Development of inspection and replacement robots for excavation tools of Tunnel Boring Machine (TBM)

Huayong Yang[1,2], *Cheng Wang*[1,2], *Haibo Xie*[1,2]

1 State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou, China

2 Institute of Advanced Machines, Zhejiang University, Hangzhou, China

Abstract.

The cutterhead of a tunnel boring machine (TBM) operates in a confined, high-pressure, high-humidity environment where manual inspection and replacement of excavation tools is risky and time-consuming. To enable robotised maintenance, we developed a TBM inspection-and-replacement system composed of a snake-like inspection robot and a heavy-load disc-cutter replacement robot. For inspection, a compact cable-driven snake robot is designed to work at pressures up to 2 MPa and temperatures up to 65 C, integrating cleaning, lighting, and zoom imaging to achieve high-precision tool wear assessment. For replacement, a 6-DOF PRRPRR manipulator driven by electro-hydrostatic actuators (EHAs) is developed for heavy-load, constrained-space operation. A position-pressure feedback control (PPFC) method is proposed to improve the system response and position accuracy. Field deployment on the 'Pioneer II' TBM in the Shenzhen Airport metro project validates the robustness and effectiveness of the system.

Keywords. TBM maintenance robots; snake-like inspection robot; disc cutter replacement; electro-hydrostatic actuator; trajectory planning; adaptive control.

1. INTRODUCTION

Urban rail transit expansion and large-diameter tunnel construction have led to a sharp increase in TBM usage. Disc cutters on the cutterhead suffer severe wear and damage due to rock-breaking loads, and their condition directly affects excavation efficiency and safety.

In deep-buried and high-water-pressure projects, manual inspection and replacement require working under high pressure, poor visibility, and muddy conditions, which introduces significant safety risks and long downtime. Engineering statistics report that tool inspection and replacement can occupy a substantial fraction of the excavation schedule and a large share of project cost, while a large proportion of TBM-related accidents are associated with manual cutter maintenance.

Robotised maintenance is therefore essential to reduce human exposure and improve machine utilization. A complete system must provide reliable inspection, accurate wear assessment, and safe replacement in a confined environment, while coordinating with the TBM control architecture.

Recently, research institutes and companies worldwide have started to develop robotic systems for cutterhead inspection and tool replacement to overcome the limitations of manual in-chamber operations and to move toward robots instead of humans. Herrenknecht has developed an auxiliary cutter inspection robot [1]. The main body uses a folding arm, with lighting, a camera, and a high-pressure water device at the end, plus an industrial endoscope that can pass through the cutterhead to observe tools; the system is still under development. OC Robotics built a snake-like inspection prototype, JetSnake [2], and tested it in the Port of Miami and the Hong Kong International Airport projects. Public information indicates that their tests were performed only at atmospheric pressure, without reliability validation under high-pressure and high-humidity conditions [3]. The University of Tokyo designed a cutter inspection robot for a 5 m class TBM, WInBot [4], with a telescopic structure [5] that can extend 2.7x vertically and 1.5x horizontally, enabling operation in narrow spaces around the cutterhead. However, its limited DOF allows inspection in only one direction, and no field application has been reported. CREG invented a shield machine inspection robot system [6] using a telescopic design to wash and inspect cutters. CSIC Haiwei Zhengzhou High-Tech Co. proposed a snake robot for shield inspection [7] that remains at the proof-of-concept stage. Beijing Institute of Petrochemical Technology developed a folding-arm cutterhead cleaning robot [8] that can clean cutters with a high-pressure water gun and observe the excavation chamber, but it did not address the complex soil chamber environment and has limited obstacle avoidance, with no follow-up development. Shanghai Jiao Tong University studied a snake-arm inspection robot [9], but the work remains at simulation level and does not consider the high-pressure and high-humidity TBM soil chamber.

The earliest exploration of robotic cutter replacement was by Bouygues, which launched the TELEMACH project in 2007 with funding from the French National Research Agency. After years of development, TELEMACH was demonstrated in June 2015 during the Tuen Mun to Chek Lap Kok tunnel project in Hong Kong using a 17.6 m diameter Herrenknecht TBM. The TELEMACH replacement robot is based on a KUKA KR FORTEC industrial robot with 500 kg payload and a dedicated end effector for cutter replacement. The main contribution was a new cutter system for robotic replacement and supporting tooling for cutter assembly and disassembly. However, because a standard industrial robot was used, the system is large and poorly suited to confined spaces; it can only be installed on large-diameter TBMs and is not applicable to small-diameter machines [10-11]. Shanghai Hongrun Construction Co. and the Shanghai University Robotics Institute developed a multi-DOF manipulator in which a six-DOF arm is mounted on a three-DOF linear track. All joints are motor-driven and the end payload exceeds 200 kg [12-13].

This paper consolidates the design and validation of a complete inspection-and-replacement robot system for TBM cutterhead maintenance. The system integrates a snake-like inspection robot for cleaning and visual inspection, and a heavy-load replacement robot for cutter swapping. We present the mechanical design, workspace planning, kinematics and dynamics modeling, EHA-driven control strategies, and laboratory/field verification.

2. SYSTEM ARCHITECTURE

The TBM robotised maintenance system consists of: (1) a snake-like inspection robot responsible for cleaning and imaging cutter tools, and (2) a heavy-load replacement robot for removal and installation of disc cutters. The inspection robot provides real-time assessment of cutter wear and damage, supporting maintenance decision-making, while the replacement robot executes planned trajectories to swap cutters through the access gate.

The workflow of the TBM robotised maintenance system is shown in Fig. 1. Embedded tool sensors monitor cutter condition online and provide preliminary fault locations. The supervisory computer decides whether in-chamber inspection is needed. If required, the inspection robot enters the chamber, moves near the target cutter, cleans it, and performs visual inspection. Based on the visual results, the system decides whether replacement is necessary; if damage is confirmed, the replacement robot enters the chamber to swap the cutter.

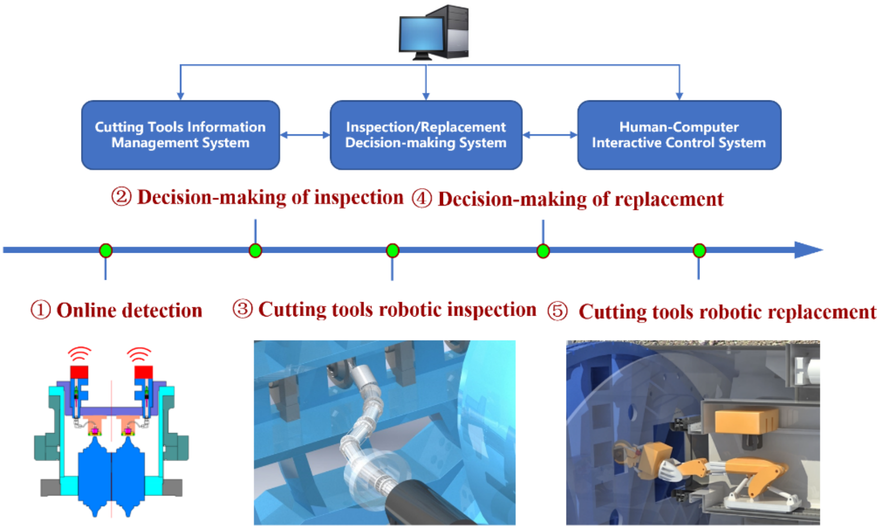


Fig. 1 Workflow for TBM cutter inspection and replacement

3. SNAKE-LIKE INSPECTION ROBOT

The snake-like inspection robot is cable-driven and segmented to enable long reach and high dexterity. Actuators are located in the rear module to avoid direct exposure to high pressure and water. The front section integrates a cleaning module, lighting, and an industrial zoom camera for in-situ inspection.

3.1. Inspection Coverage and Key Parameter Design

To support installation and testing on a TBM, we cooperated with CREG to design an inspection-robot prototype for a 6 m diameter EPB shield. Because various devices are installed behind the bulkhead of a typical 6 m EPB TBM, there is no extra space for a robot cabin. After discussions with CREG engineers, the available cabin space was determined to be a cylinder 600 mm in diameter and 2600 mm in length, as shown in Fig.2. The cabin center is 2207 mm from the TBM center, and the line connecting the two centers forms a 31 deg angle with the horizontal.

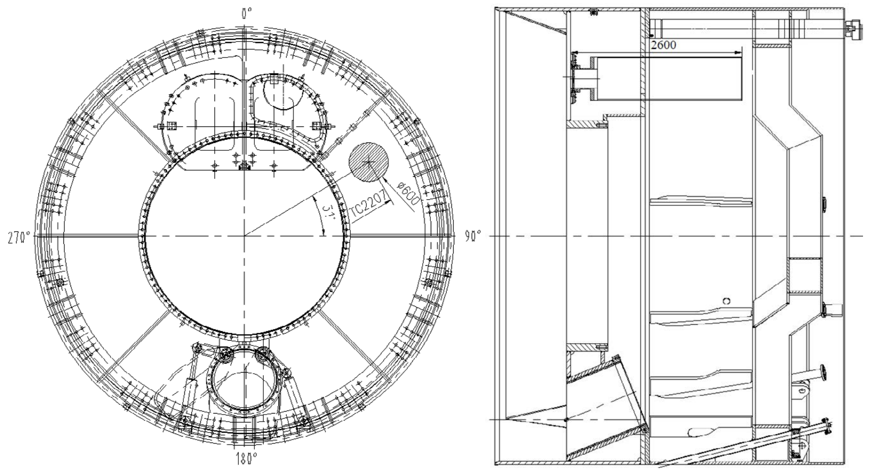


Fig. 2 Installation space of the inspection robot cabin in a 6 m class TBM

The snake-like inspection robot consists of a manipulator section and a drive module. The arm length determines the inspection reach, while the drive module length limits the maximum cable displacement and thus the joint angle range. To maximize inspection coverage within the limited installation space, we analyzed the robot's motion envelope inside the sealed chamber, obtained the maximum cable displacements in the drive space, and determined the screw stroke accordingly. This process finalized the key parameters of the snake robot.

Each joint of the snake robot has two degrees of freedom and can bend in arbitrary directions. Therefore, its workspace is symmetric. By analyzing planar motion, the maximum inspection range inside the TBM can be determined. Fig. 3 illustrates the workspace analysis of the snake robot in the XOY plane. The origin O is at the cabin door center and is 2207 mm from the TBM center. The Y-axis is aligned with the robot's centerline and points toward the cutterhead; the X-axis points to the cutterhead center. The distance from the cutter back edge to the bulkhead (along the X-axis) is 1300 mm. The wrist joint is denoted as a_n and the end link as a_{n+1}. The robot must pass through a narrow hatch between the robot cabin and the sealed chamber; this hatch is installed in the bulkhead and can be designed as an electric gate or replaced by a large-diameter ball valve. As shown in Fig. 3 the cabin outlet has a size D, and the robot must avoid interference with this opening during inspection. For cleaning and inspection, the robot should adopt a posture behind the cutterhead; an ideal pose is with the end link normal to the cutterhead and 300 mm from the cutter back edge. The inverse kinematics is solved to keep the end link horizontal (aligned with the Y-axis) while approaching edge and center cutters as close as possible to the 300 mm standoff. If a perpendicular end pose is infeasible, the end joint is tilted by a certain angle to observe the cutters. Using the optimal inverse-kinematics method, the maximum inspection range in the XOY plane is obtained.

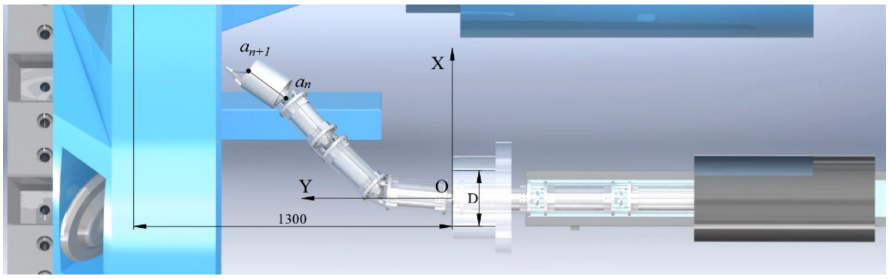


Fig. 3 Inspection range of the snake robot in the XOY plane

Equation (1) gives the inverse-kinematics model. The total length of the robot arm section is set to 1900 mm. The objective function drives the end-effector to stay as close as possible to the line Y = 1000, with constraints that prevent any link from interfering with the hatch during exit. The initial slope vector of the end link is set to k = $[0\ 1\ 0]^T$ When the inverse-solution algorithm cannot continue, *k* is adjusted so that the end link adopts a tilted pose to observe the cutters.

$$\begin{aligned}
&\min \quad \left\| y_{a_{n+1}} - 1000 \right\| \\
&s.t. \quad \begin{cases}
q_i \le \max JointAngle, i = 1,\dots,n \\
x_{a_1} = 0 \,\&\, z_{a_i} = 0, i = 1,\dots,n+1 \\
-1030 \le x_{a_{n+1}} \le 2200 \\
\left\| a_i - a_{i+1} \right\| = L_i, i = 1,\dots,n \\
a_{n+1} = a_n + k \cdot L_n \\
if \;\; y'_{a_i} < 0, then \;\; \dfrac{x_{a_{i+1}} - x_{a_i}}{y_{a_{i+1}} - y_{a_i}} \cdot \left| y_{a_i} \right| + x_{a_i} \le \dfrac{D}{2}, i = 1,\dots,n
\end{cases}
\end{aligned} \qquad \textbf{(1)}$$

Using the optimal inverse-kinematics method, the inspection range in the XOY plane is obtained as shown in Fig. 4 The robot can keep the end link perpendicular to the cutterhead and 300 mm from the cutter back edge within x = -1030 to x = 1300 mm,this is defined as the complete inspection range. When x > 1300 mm, the end link can be tilted by a certain angle for cleaning and inspection; this is defined as the tilted inspection range. At the limit, the distance between the end link and the back edge of the center cutter is 600 mm.

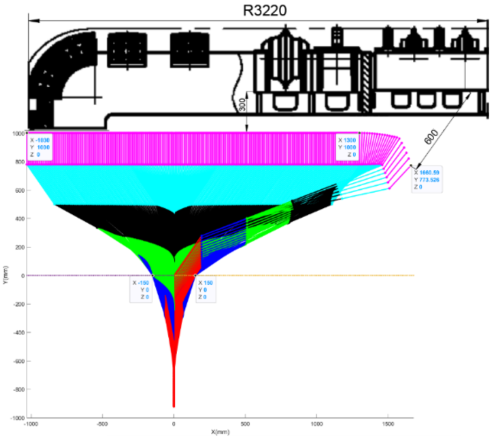


Fig. 4 Inspection range of the snake robot in the XOY plane for a 6 m class TBM

The maximum displacement of the drive cable is 150 mm. Considering a 30 mm slider length in the screw-nut pair and a safety margin, the screw length is set to 200 mm. The motor and coupling length is 180 mm; the fixed link length is 140 mm (equal to the hatch thickness); and a 150 mm cable space is reserved behind the robot. The total arm length is thus 1920 mm. The minimum end-link length is 220 mm, so the remaining five links are each 340 mm long. The overall dimensions are shown in Fig. 5.

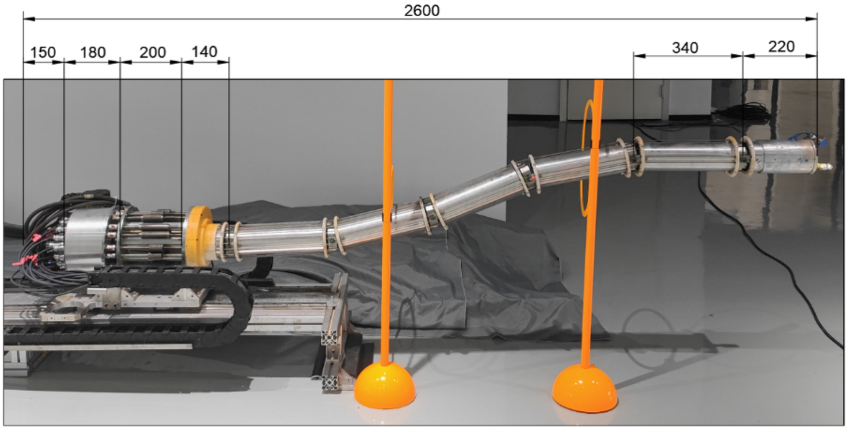
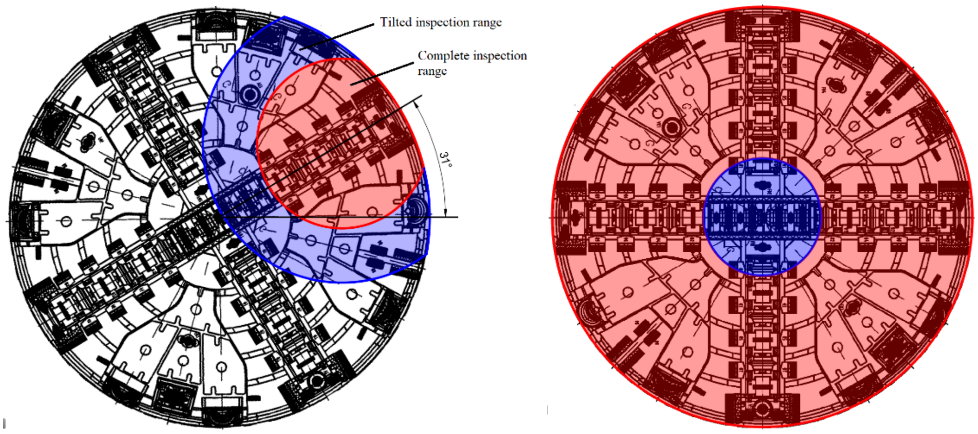


Fig. 5 Dimensions of the TBM snake-like inspection robot

After determining the design parameters, the cutterhead inspection coverage is calculated using this method, as shown in Fig. 6 (a), where the red area is the complete inspection range and the blue area is the tilted inspection range. In practice, cutterhead rotation can be coordinated with the robot to inspect more cutters; the resulting coverage is shown in Fig. 6 (b).By computing the ratio of the inspection area to the total cutterhead area under different conditions, Table 1 is obtained. The results show that full cutterhead coverage can be achieved when inspection is coordinated with cutterhead rotation.



(a) Inspection range with cutterhead stationary (b) Inspection range with cutterhead rotation

Fig. 6 Cutterhead inspection coverage of the snake robot

	Complete inspection range	Tilted inspection range	Total inspection range
Cutterhead stationary	15.11%	16.82%	31.93%
Cutterhead rotating	92.19%	7.81%	100%

Table 1 Cutterhead inspection coverage for a 6 m class TBM

3.2. End-effector cleaning and sensing

To ensure reliable inspection in muddy conditions, the end-effector integrates a self-balancing high-pressure nozzle (35 MPa) with one forward jet and three backward jets (120 deg spacing). The nozzle diameter is 1.0 mm with an orifice diameter of 0.68 mm, delivering about 30 L/min while keeping recoil below 10 N.

High-power lighting, a zoom industrial camera, and an air-knife/laser module are used to clean and illuminate the target area before image capture. The combined cleaning and imaging arrangement allows accurate detection of wear, cracks, and missing cutter components.

3.3. Protection Design in Harsh Environments

The harsh-environment protection design of the TBM snake inspection robot is shown in Fig. 7. The industrial camera at the end effector uses a pressure housing rated to 2 MPa so the camera operates at normal pressure and humidity. The magnetic rotary encoder boards inside the joints are potted, isolating them from high pressure and humidity without compromising measurement accuracy. In addition, the arm is enclosed by a pressure-resistant bellows that runs through the entire manipulator. A double-seal design is used at the base: the inner seal clamps the bellows root, and the outer seal connects to the base, further ensuring safe and reliable operation of precision joint components and magnetic rotary encoders.

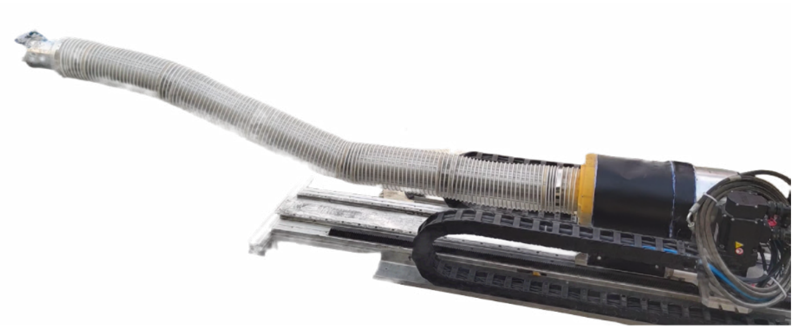


Fig. 7 Protective design of the snake robot for harsh environments

4. HEAVY-LOAD DISC CUTTER REPLACEMENT ROBOT

The replacement robot is a 6-DOF PRRPRR serial manipulator, as shown in Fig.8. Joint 1 is a linear slide for horizontal positioning; joint 4 is a telescopic arm for depth adjustment; joints 2 and 3 are hydraulic cylinders for boom angle and reach; and joints 5 and 6 are rotary swing cylinders for end-effector orientation. The design provides high payload capacity and sufficient stiffness for cutter handling.

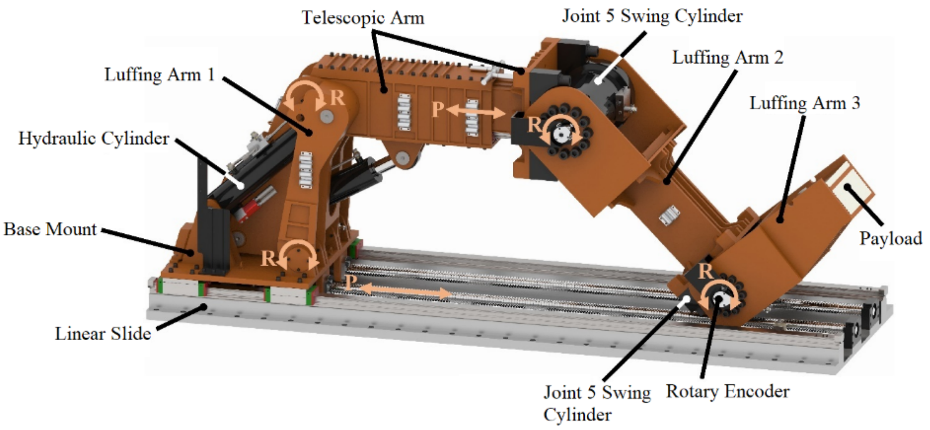


Fig. 8 Mechanical configuration of the replacement robot (joint layout)

4.1. *Installation space and access*

The robot is designed for an installation space of approximately 1 m x 1 m x 3 m and passes through a 0.65 m diameter, 0.39 m long access gate, as shown in Fig.9. The layout of the TBM chamber, partitions, and access door constrains robot motion. Manual maintenance under these conditions is hazardous, motivating robotised replacement.

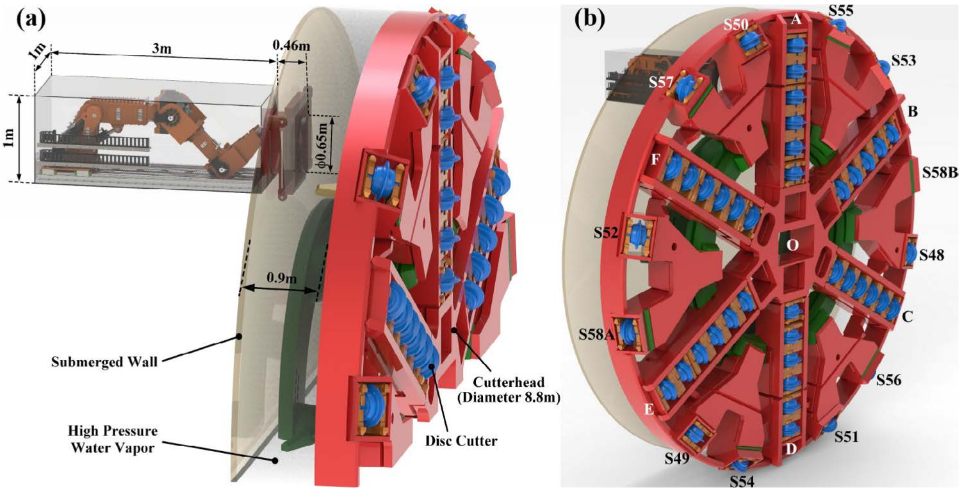


Fig. 9 TBM chamber layout and access positions for cutter replacement

4.2. *Kinematics and dynamics modeling*

A D-H based kinematic model is established to compute forward and inverse kinematics, as shown in Fig.10. And the D-H parameters table for the replacement robot is shown in Table 2. Redundancy is resolved by constraining joints 2 and 3 to reduce energy consumption and avoid collisions in the confined workspace. The cutterhead of an 8.8 m EPB TBM includes 35 radial cutters and 12 edge cutters, all of which must be reachable.

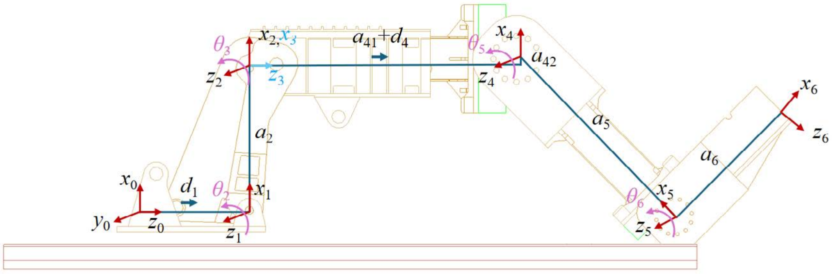


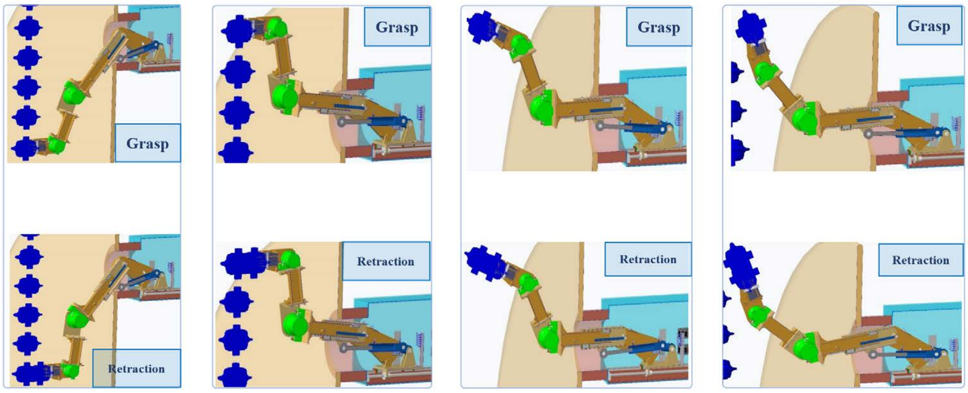
Fig. 10. Coordinate frames and kinematic parameters of the replacement robot

	θ_i	d_i	a_i	α_i
Joint 1	0	d_1	0	-90°
Joint 2	θ_2	0	a_2	0
Joint 3	θ_3	0	0	90°
Joint 4	0	$a_{41}+d_4$	a_{42}	-90°
Joint 5	$45°+\theta_5$	0	$-a_5$	0
Joint 6	$-90°+\theta_6$	0	a_6	90°

Table 2. D-H parameters table for the replacement robot

4.3. *Constrained-space trajectory planning*

A region-based joint-space planning strategy is proposed. Cutters are divided into middle, lower, and upper regions. For each region, a small number of key poses (initial, one or two intermediate poses, and target pose) are selected to minimize joint reversals, especially for joints 2 and 3. Trajectories are generated using cubic spline interpolation to ensure smooth velocity and acceleration profiles. Fig.11 shows cutter replacement process for multiple tool locations.



The most central radial tool grasping/retracting attitude
Outermost radial tool grasping/retracting attitude
Minimum angle of inclination edge tool grasping/retracting posture
Maximum angle of inclination edge tool grasping/retracting posture

Fig. 11 Demonstration of cutter replacement process for multiple tool locations

4.4. EHA Modeling and Control

Electro-hydrostatic actuators (EHAs) drive joints 2 to 6. As shown in Fig. 12， it includes two major parts, the first part is mainly comprised of a servomotor, an EHA pump, a pressurized tank and a series of cartridge valves, mounted on the manifold block. And the second part is an integrated cylinder, which includes an internal magnetostrictive displacement sensor and an external dual pilot operated check valve. The position control strategy using both position feedback and pressure feedback is proposed. Here, the high gain pressure loop only comes into effect at the beginning of reversing. Hence the pressure in the contained volumes can be raised as soon as possible, which is beneficial for increasing the response speed of the actuator.

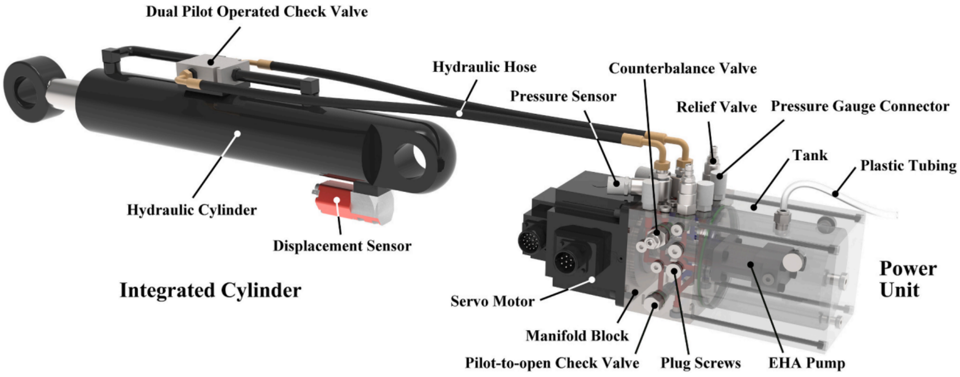


Fig. 12 Global 3D view of the electro-hydrostatic actuator (EHA)

Fig. 13 is the schematic diagram of the presented EHA system, and the corresponding 3D structure diagram is shown in Fig. 12. In this paper, the integrated cylinder is separated from the power unit, which is connected by hydraulic hoses. The integrated hydraulic cylinder is installed on the manipulator and is located in its installation space, while the power unit of the EHA is installed outside the manipulator's installation space.

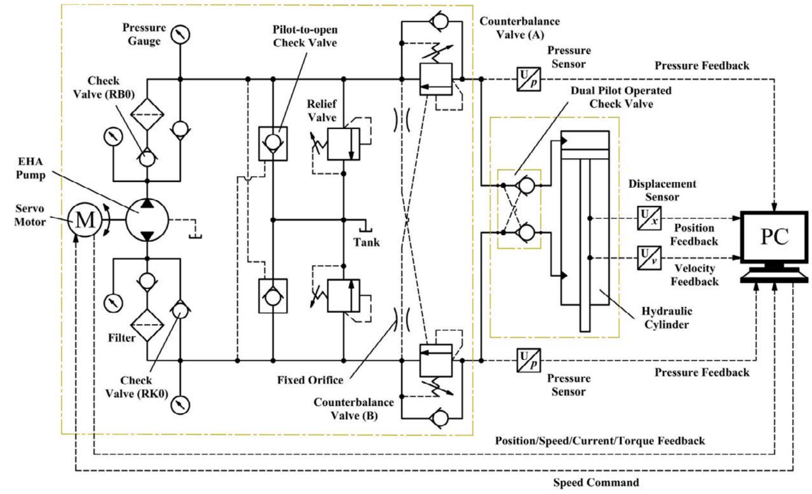


Fig. 13 Schematic diagram of the EHA

The control strategy combines two control loops, a high-gain pres-sure loop and a traditional position loop, as shown in Fig. 14. The goal of the high-gain pressure loop is to increase the speed of system response by increasing the pressure build-up speed of the working chamber when the piston rod moves in reverse, where the pressure controller is a high gain P controller. The position loop is used to realize the precise position control of the actuator, where the position controller is a PD controller. Adopting position-pressure feedback control (PPFC) strategy is to achieve both high positioning accuracy and high dynamic response of the pump control system.

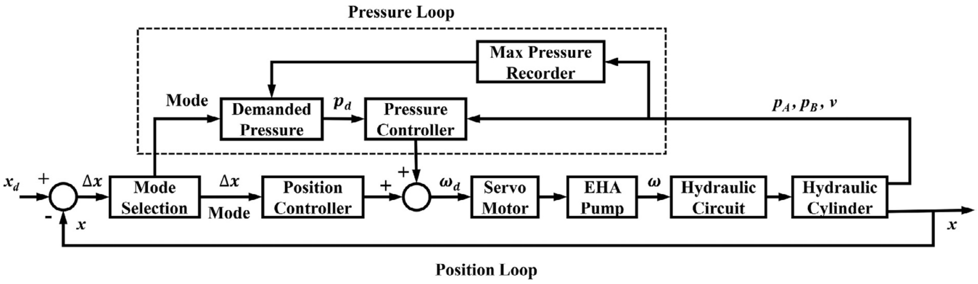


Fig. 14 Block diagram of the control strategy for the EHA

5. FIELD APPLICATION

The inspection-and-replacement system was deployed on the 'Pioneer II' TBM in the Shenzhen Airport metro tunnel project. The TBM operated in mixed geology. The overburden depth along the interval tunnel ranged from 10.13 to 265.81 m, with a maximum longitudinal gradient of 28%. The minimum horizontal curve radius was 568 m. The tunnel section passed through 3965 m of moderately to slightly weathered granite (87% of the alignment), while the remaining sections were gravelly cohesive soil and completely to strongly weathered granite, crossing seven fault zones and four densely jointed zones.

The engineering application of the inspection/replacement robots was first evaluated at the Foshan assembly plant to verify installation inside the TBM and to conduct cutter inspection tests, shown in Fig.15.

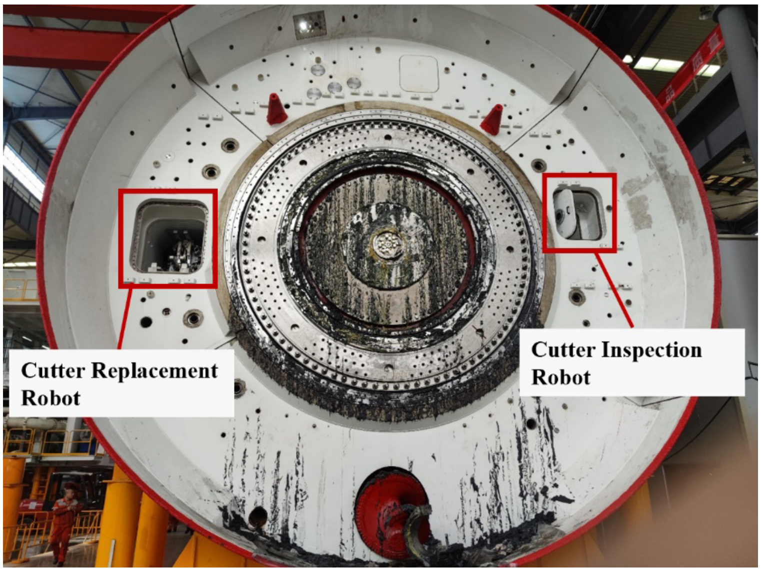


Fig. 15 The inspection-and-replacement system deployed on the 'Pioneer II' TBM

After installation, the snake robot was controlled via a virtual-environment human-machine interaction platform to conduct cutter inspection tests shown in Fig. 16. The platform includes a 3D cutterhead model; the cutterhead status displayed in software together with the robot's real-time posture was used to determine the relative position between the robot and the cutter. A serpentine motion-control method combined with end-camera images enabled cutter inspection.

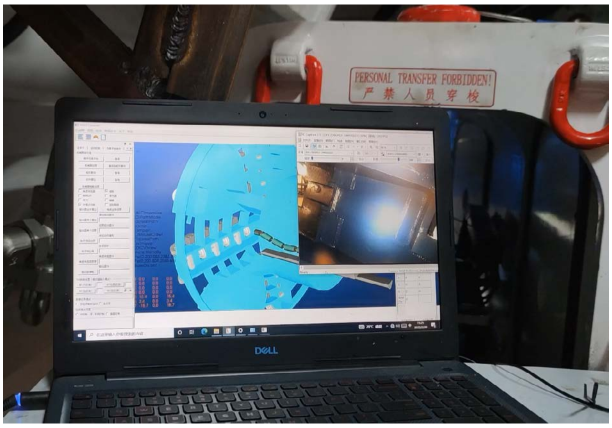


Fig. 16 Cutter inspection using the virtual-environment human-machine interaction platform

During installation and commissioning, the in-TBM installation issue of the snake robot was resolved. As shown in Fig. 17, a complete out-of-cabin inspection and retraction test was performed, preliminarily verifying the robot's operational capability inside the TBM.

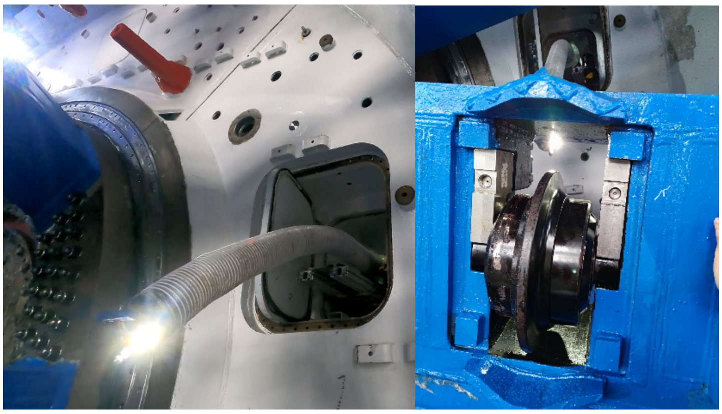


Fig. 17 The snake robot exiting the cabin for cutter inspection.

During field operation, the snake robot completed cleaning and inspection of front cutters, and the replacement robot validated safe access for disc-cutter replacement. Fig. 18 shows the snake robot performing cutter cleaning at the tunneling site.

Fig. 18 The snake robot performing cutter cleaning at the tunneling site

6. DISCUSSION AND FUTURE WORK

While the proposed system demonstrates reliable inspection and replacement in harsh environments, several challenges remain: (1) current work is limited to visual image examination, future work should integrate specialized equipment such as depth-sensing cameras and laser profilometers to achieve precise wear measurement of the cutters, (2) the intense vibrations during TBM tunneling can easily cause failures in the cutter inspection and replacement robot, future work should consider implementing vibration-resistant design to enhance the robot's reliability. Future work will address these issues and extend the system to larger TBM diameters and deeper burial depths.

7. CONCLUSION

A TBM robotised maintenance system combining a snake-like inspection robot and a heavy-load cutter replacement robot has been developed and validated. The inspection robot integrates cleaning and visual sensing for high-precision wear assessment under extreme conditions, while the replacement robot employs region-based trajectory planning and EHA control to achieve safe, accurate cutter swapping. Field application confirm reliability of the inspection robot in harsh environments, as well as its effectiveness in cutter cleaning and inspection.

8. REFERENCES

[1] Edelmann T. Monitoring of cutting tools in TBM[R].2013.

[2] OCRobotics. OC Robotics successfully delivers new JetSnake system to Dragages/Bouygues joint venture in Hong Kong[EB/OL]. https://www.ocrobotics.com/news-en/oc-robotics-successfully-delivers-new-jetsnake-system-to-dragagesbouygues-joint-venture-in-hong-kong/.

[3] Bruno COMBE E L. Innovations in TBM Tunneling[R].2019.

[4] Yamada Y, Fukui R, Warisawa S, Morioka E, Uetake M, Terada S. WInBot: A Disc Cutter Wear Inspection Robot for a Tunnel Boring Machine[C]//: IEEE, 2019: 1837-1843

[5] TSUBAKIMOTO. Zip Chain transmission device [EB/OL]. https://tt-net.tsubakimoto.co.jp/tecs/pdct/sad/pdct_ZCA.asp.

[6] Liu Feixiang, Shao Jizhou, Zeng Hua, Zhu Chen, Ma Jianbing, He Tao, Huang Chunxia. Inspection robot system for shield machine and its inspection method [P]. 2020-08-07.

[7] Chen G. Design and Test of Intelligent Inspection and Replacement System of TBM Excavation Tools[C]//: IEEE, 2019: 219-222

[8] Xue Long, Cao Yingyu, Wang Kun, Liu Feixiang, Cheng Yongliang. Shield machine cutterhead cleaning robot system and cleaning method [P]. 2018-06-12.

[9] Xiong Zhilin. Research on key technologies of a snake-arm robot for shield cutter inspection [D]. Shanghai Jiao Tong University, 2018.

[10] https://vimeo.com/118895178. [EB/OL], 2015

[11] Rubrecht S. Contributions to the control of constrained robots [D]. Universite Pierre et Marie Curie-Paris VI, 2011.

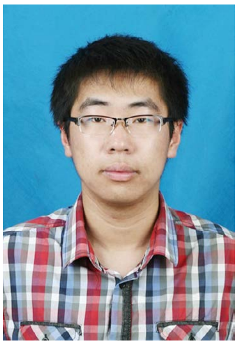
[12] Du L., Yuan J., Bao S., et al. Robotic replacement for disc cutters in tunnel boring ma-chines[J]. Automation in Construction, 2022, 140: 104369.

[13] Yuan J., Guan R., Du J. Design and implementation of disc cutter changing robot for tun-nel boring machine (TBM)[C]//2019 IEEE International Conference on Robotics and Bio-mimetics (ROBIO). IEEE, 2019: 2402-2407.

Biographies

Huayong Yang received the Ph.D. degree in fluid power transmission and control from the University of Bath, Bath, U.K., in 1988. He is an Academician of the Chinese Academy of Engineering. His current research interests include motion control and energy saving of mechatronic systems, microfluidic devices and systems, and R&D of fluid power components.

Haibo Xie received the Ph.D. degree in mechatronic engineering from Zhejiang University, Hangzhou, China, in 2004. He is a Professor with the State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University. His research interests include redundant robotics, mobile hydraulic control systems and components, and tunnel boring machine driving technique.



Cheng Wang received the Ph.D. degree in mechatronic engineering from Zhejiang University, Hangzhou, China, in 2023. He currently works as a researcher at Institute of Advanced Machines, Zhejiang University. His research interests include cable-driven mechanisms, redundant manipulators, mechanics-based modeling, and control.