Automation in Construction 93 (2018) 192–199

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Pose and trajectory control of shield tunneling machine in complicated stratum

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ARTICLE INFO

Keywords:
Shield tunneling machine
Thrust system
Electro-hydraulic control
Spatial parallel mechanism
Complex stratum

ABSTRACT

The present study is focused on developing a method for controlling the pose and trajectory of a shield tunneling machine (STM) applied in complicated stratum. Lacking method to determine target motions of thrust cylinders and suitable electro-hydraulic control system are major restrictions for the STM to realize automatic pose control. To overcome these bottlenecks, a mathematical method for determining the target motions of thrust cylinders is proposed based on kinematic analysis of the thrust mechanism. With this method, target motions of thrust cylinders when the STM excavates along any specific curves can be obtained and used as the input signal of the pose control system. A multi-cylinder control system is proposed based on master/slave control strategy to control the length of each kinematic chain in order to adjust the pose of the thrust mechanism. Experiments are carried out to evaluate the performances of this control system. The experimental results verify that the proposed pose control system is effective in controlling the pose and trajectory of the shield machine no matter it advances along a straight or a curved tunnel axis. Considering the complex loads during the experiments, the proposed system has great potential for applying in practical tunnel construction.

1. Introduction

Recently, shield tunneling machines are widely applied in tunnel constructions, since the shield tunneling method has distinct advantages over other methods in terms of efficiency, safety, environmental friendliness, etc. The main structure of a typical shield tunneling machine (STM) is shown in Fig. 1. A number of circular- distributed thrust cylinders are installed on the STM, and these cylinders compose the thrust mechanism.

The construction quality of a tunnel with shield tunneling method is directly related to the deviation between the actual tunnel axis and the designed tunnel axis (DTA). During the process of tunnel excavation, the pose of the STM needs to be adjusted real-timely to keep it advancing along the DTA. That is, by adjusting the pose of a STM, its moving direction can be changed and its trajectory can be controlled. The pose adjusting torque and the thrust force are provided by the thrust cylinders which are driven by hydraulic power. Therefore, controlling the thrust cylinders properly is the key to reducing tunnel excavation error and improving tunnel construction quality.

At present, the pose of the STM is adjusted manually in practice. During the tunneling process, the operators of the STM adjust the speed of the thrust cylinders according to the shield pose and trajectory data acquisitioned by the attitude measuring and monitoring system. As the performance of the manual method is closely related to the experiences and skills of the operators, researchers keep trying to develop an effective automatic pose control system to replace the manual system. These works can be generally categorized into two types. Some research works are focused on trajectory tracking control by observing the trajectory error and control the thrust system based on this error. Manabe et al. [1] proposed an automatic direction control technique for a micro-tunneling machine. With real-timely measured position and posture of the STM, a liner quadratic integral control system with state observer was proposed to achieve automatic direction control. Similar work was done by Sapiński et al. [2] using neural network. Yue et al. [3,4] applied sliding mode control for coordinated control issue of attitude correction and developed a double closed-loop controller. As the pose and trajectory of a STM is actually determined by the displacement of the thrust cylinders, some other researchers try to develop a different way to control the attitude of the STM. These works are analogous to the motion synchronization control of a dual-cylinder or a multi-cylinder system [5–7]. In this regard, Yang et al. [8] proposed an electro-hydraulic system for the synchronizing control of thrust cylinders, in

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https://doi.org/10.1016/j.autcon.2018.05.020
Received 6 December 2017; Received in revised form 4 April 2018; Accepted 13 May 2018

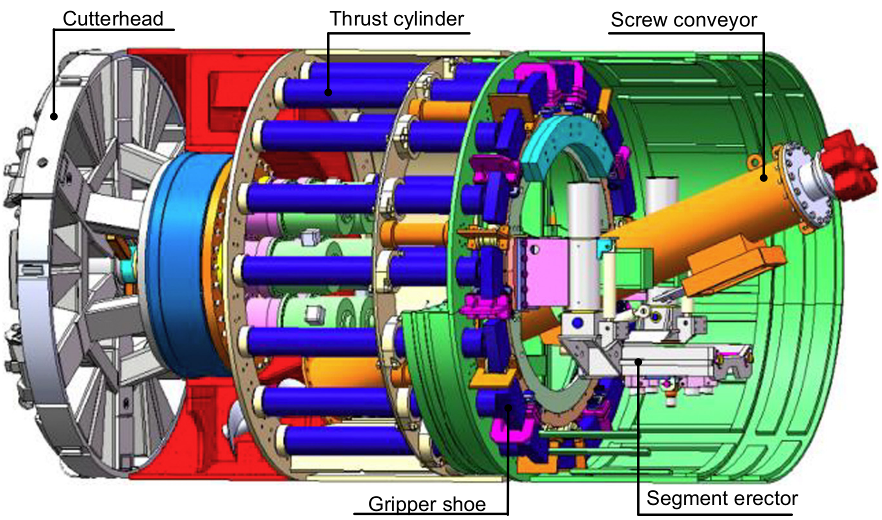

Fig. 1. Main structure of the STM.

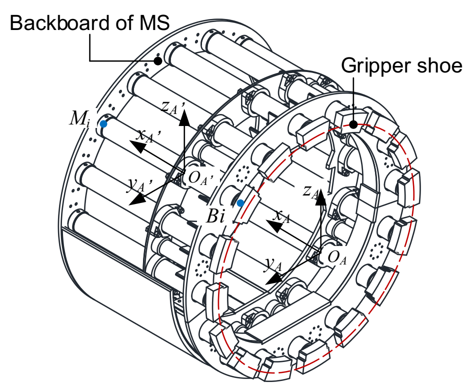

Fig. 2. Detailed structure of thrust mechanism [12].

order to keep the STM excavate along a straight line. Xie et al. [9,10] proposed an integrated control system composed of trajectory planning controller and an individual speed controller for each thrust cylinder, to achieve the automatic control of the excavating trajectory. Cascade control strategy of feedforward and feedback control was also involved. In summary, the abovementioned work showed that automatic pose and trajectory control of the STM is probable and achievable under some specific conditions. The former method can achieve high position accuracy with advanced nonlinear PID controller under favorable geological condition. And, the latter method can realize motion synchronization control of thrust cylinders to keep the STM excavate along a straight DTA in complicated stratum.

However, automatic pose and trajectory control of the STM still imposes significant challenges in practice for the diversity of stratum and high computational cost of complicated control algorithm. When the STM excavates under a complicated geological condition, the stratum distributed on the excavating face of the tunnel can be complex and diverse. Non-uniformly distributed rock/soil can result in unbalanced force on the cutterhead of a STM and cause the STM deviating from its target route. As the pose control system is a dynamic system with large inertia and time lag, the STM with an automatic control system based on trajectory error feedback control usually zigzags forward in practice [11]. This influences the quality of the tunnel adversely. On the other hand, the pose and trajectory control system based on controlling the displacements of thrust cylinders are promising, since its performance is almost irrelevant to external earth load. However, its range of application has been restricted to the straight tunnels. By now, this method cannot be applied in practice when the STM excavates along a curved line as a result of lacking method to determine the target motion of each thrust cylinder.

Motivated by the above observations, this paper aims to propose an effective method for controlling the pose of the STM excavating along curved DTAs in complicated stratum. The whole method comprises a mathematical method for determining the target motion of each thrust cylinder when the STM excavates along a specific DTA. In addition, an effective pose control system based on target motion determination algorithm and displacement control of thrust cylinders is proposed. With this new system, the pose and trajectory of the STM can be automatically adjusted when it excavates along a curved line rather than only along a straight line as before. Experiments are also carried out to validate the effectiveness and evaluate the performance of the proposed control system.

2. Kinematic analysis of the thrust mechanism

As shown in Fig. 2, the thrust mechanism of the STM is an n-SCS (n: number of thrust cylinders, S: spherical joint; C: cylindrical joint) spatial parallel mechanism. Driven by electro-hydraulic system, the speed and displacement of each thrust cylinder are adjustable. In this way, the excavating speed and direction of the STM are controllable.

Generally, a STM can be divided into three parts, namely the front shield (FS), the middle shield (MS) and the rear shield (RS). The thrust mechanism is located in the MS. To describe the thrust mechanism mathematically, coordinate systems are established as shown in Fig. 2. The global coordinate system $\{A\}$ is attached to the gripper shoes and its original point O_A is located at the distributing center of gripper shoes. The plane O_A-y_Az_A is parallel to the plane $B_1B_2 \ldots B_n$ and x_A-axis is perpendicular to plane $B_1B_2 \ldots B_n$. Here, B_i denotes the central point of the spherical joint connecting the ith thrust cylinder and its gripper shoe; M_i denotes the central point of the spherical joint connecting the ith thrust cylinder and the backboard of middle shield (BMS). The origin point of local coordinate system $\{A'\}$ $O_{A'}$ is attached to the center of the BMS, and its $x_{A'}$-axis is perpendicular to the plane $M_1M_2 \ldots M_n$. As the end-effector of the thrust mechanism, the BMS is fastened to the FS and MS. Hence, the pose of STM is indeed the pose of the thrust mechanism.

The origin point of the local coordinate system $O_{A'}$ is chosen as the reference point to describe the position of the end-effector of the thrust mechanism. In this paper, the pre-super script of a vector is used to indicate the coordinate system in which this vector is described. In the global coordinate system $\{A\}$, the vector's coordinate of point O_A connecting point $O_{A'}$ is defined as