground.

However, even the aforementioned researches become more and more active, few of them has successfully been employed into practical application due to complicated environmental situation and working conditions. Herein, we summarize the key difficulties for cutter changing task.

1). The requirement of automatic cutter replacement is arose after the traditional TBM, which is designed based on manual replacement and is still in service. The path for operators (also, must for a robot) to get through is very long and narrow, but the working space is relative large. In the Herrenknecht's 6.4m diameter shield machine, for instance, the dimension of that path is with 3m length and 0.6m section diameter, while, the working space is about 1.4m width with about 6.4m section diameter. A robot system must be designed in a total different way with sufficient degrees of freedom and payload ability, and proper configuration.

2). The robot is worked in a semi-structured environment, where the model of TBM, the relative orientation of robot, the coordinates of cutters, gates opening/closing, is well known by the control system. However, the unstructured parameters, such as working pressure, wear rate, rustiness, visibility, greatly affect the performance of cutter replacement.

3). The working procedure is complicated. As shown in Fig.1, the operators must perform loosening/tightening the nuts, move/insert the hub, besides the cutter changing task itself. In addition, the operators have to open/close the gates. Therefore, an optimized and feasible design of the robot, especially the end effector must be carried out, by comparing the main difference between manual and automatic replacement. It is necessary and helpful to partially redesign the surrounding structure of TBM, but a minor modification is obviously desired.

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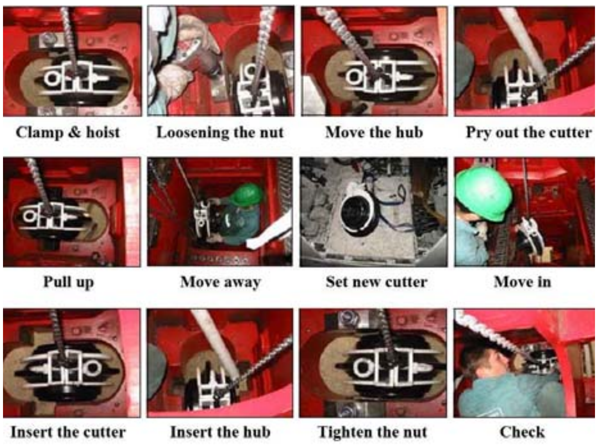

Figure 1. Manual cutter changing procedure

4). A teleoperation control system is prefer but not a fully automated one [16]. In addition, as suggested by French scholar Sebastien Rubrecht, a suitable control system for cutter replacement must be equipped with adaptability, robustness, multi-function, and real time features [13].

The later part of this paper gives a proposal of articulated manipulator that is possible for cutter changing, then explains our solutions answering several main challenges, such as the working space and payload problem, the semi-automated cutter changing procedure problem, and safety problem. After that, an implementation and test of the prototype is discussed. Finally, a conclusion is given.

II. Proposal And Analysis

A. Proposal of Geometric configuration

Herein, we take the Herrenknecht's 6.4m diameter shield machine as an example to illustrate the design issue. Fig.2 shows a planar section sketch of the front portion of TBM where the robot goes through the ***path*** and perform the cutter changing task at ***working space***. An articulated manipulator is desired so that it can be stored in the ***path*** occupying a minimum space and be extended to reach the five disc cutters in front and work there.

A TBM usually has dozens of disc cutters in its cutter head, but it is sufficient for the robot to change the five cutters only in one o'clock direction, as shown in Fig.3, associated with

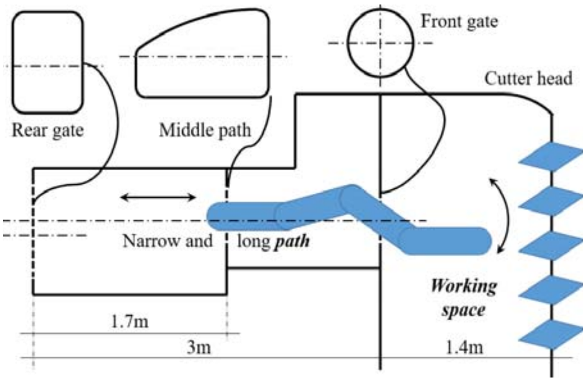

Figure 2. ***Path***, ***working space*** and robot reach

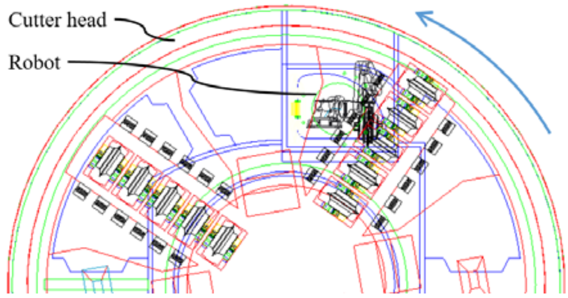

Figure 3. Cutter head and robot

the rotation of cutter head.

As shown in Fig.4, we propose a 6 degrees of freedom (DoFs) articulated manipulator installed onto a 2 DoFs translation stage, with a 1 DoF gripper attached at the end of the manipulator, totally 8+1 DoFs. ***Axis*** 1 to ***axis*** 6 are with orthonormal and almost equidistant configuration. None of the linkage is allowed much longer than others since the manipulator has to go through the ***path***, especially from the front gate entering the ***working space***.

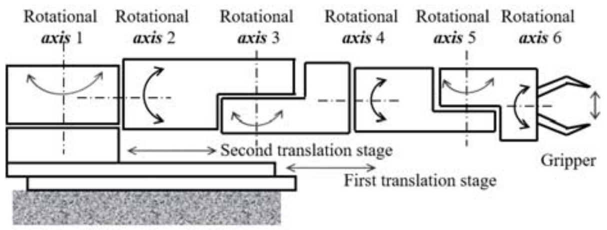

Figure 4. The proposal of articulated manipulator

The 2 DoFs stage provides same moving direction and long stroke but short storage length, making the whole system is possible to be installed into an existing TBM, without much modification. The second translation stage is design with the pinion and rack, which support fast separation of the translation stage. The 6 DoFs manipulator can be withdrawn from ***path*** through the rear gate.

B. Minimum modification of TBM

Both the ***path*** and gates (shown in Fig.2) are designed and manufactured for the operator to go through but not a robot, therefore they are not with a fully structured aspect, nor electric features. Therefore, firstly, it is necessary to perform a mechanical modification of the ***path*** to meet the basic requirement of automatic control.

In a teleoperation system that persons are not in front of the working spot, when the robot is ready to perform a specific task, the gates should also be controlled open or close automatically. Consequently, it is also necessary to carry out an electrical modification.

Usually, there is 3 to 5 atmospheres in the ***working space*** underground. Before the front gate is open, the atmosphere in the ***path*** must be readjusted to drop the gap. The electrical part should also be powerful to resist the pressure.

It is also necessary to modify a minimum structure of either the cutter head or disc cutter, in order to meet the automated requirement. The cutter changing procedure in Fig.1 is not

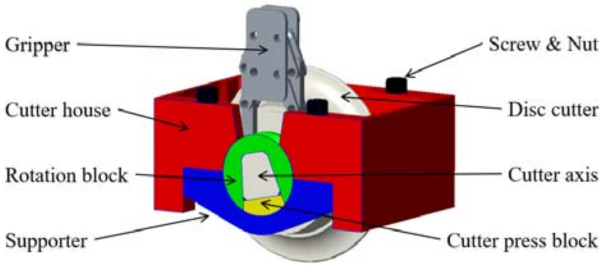

Figure 5. A design concept of rotation method

suitable for a robot, because a single gripper cannot handle many kinds of parts, such as nuts, hub, and cutter.

C. The gripper and disc cutter

Simplicity and robustness are the most optimal issues in end effector design. Therefore, we decide to use a single DoF gripper (hold/release) to finish the cutter changing task.

Instead of using screw and nut to loose/tighten the disc cutter, we use a rotation method to unlock/lock it. Fig.5 shows a design concept of the rotation method, where a disc cutter is locked into the cutter house initially. A cutter press block is attached and fixed onto the cutter axis, and a rotation block is attached (but not fixed) around the cutter axis. The rotation block together with the cutter press block combine a cylinder-like assembly (*co-axis*). Screws and nuts are used to tighten the supporters to the cutter house, so that the cutter house together with the supporter form a hole with perfect circle.

The *co-axis* assembly is designed exactly a cam-like outer shape with two layers in its axial direction, as shown in Fig.6. Both the two layers are with almost same diameters with the hole, but a little bias (Δ) in their centers. With this cam-like structure, the *co-axis* assembly will be locked into the cutter house when rotated by the manipulator.

Consider a simple gripper holds the *co-axis* assembly to rotate, as shown in Fig.5 and Fig.7, similarly with the nut screwing motion. Together with the *co-axis* assembly, the disc cutter is finally rotated from Fig.7 (a) to (e), from a locked position to unlocked position, where the disc cutter (with the fixed cutter press block) is ready to remove through a specially designed path in cutter house.

During the whole procedure, it is unnecessary to loose or re-tighten the nuts. The motion demanded to a gripper is to grasp and hold. The rotation is provided by the manipulator. The design concept is feasible since it simplifies the cutter changing task into two simple motions (grasp and rotation), and effectively utilizes the manipulator's ability.

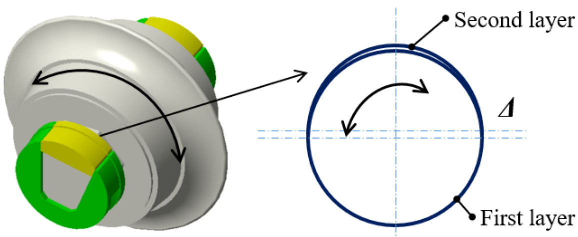

Figure 6. A cam-like co-axis assembly with small eccentricity

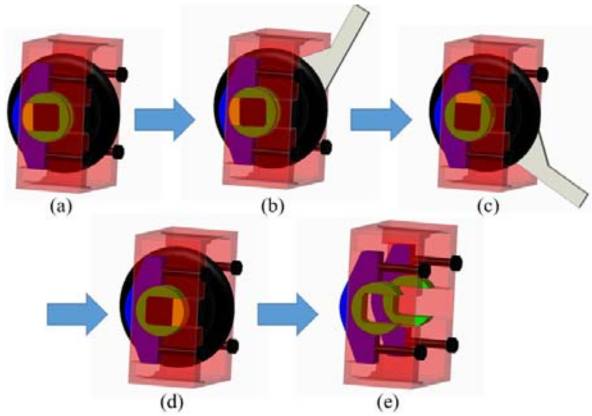

Figure 7. Automatic cutter changing procedure

This design extremely utilizes the existing structures of the disc cutter and cutter house. The minor modification does not affect the manufacture much.

D. Tele-operated control and auxiliary sensor system

As aforementioned, we propose a teleoperation system to control the redundant DoFs manipulator, and a sensor system to handle the complicated environmental information and auxiliary tasks. Multi-functional sensors (CCD cameras, humidity, pressure, temperature, et al.) are necessary and helpful to inspect unknown situation. In addition, lights, water gun, a compact high-pressure water cutting knife are also expected to be equipped onto the manipulator solving the darkness, mud and rustness problems.

Our goal is to implement a semi-automated control system that is capable of performing automated programs when the manipulator is doing a pre-determined motion in structured environment. In this case, the tele-operator can get helpful relaxing time, and the operation efficiency and safety are also enhanced. However, when the robot is handling unstructured problem, the tele-operator must execute a careful and skillful operation with sufficient feedback information from the sensor system.

We propose an EtherCAT bus configuration in the control system with less wiring problem and larger bandwidth. All the control signals and feedback information are hung onto the bus. In addition, the manipulator is designed with hollow axis structure, so that all the electrical cables are able to go through from its center.

Following the EtherCAT bus and hollow axis consideration, it is possible to realize a full sealing mechanical structure for the manipulator by considering the aforementioned 3 to 5 atmospheres working pressure underground. Especially, it is a very challenging design issue when the manipulator is working under an alternating working pressure between ordinary and high pressure.

III. Implementation And Tests

A. Ayalysis of the load

The load of whole system includes the gravity of the disc cutter, the force to install the disc cutter and torque to rotate the cutter. The force to install cutter is to push the disc cutter into cutter house or drag it out. The external force need to overcome during the install process includes collision force, friction or extra force to drag cutter when there are rust. The magnitude of collision force or friction depends on actual operation. If operator control the robot to install the cutter with bad posture or position, the force will be large. Inversely, the force can be decease to zero in ideal install posture and position. The extra force used to drag the cutter when there are rusts between cutter and cutter house is empirical data. According to the manual cutter changing procedure, maximum value is about 2kN.

There are bearings between the cutter blade and cutter shaft. The cutter will suffer the force about 200kN caused by rock [17] when the TBM is tunneling. This force is transmitted to the rotation block and cutter house. In working state, the friction between the rotation block and cutter house is static friction. The torque that the rotation block needs to overcome to rotate is much greater than the torque transmitted through the bearing, which means the requirement of pre-tensioning torque is low. The pre-tensioning torque is determined by the final extrusion force between cutter press block and supporter when the cutter achieve the locking position. By adjusting the gap between supporter and cutter house, the pre-tensioning torque can be adjusted.

The gravity of a disc cutter is about 1.5kN. It is appropriate to design the payload of an end effector no less than 3.5kN by considering a sufficient redundancy for reaction force from environment in task and other uncertainty. To consider the situation that the cutter has rust, the translation stage is designed to be capable of providing 2kN drag force.

B. Hardware system

Fig.8 shows a sketch of the hardware system. The core hardware includes the upper computer and the lower computer. The user interface is on the upper computer and the operator can control the robot system by the upper computer. The main control algorithms and real-time control system are responsible by the lower computer. By using Socket between two computers with internet cable, the system supports teleoperation.

The upper computer is set outside the ***path*** ensure the operator can avoid suffering the high air pressure or other risks. The video information from cameras install in the whole system is collected by the video collector and it is used to provide information to monitor robot situation and help operation.

The lower computer is installed in the electrical cabinet, which is beside the robot. The lower computer and servo drives support EtherCAT bus, which makes the layout of drives more flexible. The drives are designed in the body of the robot and connect each other in series. Each drive is near to its corresponding servo motor, which improves the control stability and performance. The lower computer has the digital signal output and can be used to control switch signals, such as the gripper, lights and motor brakes.

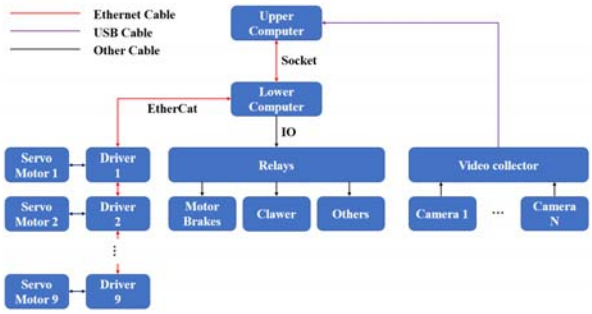

Figure 8. A sketch of the teleoperation system

C. Control of the redundant robot system

In the process of mathematical modeling, 2 DoFs of the translation stage can be consider as 1 DoF (d_0). With the 6 DoFs articulated manipulator (θ_1, θ_2, θ_3, θ_4, θ_5, θ_6), the robot will be regard as the 7 DoFs redundant robot system. By using the Modified D-H Method [18], the establishment of coordinate system is shown as the Fig.9.

The forward kinematics T_F can be calculated by (1). ${}^{i+1}_{i}T$ is the homogeneous coordinate transformation matrix of each axis and ${}^{T}_{7}T$ is the homogeneous coordinate transformation matrix of the end effector.

$$T_F = {}^{1}_{0}T\,{}^{2}_{1}T\,{}^{3}_{2}T\,{}^{4}_{3}T\,{}^{5}_{4}T\,{}^{6}_{5}T\,{}^{7}_{6}T\,{}^{T}_{7}T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The structure of the robot conforms to configuration that the axes of last three axes (θ_4, θ_5, θ_6) converge at one point, which means the robot has the analytical solution. The inverse kinematics can be calculated by analytical method [19]. To find the solution make T_F equal to T_T (the target matrix), make the matrix transformation as (2) shows.

$${}^{2}_{1}T^{-1}\,{}^{1}_{0}T^{-1}\,T_F\,{}^{T}_{7}T^{-1} = {}^{2}_{1}T^{-1}\,{}^{1}_{0}T^{-1}\,T_T\,{}^{T}_{7}T^{-1} \tag{2}$$

The elements of the matrix in both side of equation should be equal and the three position elements only includes four variables of axes (d_0, θ_1, θ_2, θ_3) as (3) shows.

$$\begin{cases} A\times C_1 + B\times S_1 = -d_4 C_2 S_3 \\ -A\times S_1 + B\times C_1 = d_2 + d_4 C_3 \\ C = d_4 S_2 S_3 \end{cases} \tag{3}$$

A, B and C can be calculated by (4); $\sin\theta_i$ and $\cos\theta_i$ are recorded as S_i and C_i; d_1, d_2, d_4 and d_7 are the constant

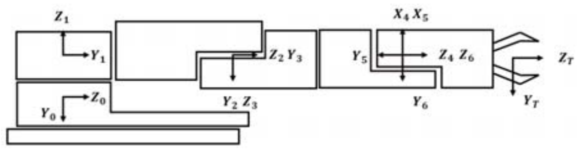

Figure 9. Establishment of coordinate system

of D-H parameters; p_{tx} , p_{ty} , p_{tz} , a_{tx} , a_{ty} and a_{tz} are the elements of the T_T which are known value.

$$\begin{cases} A = p_{tx} - d_7 a_{tx} \\ B = p_{ty} - d_7 a_{ty} - d_0 \\ C = p_{tz} - d_7 a_{tz} - d_1 \end{cases} \tag{4}$$

To calculate the sum of the squares of three equations in (3), the equation which only includes two variables of ***axis*** (d_0 , θ_3) is shown as (5). When the d_0 or θ_3 is determined, the rest three variables can be calculated by the analytical method by (3). Further, the other three variables (θ_4 , θ_5 , θ_6) can be calculated by rotation elements in the matrix in (2).

$$A^2 + B^2 + C^2 = d_2^2 + d_4^2 + 2d_2 d_4 C_3 \tag{5}$$

So, the strategy to get the solution is to choose the different d_0 and then calculate the rest variables. Finally, the best group of solutions of seven variables is selected by the penalty function which considers the variation, continuity, limitation, collision and other factors.

D. The best replacement position for each cutter

There are five disc cutters install on the cutter head at different position. The cutter head can rotate and stop in a certain angle to do the auto cutter changing. The reachable workspace of the robot system is limited. For each cutter, to realize locking or unlocking the cutter by rotating the cutter by the manipulator, the robot system should have ability to catch the cutter and rotate it with a certain angle for several times without any collision. The main possibility of collision is between robot body and front gate during rotating the cutter. It is necessary to find a best replacement position of each cutter to ensure the robot can finish this action.

This problem includes 8 variables: the angle of the cutter head (θ_{CH}) and 7 variables of redundant robot system(d_0 , θ_1 , θ_2 , θ_3 , θ_4 , θ_5 , θ_6). To ensure the rotation without collision, three target matrices (left and right rotation limitation position and middle position) should be checked for each potential cutter changing position. The range of θ_{CH} can be limited between −30° and +10° as the Fig.10 shows, because the front gate is bias.

The genetic algorithm is an effective method to solve different kind of problems by suitable design of fitness function. Application of the genetic algorithm can find the best replacement position for each cutter. In this problem,

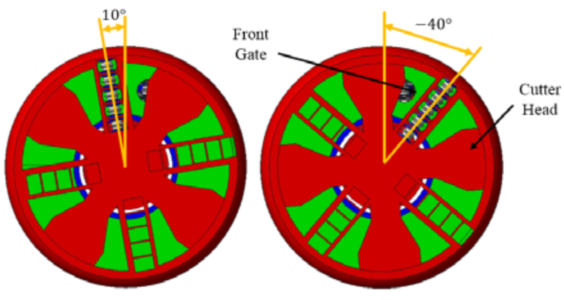

Figure 10. Rotation range of the cutter head

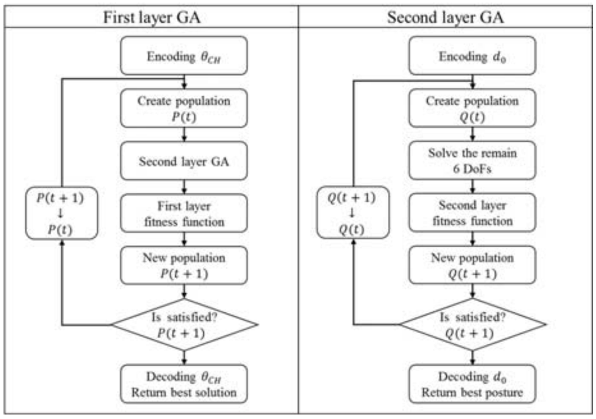

Figure 11. Logic diagram of double genetic algorithm

using genetic algorithm to solve 8 variables directly is undesirable because the feasible range of θ_{CH} for each cutter is narrow which will cause a lot of unnecessary calculations. Further, the solution of 7 variables of robot system can be calculated by analytical method or other method which is more fast than genetic algorithm. To improve efficiency, the double layer genetic algorithm is applied to solve this problem and the logic diagram is shown as the Fig.11. The first layer is to use to find the best θ_{CH} for one cutter and the second layer is to use to find the best posture according to the target matrix.

In the second layer GA, because the remain 6 DoFs can be solved by the analytical method in chapter III-C when the d0 is determined, to find the best posture is to find the best d_0 . Because the ***axis 1*** and the axis of the front gate are designed the same vertical plane, collision possibility can be reflected by θ_1 when the robot is through the front gate and at the front of the ***path***. θ_1 is more approach to zero and the collision possibility is lower. The fitness function of second layer is to find the posture which θ_1 is closest to zero.

In the first layer GA, the best posture of the robot for each of the three target matrices at one θ_{CH} will be calculate by second genetic algorithm. The fitness function of first layer reflects comprehensive evaluation of the three postures. Only all three best postures exist at the same time and each posture has no collisions, the fitness value of individual will be higher.

The double genetic algorithm is applied on each cutter and get the best solution of θ_{CH} to ensure cutter changing is feasible. As the Fig.12 shows (the third cutter), the result is θ_{CH}=4° and the robot realizes the rotation without collision at this situation.

E. Process of the teleoperation

To realize the faster and more convenient cutter changing, the whole process of the cutter changing is divided in to automatic program part and manual operation part.

The processes of the robot pass through the ***path***, the front gate and arrive the front area of the target cutter are designed as automatic program, which are complex but fixed.

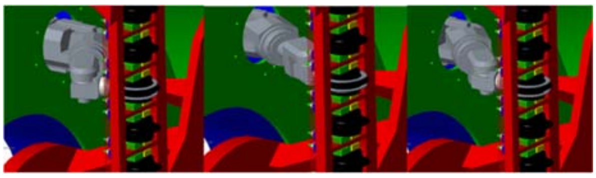

Figure 12. Three postures of the third cutter at θ_{CH}=4°

When the gripper arrives the catch ready area, the robot will be operated manually to catch the cutter because the actual position of the target cutter exist inaccuracy causing by the low accuracy of the rotation of cutter head. The operator should control the gripper move to the correct position to catch the cutter by video information from cameras installed on the gripper.

After the gripper catch the cutter, the actual position of the cutter can be recorded and the rotation trajectory to lock or unlock the cutter can be created. The remain processes are designed as automatic program part when the actual cutter position is known, such as robot rotating cutter, returning the ***path*** with cutter, installing the new cutter and locking cutter.

F. The test in simulated experimental environment

To realize the test, a simulated experimental environment is built, which simulates the internal environment of the TBM in equal proportion. The experimental environment simulates the corresponding structure of the ***path*** and front gate. The position and posture of the cutter house are same with the situation in actual TBM.

In this experimental environment, the whole process of the cutter changing is tested. The process of catching cutter was finished by the operator and the other processes are finished by the automatic program. The main processes of uninstalling and installing the cutter are shown in Fig.13. The whole process was finished without collisions and other problem. This test preliminarily verifies the feasibility of the design.

IV. CONCLUSION

The prototype of automatic cutter changing robot indicated that the design of the 6 DoFs articulated manipulator with 2 DoFs translation stage is capable of finishing complicated actions in the TBM limited working space. The rotation method to loose\tighten the disc cutter is also verified in the test and this design increase simplicity and robustness of the automatic cutter changing.

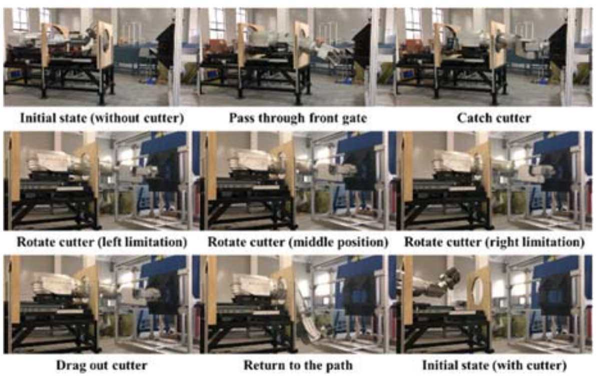

Figure 13. Main processes of automatic cutter changing test

By the hardware system that support tele-operated control and the corresponding control algorithms of redundant robot, an operator can control the whole robot system to finish the whole process of automatic cutter changing safely by the upper computer.

The further tests will be carried out on the actual TMB and the improvements will be made according to tests. We believe that the robot system will gradually realize the automatic cutter changing and decrease accidents caused by cutter changing. In the future, the robot system will consider to be compatible with more different TBMs and make contribution to improve degree of the automation of TBM.

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