A-TBM TUNNELING IN CHINA

Bai Yun & Zhang Yuzhe
BY Civil Engineering Consulting Co., Ltd, Shanghai, China

ABSTRACT: TBM tunnelling is characterized by variable ground conditions, construction uncertainty, and a cyclic driving process, creating a strong rationale for integrating artificial intelligence (AI) and machine learning into TBM operations. A-TBM tunnelling refers to the application of AI technologies to TBM-based tunnel construction, and recent projects in China have begun adopting self-driving mode. Compared with autonomous road vehicles, self-driving TBMs face additional challenges, including incomplete and changing geological condition, multi-objective control requirements (e.g., settlement/environmental disturbance control and alignment accuracy), complex 3D positioning, tightly coupled multi-layer machine subsystems, etc.

This article frames A-TBM as a continuous "Perceive–Decide–Act" closed-loop: (i) comprehensive perception via real-time muck/geology sensing, forward exploration, and dense equipment health monitoring; (ii) intelligent decision-making using data modelling and multi-objective optimization to generate predictive and prescriptive outputs; and (iii) adaptive control that combines data-driven regulation in normal conditions with knowledge-driven rule sets for emergencies.

Big data—summarized through the 4V characteristics—underpins geological risk mitigation, operational optimization/automation, and predictive maintenance, ultimately enabling a data-driven "digital twin" for closed-loop improvement.

Reported practice indicates improved construction performance, with self-driving EPB tunnelling achieving approximately 25% lower average ground settlement than manual driving in Shanghai soils.

The paper concludes that A-TBM innovations, accelerated by cross-industry advances in IT, are poised to be a game changer for the tunnelling industry.

1. PREFACE

TBM tunnelling mainly involves three features: diversity in ground condition, uncertainty in construction and periodical process during driving. The first feature requires fully understand of ground condition, precise theoretical prediction and past construction experience. Fully understand of ground condition needs collecting big data from ground and precise prediction can be effectively improved with machine learning technique. The second feature requires flexible machine and real time instrumentation. Live data process in digital platform can realize the real time instrumentation. The third feature provides convenience for application of artificial intelligence (AI). A-TBM tunnelling refers to the integration of AI technologies into the process of tunnel construction using TBMs. Therefore, application of AI and machine learning in TBM driving is a suitable application. In recent years, several TBMs start to adapt self-driving mode (also called unmanned, intelligent, or automatic) in tunnelling projects in China.

2. MAIN FEATURES IN APPLICATION OF AI IN TBM CONSTRUCTION

Compared with the self-driving vehicle, the self-driving TBM is more difficult to develop due to the following reasons: Firstly, when the TBM excavates a tunnel, the surrounding ground condition is incompletely foreseeable and constantly variable. During tunnelling process, the TBM faces difficulties in obtaining accurate geological information and faces challenges in unexpected geological conditions. Secondly, the control targets of tunnelling are multi-dimensions. The consideration of driving control is from minimum environmental disturbance to the surrounding ground to enhance environmental safety and accurate tunnelling according to the designed tunnel axis to ensure the tunnel quality. Thirdly, the TBM positioning is more complicated than that of the automobile as it is within an unconstrained movement of three-dimensional (3D) space. Fourthly, the TBM has many levels of control systems, and its automatic control system consists of a hydraulic thrust system, cutter head driving system, tail sealing system, soil conditioning system, an attitude positioning system, and grouts injection system. In addition, each system has independent controlled sub-systems, coupled and interacting with each other to complete the tunnelling goal (see Figure 1 (Min Hu 2022 et all.)). Finally, the monitoring methods are other challenges facing the self-driving shield. The TBM faces the risks of inaccuracy, instability of the instrumentation results.

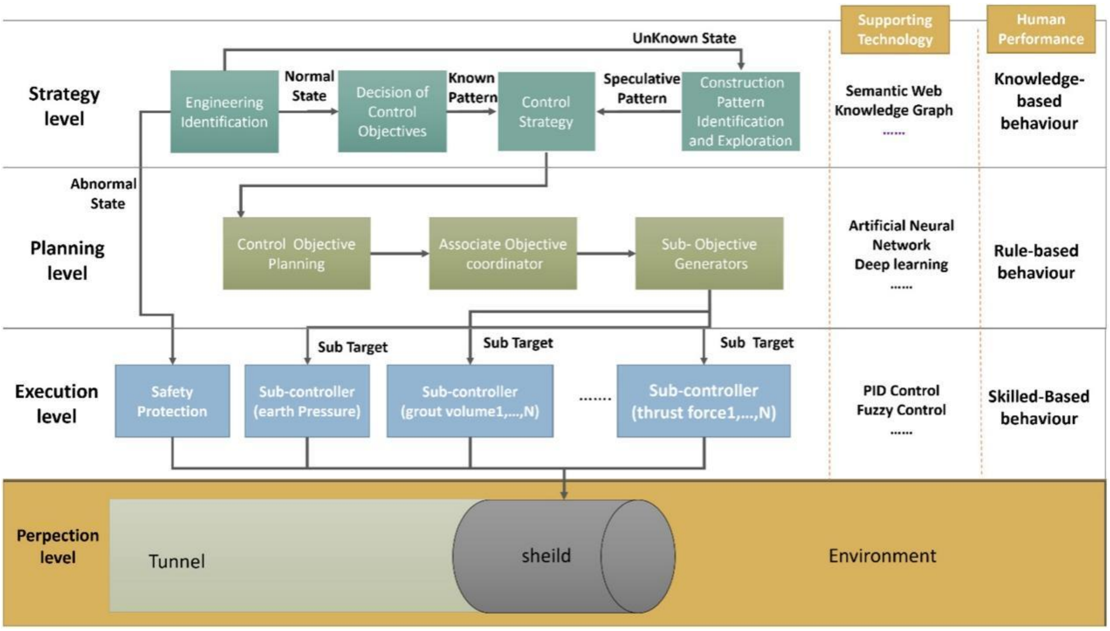

Figure 1. Shield intelligent control system framework for self-driving

The A-TBM control model relies on knowledge, experience, and massive historical data. The control models under different strata are established by analysing the historical data of hundreds of tunnels built with TBM tunnelling. The control model is modified, and the controller output is dynamically adjusted according to the learning real-time data of the current project (Figure 2).

2.1 AUTOMATION AND REMOTE CONTROL

AI can enable remote operation and control of TBMs, reducing the need for human operators to be physically present underground. This enhances safety and allows experts to oversee multiple machines across different locations.

2.2 DATA ANALYSIS

Optimization of earth pressure, thrust speed, and grouting volume through machine learning. AI can process vast amounts of data generated during the tunnelling process, extracting valuable insights that can inform future projects and improve overall efficiency.

2.3 RISK MANAGEMENT

By analysing geological and environmental data, AI can help identify potential risks and suggest mitigation strategies, reducing the chances of accidents or unexpected disruptions.

2.4 DECISION SUPPORT

In combining knowledge-driven and data-driven approaches, AI can provide real-time information and recommendations to construction teams, helping them make critical decisions related to excavation speed, equipment adjustments, and more. Different intelligent decision-making models have developed, for example, intelligent decision-making model for shield thrust speed and cutter head speed, predictive model for shield attitude and position, etc.

2.5 EFFICIENCY AND COST SAVINGS

AI-driven TBM tunnelling can lead to faster construction times, reduced resource wastage, and improved project management, resulting in cost savings.

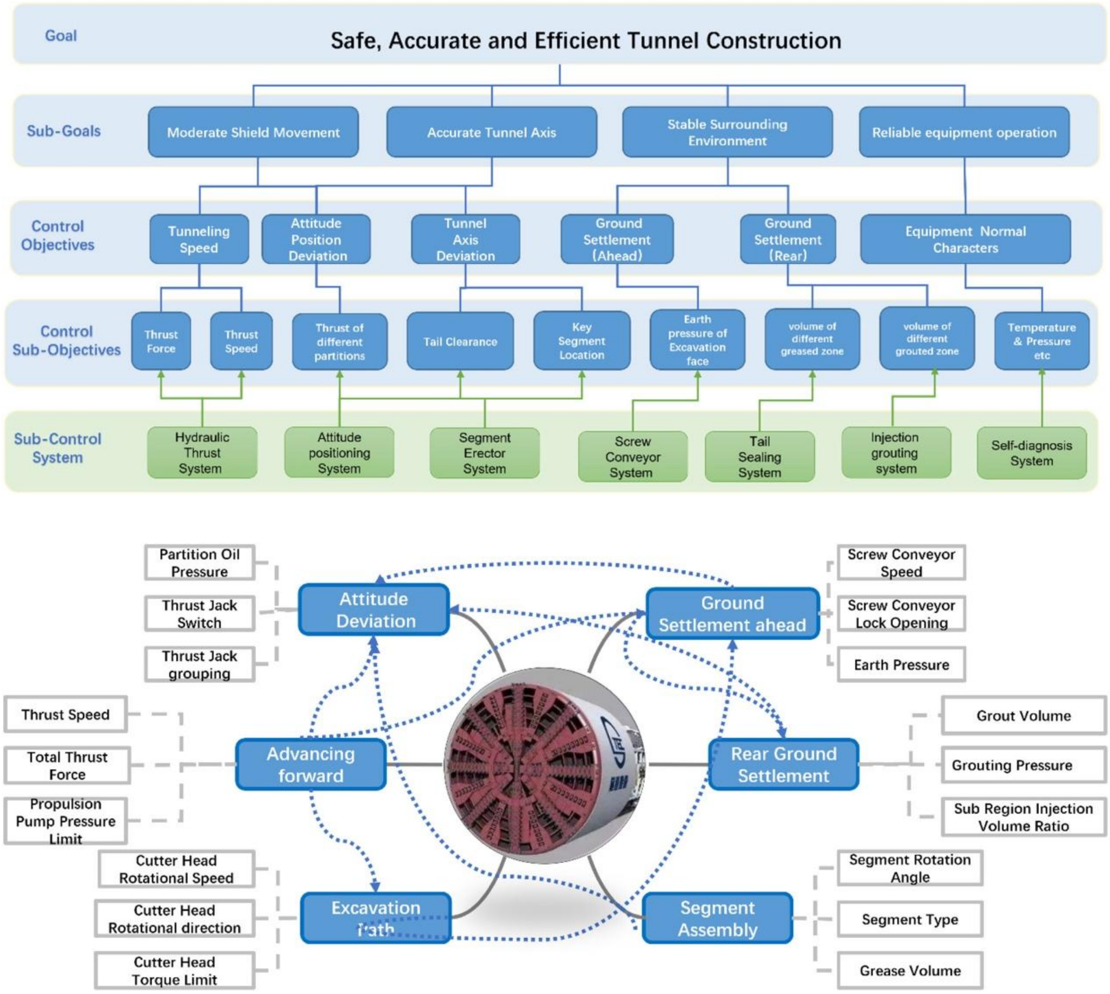

Figure 2. Breakdown diagram of control targets in TBM tunnel construction (Min Hu 2022 et all.)

3. THE WORKING PRINCIPLE OF A-TBM

The working principle of an A-TBM can be best understood as a continuous "Perceive-Decide-Act" closed-loop, inspired by a human-like cognitive model. It aims to replace operator guesswork with data-driven automation. At its core, the A-TBM system functions like an intelligent robot. It uses sensors to perceive geological environment and machine status, uses algorithms to analyze and decide on the best action, and then automatically executes that decision through the machine's controls. This cycle creates a self-optimizing loop that aims to achieve objectives like maximum efficiency, minimum energy use, and reduced risk. Here is a breakdown of the key steps and technologies involved in the A-TBM's workflow:

3.1 STEP 1: COMPREHENSIVE PERCEPTION (THE "EYES AND SKIN")

This is the data-gathering phase, where the machine senses its environment. Key methods include:

· Real-time Geology Sensing: Uses visual cameras and vibration sensors on the conveyor belt to analyze the shape and composition of excavated muck, identifying changes in geology.

· Advanced Exploration: Integrates systems like infrared camera and TSP monitoring to detect water sources or faults meters ahead of the machine.

· Equipment Monitoring: A dense network of sensors collects thousands of data points (torque, thrust, temperature, pressure, etc.) from the TBM itself to assess its health.

3.2 STEP 2: INTELLIGENT DECISION-MAKING (THE "BRAIN")

Raw data is processed into actionable intelligence. This involves:

· Data Modeling: Building a database of geology, machine parameters, and outcomes. AI models like Random Forest (RF) and deep learning networks learn the complex relationships between these parameters.

· Multi-Objective Optimization: Algorithms (like Particle Swarm Optimization (PSO)) crunch data to find the "sweet spot" for operating parameters, balancing speed, energy use, and tool wear.

· Predictive & Prescriptive Output: The system doesn't just predict issues like equipment failure; it also prescribes optimal solutions, such as recommending the best cutterhead rotation speed or specific support patterns for the ground.

3.3 STEP 3: ADAPTIVE CONTROL (THE "HANDS")

The final step is executing decisions. The control system has two main modes:

· Data Driving for Normal Conditions: Automatically adjusts key parameters like propulsion and cutterhead speed in response to real-time geological feedback to maintain optimal performance.

· Knowledge Driving for Emergencies: Switches to pre-programmed expert rules when encountering severe risks (like a major fault zone) to ensure safety, often by slowing or halting operations.

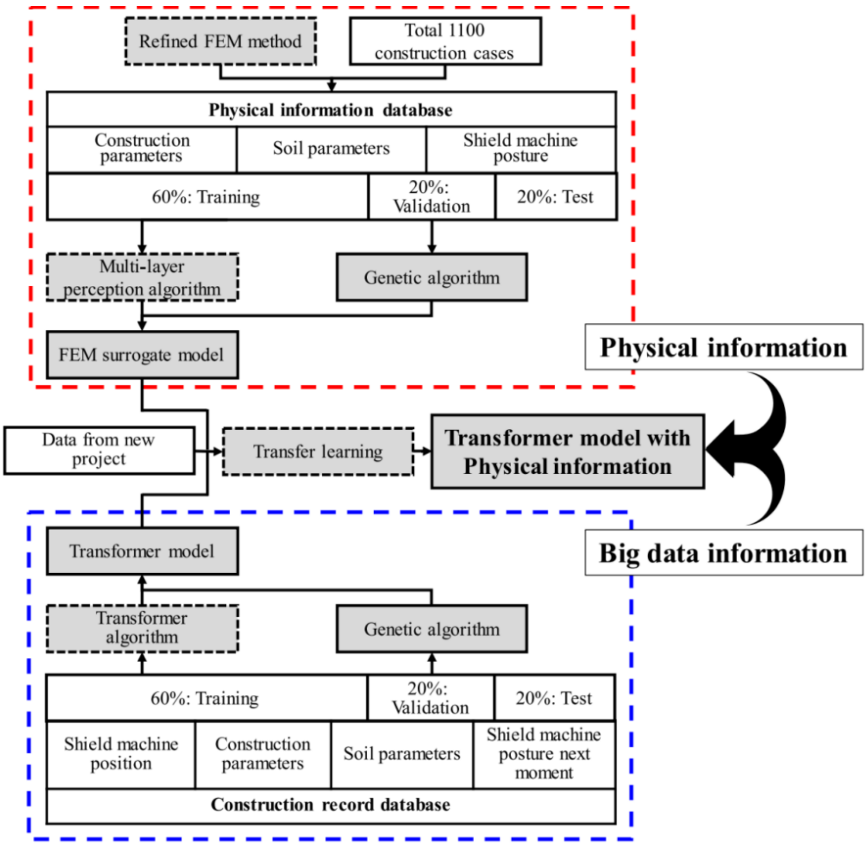

Figure 3 The flowchart of A-TBM attitude prediction by Physical information fusion machine learning (Jiaqi Chang et all.)

4. THE ROLE OF BIG DATA IN A-TBM

The features of engineering data can be summarized int 4V (Volume, Variety, Velocity and Value). Big data is transforming Tunnel Boring Machines (TBMs) from heavy, manually operated equipment into intelligent, adaptive, and predictive systems. Its core role is to replace operator guesswork with data-driven insights across the entire tunnel excavation period. The detailed functions of big data are as follows:

Geological Prediction & Risk Mitigation: Analyzes real-time and historical data to identify adverse conditions like faults, preventing collapses and guiding strategy.

Operational Optimization & Automation: Processes machine data to recommend or auto-adjust parameters (thrust, torque, etc.), boosting efficiency and safety.

Predictive Maintenance & Planning: Predicts wear (e.g., cutter consumption) and models scenarios for better resource and schedule planning.

The ultimate role of big data is to forge a data-driven "digital twin" for the tunneling process. It closes the loop from data collection to intelligent feedback, making A-TBM construction more powerful.

In order to maximize the facility of bid data, the following points should be kept in mind:

Data sources, data transactions, and the process of generating value from data are the prerequisites of big data development.

The core of big data development lies in extracting new value from massive amounts of unstructured and semi-structured data. The value derived from data serves as the primary driving force for data transactions.

Big data uncovers objective truth by studying data correlations, relying on the authenticity and diversity of data. How data is shared and opened remains a critical weakness and a major challenge that needs to be addressed in big data development.

The total volume of engineering digital data resources in China is relatively low compared with other sectors like commercial and industrial sectors, and the limited data resources suffer from poor standardization, accuracy, and completeness, resulting in low utilization value. This significantly diminishes the overall value of the data.

Enterprises of any scale always generate vast amounts of data, but how can this data be collected and refined are still a big challenge.

The significance of big data technology lies not in merely possessing massive amounts of data but in intelligently processing it to extract valuable insights.

How can large amounts of valuable data be obtained is still an open question.

5. THE BENEFITS USING AI TECHNOLOGY IN TBM CONSTRUCTION

Despite all these challenges, Research on TBM driving have still moved from kinetic and numerical analysis to data-driven and AI algorithms. All that research offered a good foundation and technical support for the development of the self-driving shield. It proved that the self-driving TBM-EPB's construction quality is significantly better than the manually controlled one.

The inclusion of AI in TBM tunneling offers several benefits:

5.1 PREDICTIVE MAINTENANCE

AI can monitor the condition of the TBM components and predict when maintenance is required. This proactive approach helps prevent breakdowns and reduces downtime.

5.2 REAL-TIME MONITORING

AI sensors and data analytics can monitor various aspects of the tunnelling process in real time, including ground conditions, machine performance, and more. This information can help make informed decisions during the construction process.

5.3 OPTIMIZED TUNNELING

AI algorithms can analyse geological data and adjust the TBM's operations accordingly. This can lead to optimized excavation techniques based on the specific characteristics of the ground being dug through.

The following table (Table 1) is the comparison of manual and self-driving TBM in terms of ground settlement control in Shanghai soil. From Table 1, we can find that the ground settlement induced by self-driving tunnelling is around 25% smaller in average than manually driving in all stages of shielding tunnelling.

Table 1 The comparison table of ground settlement (mm)

Ring Number	Control mode	Before cutter		During shield		After shield	
No. 1~300, 302~304, 308-313, 316-378, 384-390,396	Manually driving	0.75	2.15	0.73	2.72	0.84	2.03
No. 301,305-307, 314-315,379-383, 391-395	Self driving	0.63	1.79	0.45	1.74	0.41	1.97

Note: the settlement data in each stage is minimum and maximum.

6. CONCLUSION

It's worth noting that while the concept of TBM tunnelling with AI holds great potential, its implementation might vary depending on the level of technological advancement, the complexity of the project, and regulatory considerations. A-TBM tunnelling are advancing to a level inconceivable even several years ago. It should also thanks to the profound interplay character of new technology from other industry, especially in IT. It is easily to agree that the innovations of A - TBMs will be the game change in tunnelling industry.

LITERATURE

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Professor, Bai Yun
BY Civil Engineering Consulting Co., Ltd.
09150@tongji.edu.cn

Engineer, Zhang Yuzhe
BY Civil Engineering Consulting Co., Ltd.
zhangyuzhe1997@foxmail.com