

PROPULSION CONTROL METHOD FOR ACTIVE ARTICULATION

TYPE BORING MACHINE, CONTROLLER, AND CONTROL

SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present disclosure is based on and claims priority of Chinese application for invention No. 202410054506.4, filed on January 15, 2024, the disclosure of which is hereby incorporated into this disclosure by reference in its entirety.

TECHNICAL FIELD

[0002] This disclosure relates to the field of tunnel construction, particularly to a propulsion control method, a controller, and a control system for an actively articulated tunnel boring machine.

BACKGROUND

[0003] Tunnel boring machine (TBM) is the primary equipment for tunnel construction. With major global TBM design and development enterprises investing in equipment upgrades and construction efficiency improvements, TBMs are evolving towards automation, intelligence, greater depth, larger cross-sections, and longer distances. Tunnel boring machines can be classified into non-articulated, passively articulated, and actively articulated types based on their articulation forms, where actively articulated tunnel boring machines are widely used due to their small turning radius. Currently, in addition to standard construction procedures such as advancing, stopping, and segment assembly, tunnel boring machines can achieve simultaneous advancement and segment assembly by retracting and deactivating a portion of their propulsion cylinders. This method, known as continuous mining mode, is employed to improve construction efficiency.

DISCLOSURE OF THE INVENTION

[0004] According to one aspect of the present disclosure, there is provided a propulsion control method for an actively articulated tunnel boring machine, including: obtaining an actual position of the actively articulated tunnel boring machine, a designed axis, and a segment uplift amount; calculating a planned tunneling trajectory based on the actual position, the designed axis, and the segment uplift amount; and adjusting at least one of an actual correction torque of a propulsion system or an actual articulation angle of an articulation system of the actively articulated tunnel boring machine to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory.

[0005] In some embodiments, obtaining a clearance between a shield tail of the actively articulated tunnel boring machine and a segment in a predetermined direction; and adjusting the planned tunneling trajectory in a case where the clearance in the predetermined direction is less than a clearance threshold and the actively articulated tunnel boring machine is excavating in the predetermined direction.

[0006] In some embodiments, adjusting at least one of the actual correction torque of the propulsion system or the actual articulation angle of the articulation system of the actively articulated tunnel boring machine includes: adjusting a first target correction torque of the propulsion system to obtain a second target correction torque in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and adjusting the actual correction torque to match the actual correction torque with the second target correction torque.

[0007] In some embodiments, adjusting at least one of the actual correction torque of the propulsion system or the actual articulation angle of the articulation system of the actively articulated tunnel boring machine includes: adjusting a first target articulation angle of the articulation system to obtain a second target articulation angle in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and adjusting the actual articulation angle to match the actual articulation angle with the second target articulation angle.

[0008] In some embodiments, adjusting at least one of the actual correction torque of the propulsion system or the actual articulation angle of the articulation system of the actively articulated tunnel boring machine includes: adjusting a first target correction torque of the propulsion system to obtain a third target correction torque and adjusting a first target articulation angle of the articulation system to obtain a third target articulation angle, in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and adjusting the actual correction torque to match the actual correction torque with the third target correction torque, and adjusting the actual articulation angle to match the actual articulation angle with the third target articulation angle.

[0009] In some embodiments, adjusting the first target correction torque of the propulsion system to obtain the second target correction torque includes: calculating, based on the actual position of the actively articulated tunnel boring machine, a planned attitude corresponding to the actual position on the planned tunneling trajectory; and adjusting, based on an attitude deviation between an actual attitude of the actively articulated tunnel boring machine and the planned attitude, the first target correction torque to obtain the second target correction torque.

[0010] In some embodiments, obtaining sample correction torques and sample attitude deviations; and training a machine learning model, using the sample correction torques and the sample attitude deviations as training data, with sample correction torque adjustment amounts as label values, to obtain a trained correction torque adjustment model, where adjusting, based on the attitude deviation between the actual attitude of the tunnel boring machine and the planned attitude, the first target correction torque to obtain the second target correction torque includes: obtaining a first correction torque adjustment amount by inputting the first target correction torque and the attitude deviation into the correction torque adjustment model; and adjusting the first target correction torque using the first correction torque adjustment amount to obtain the second target correction torque.

[0011] In some embodiments, adjusting the first target articulation angle of the articulation system to obtain the second target articulation angle includes: calculating, based on the actual position of the actively articulated tunnel boring machine, a planned attitude corresponding to the actual position on the planned tunneling trajectory; and adjusting, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude, the first target articulation angle to obtain the second target articulation angle.

[0012] In some embodiments, obtaining sample articulation angles and sample attitude deviations; and

training a machine learning model, using the sample articulation angles and the sample attitude deviations as training data, with sample articulation angle adjustment amounts as label values, to obtain a trained articulation angle adjustment model, where adjusting, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude, the first target articulation angle to obtain the second target articulation angle includes: obtaining a first articulation angle adjustment amount by inputting the first target articulation angle and the attitude deviation into the articulation angle adjustment model; and adjusting the first target articulation angle using the first articulation angle adjustment amount to obtain the second target articulation angle.

[0013] In some embodiments, adjusting the first target correction torque of the propulsion system to obtain the third target correction torque and adjusting the first target articulation angle of the articulation system to obtain the third target articulation angle includes: calculating, based on the actual position of the actively articulated tunnel boring machine, a planned attitude corresponding to the actual position on the planned tunneling trajectory; and adjusting the first target correction torque to obtain the third target correction torque, and adjusting the first target articulation angle to obtain the third target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude.

[0014] In some embodiments, obtaining sample correction torques, sample articulation angles, and sample attitude deviations; and training a machine learning model, using the sample correction torques, the sample articulation angles, and the sample attitude deviations as training data, with sample correction torque adjustment amounts and sample articulation angle adjustment amounts as label values, to obtain a trained adjustment model, where adjusting the first target correction torque to obtain the third target correction torque, and adjusting the first target articulation angle to obtain the third target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude includes: obtaining a second correction torque adjustment amount and a second articulation angle adjustment amount by inputting the first target correction torque, the first target articulation angle, and the attitude deviation into the adjustment model; and adjusting the first target correction torque using the second correction torque adjustment amount to obtain the third target correction torque, and adjusting the first target articulation angle using the second articulation angle adjustment amount to obtain the third target articulation angle.

[0015] In some embodiments, calculating the planned tunneling trajectory includes: obtaining a first trajectory deviation, a first deviation speed, and a first deviation acceleration corresponding to an initial position of the actively articulated tunnel boring machine, as well as a second trajectory deviation, a second deviation speed, and a second deviation acceleration corresponding to an end position of the actively articulated tunnel boring machine, where the second trajectory deviation is determined based on the segment uplift amount and a curvature of the designed axis; constructing a trajectory deviation polynomial between the planned tunneling trajectory and the designed axis based on a driving position and the initial position of the actively articulated tunnel boring machine; solving, based on the first trajectory deviation, the first deviation speed, the first deviation acceleration, the second trajectory deviation, the second deviation speed, and the second deviation acceleration, the trajectory deviation polynomial to obtain values of unknown constants of the trajectory deviation polynomial; obtaining a trajectory deviation corresponding to the actual position using the trajectory deviation polynomial; and obtaining the planned tunneling trajectory based on the trajectory deviation.

[0016] In some embodiments, calculating a planned tunneling trajectory includes: obtaining a first trajectory

deviation, a first deviation speed, and a first deviation acceleration corresponding to an initial position of the actively articulated tunnel boring machine, as well as a second trajectory deviation, a second deviation speed, and a second deviation acceleration corresponding to an end position of the actively articulated tunnel boring machine, where the second trajectory deviation is determined based on the segment uplift amount and a curvature of the designed axis; constructing a trajectory deviation polynomial between the planned tunneling trajectory and the designed axis based on a driving position and the initial position of the actively articulated tunnel boring machine; solving, based on the first trajectory deviation, the first deviation speed, the first deviation acceleration, the second trajectory deviation, the second deviation speed, and the second deviation acceleration, the trajectory deviation polynomial to obtain values of unknown constants of the trajectory deviation polynomial; obtaining a trajectory deviation corresponding to the actual position using the trajectory deviation polynomial; and obtaining the planned tunneling trajectory based on the trajectory deviation; adjusting the planned tunneling trajectory includes: using a trajectory deviation corresponding to the current position as the second trajectory deviation during the calculation of the planned tunneling trajectory.

[0017] In some embodiments, obtaining a current working mode of the actively articulated tunnel boring machine, which includes a construction advance mode or a continuous mining mode, where adjusting the actual correction torque includes: adjusting the actual correction torque by adjusting a propulsion cylinder state of the propulsion system according to the current working mode.

[0018] In some embodiments, calculating an actual propulsion speed of the actively articulated tunnel boring machine; and controlling the actual propulsion speed to match a target propulsion speed.

[0019] In some embodiments, calculating an actual total thrust of the actively articulated tunnel boring machine; and controlling the actual total thrust to match the target total thrust.

[0020] According to another aspect of the present disclosure, there is provided a controller for an actively articulated tunnel boring machine, including: a data obtaining module configured to obtain an actual position of the actively articulated tunnel boring machine, a designed axis, and a segment uplift amount; a data processing module configured to calculate a planned tunneling trajectory based on the actual position, the designed axis, and the segment uplift amount; and a control module configured to adjust at least one of an actual correction torque of a propulsion system or an actual articulation angle of an articulation system of the actively articulated tunnel boring machine to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory.

[0021] In some embodiments, the data obtaining module is further configured to obtain a clearance between a shield tail of the actively articulated tunnel boring machine and a segment in a predetermined direction; and the data processing module is further configured to adjust the planned tunneling trajectory in a case where the clearance in the predetermined direction is less than a clearance threshold and the actively articulated tunnel boring machine is excavating in the predetermined direction.

[0022] According to another aspect of the present disclosure, there is provided a controller for an actively articulated tunnel boring machine, including: a memory; and a processor coupled to the memory, the processor is configured to perform the aforementioned propulsion control method based on instructions stored in the memory.

[0023] According to another aspect of the present disclosure, there is provided a control system for an actively articulated tunnel boring machine, including: the controller described above; a guidance measurement module

configured to measure the position and attitude of the actively articulated tunnel boring machine; a propulsion system configured to actuate movement of at least some propulsion cylinders of the actively articulated tunnel boring machine; and an articulation system configured to control movement of articulation cylinders.

[0024] In some embodiments, the control system further includes: a shield tail clearance measurement module configured to measure a clearance between a shield tail of the actively articulated tunnel boring machine and a segment.

[0025] In some embodiments, the control system further includes: sensors configured to measure a first pressure value and a first stroke value of some or all of the cylinders among the at least some propulsion cylinders; and measure a second pressure value and a second stroke value of some or all of articulation cylinders.

[0026] In some embodiments, the control system further includes: an interaction module configured to display information and receive user input information.

[0027] According to another aspect of the present disclosure, there is further provided a computer-readable storage medium stored thereon computer program instructions that, when executed by a processor, implement the above propulsion control method.

[0028] According to another aspect of the present disclosure, there is further provided a computer program, including: instructions that, when executed by a processor, cause the processor to perform the aforementioned propulsion control method.

[0029] Other features and advantages of the present invention will become apparent from the following detailed description of exemplary embodiments of the present disclosure with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] The accompanying drawings, which are incorporated in and constitute a portion of this specification, illustrate embodiments of the present disclosure and, together with the description, serve to explain the principles of the present disclosure.

[0031] The present disclosure will be more clearly understood from the following detailed description with reference to the accompanying drawings, in which:

[0032] Figure 1 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to some embodiments of the present disclosure;

[0033] Figure 2 is a horizontal schematic diagram of a tunneling trajectory according to some embodiments of the present disclosure;

[0034] Figure 3 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure;

[0035] Figure 4 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure;

[0036] Figure 5 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure;

[0037] Figure 6 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure;

[0038] Figure 7 is a schematic structure diagram of a controller for an actively articulated tunnel boring machine according to some embodiments of the present disclosure;

[0039] Figure 8 is a schematic structure diagram of a controller for an actively articulated tunnel boring machine according to other embodiments of the present disclosure;

5 [0040] Figure 9 is a schematic structure diagram of a controller for an actively articulated tunnel boring machine according to other embodiments of the present disclosure;

[0041] Figure 10 is a schematic structure diagram of a control system of an actively articulated tunnel boring machine according to some embodiments of the present disclosure;

10 [0042] Figure 11 is a schematic structure diagram of an actively articulated tunnel boring machine according to some embodiments of the present disclosure; and

[0043] Figure 12 is a schematic structure diagram of a control system of an actively articulated tunnel boring machine according to other embodiments of the present disclosure.

[0044] It should be understood that the dimensions of the various parts shown in the drawings are not necessarily drawn to the actual scale. In addition, the same or similar reference signs are used to denote the same or similar components.

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DETAILED DESCRIPTION OF THE EMBODIMENTS

[0045] Various exemplary embodiments of the present disclosure will now be described in detail with reference to the accompanying drawings. Notice that, unless otherwise specified, the relative arrangement, numerical expressions and values of the components and steps set forth in these examples do not limit the scope of the invention.

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[0046] At the same time, it should be understood that, for ease of description, the dimensions of the various parts shown in the drawings are not drawn to actual proportions.

[0047] The following description of at least one exemplary embodiment is in fact merely illustrative and is in no way intended as a limitation to the invention, its application or use.

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[0048] Techniques, methods, and apparatus known to those of ordinary skill in the relevant art may not be discussed in detail, but where appropriate, these techniques, methods, and apparatuses should be considered as part of the specification.

[0049] Of all the examples shown and discussed herein, any specific value should be construed as merely illustrative and not as a limitation. Thus, other examples of exemplary embodiments may have different values.

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[0050] Notice that, similar reference numerals and letters are denoted by the like in the accompanying drawings, and therefore, once an item is defined in a drawing, there is no need for further discussion in the accompanying drawings.

[0051] In recent years, with the advancement of technology, relevant research on the propulsion control of tunnel boring machines has gradually emerged. For instance, in continuous mining mode, the tunneling trajectory can be maintained within an allowable range of the designed axis by stabilizing and adjusting the resultant force point of the propulsion system. However, the tunneling conditions of a tunnel boring machine may vary significantly with geological conditions. Maintaining excavation along a designed axis poses safety risks in a case where navigating tunnel turns or encountering segment uplift. Moreover, in a case where the total propulsion

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thrust varies, the control scheme for the resultant force point exhibits instability in steering effects. A propulsion control method, a controller, and a control system for an actively articulated tunnel boring machine are provided, which are capable of reducing safety risks associated with maintaining excavation along the designed axis in a case where navigating tunnel turns or encountering segment uplift.

5 [0052] For a clear understanding of the object of the present disclosure, its technical solution and advantages, the present disclosure will be further described in detail below in conjunction with the accompanying drawings and embodiments.

[0053] Figure 1 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to some embodiments of the present disclosure, which is performed by a controller.

10 [0054] In step 110, an actual position of the actively articulated tunnel boring machine, a designed axis, and a segment uplift amount are obtained.

[0055] In some embodiments, the actual position and attitude of the actively articulated tunnel boring machine are determined by a guidance measurement module, or the actual position of the actively articulated tunnel boring machine is obtained based on the stroke values of some or all of the propulsion cylinders in the propulsion system and the stroke values of some or all of the articulation cylinders measured by sensors. The segment uplift amount is determined by comparing an upward or downward displacement of a segment after the segment has moved a certain distance away from the shield tail. The uplift amount may be input by a user via an interaction module or directly transmitted to a controller after being detected by sensors. The designed axis is a preset trajectory.

20 [0056] In step 120, a planned tunneling trajectory is calculated based on the actual position, the designed axis, and the segment uplift amount.

[0057] In some embodiments, as shown in Figure 2, within tunnel turns, the planned tunneling trajectory is located on an inner side of designed axis bends, thereby controlling and reducing construction risks. The dashed line in Figure 2 represents the planned tunneling trajectory, while the solid line represents a designed axis. The distance between the planned tunneling trajectory and the designed axis in the horizontal direction is related to the curvature of the designed axis, showing a positive correlation: the greater the curvature, the larger the distance. For example, a curve with a radius of 800m corresponds to a distance of 5mm. A curve with a radius of 500m corresponds to a distance of 10mm, etc.

25 [0058] In some embodiments, under conditions of segment uplift, the planned tunneling trajectory is positioned below the designed axis, thereby reducing the deviation between the completed tunnel and the designed axis. For example, given that the segment uplifts by 20mm after traveling a certain distance beyond the shield tail, the planned tunneling trajectory will be calculated to be 20mm below the designed axis.

[0059] In some embodiments, a controller obtains a first trajectory deviation, a first deviation speed, and a first deviation acceleration corresponding to an initial position of the actively articulated tunnel boring machine, as well as a second trajectory deviation, a second deviation speed, and a second deviation acceleration corresponding to an end position of the actively articulated tunnel boring machine, where the second trajectory deviation is determined based on the segment uplift amount and a curvature of the designed axis; construct a trajectory deviation polynomial between the planned tunneling trajectory and the designed axis based on a driving position and the initial position of the actively articulated tunnel boring machine; solve, based on the first trajectory deviation, the first deviation speed, the first deviation acceleration, the second trajectory deviation,

the second deviation speed, and the second deviation acceleration, the trajectory deviation polynomial to obtain unknown constants of the trajectory deviation polynomial; obtain the planned tunneling trajectory based on the trajectory deviation.

[0060] In some embodiments, a first-order partial derivative is taken with respect to the trajectory deviation polynomial to obtain a speed deviation polynomial, based on the driving position; and a second-order partial derivative is taken with respect to the trajectory deviation polynomial to obtain an acceleration deviation polynomial, based on the driving position, resulting in three polynomials. By substituting the first trajectory deviation, the first deviation speed, and the first deviation acceleration corresponding to the initial position of the tunnel boring machine, as well as the second trajectory deviation, the second deviation speed, and the second deviation acceleration corresponding to the end position of the tunnel boring machine into the polynomials, the unknown constants of the trajectory deviation polynomial are then solved. Subsequently, the actual position is substituted into this trajectory deviation polynomial to obtain a trajectory deviation. This trajectory deviation is then transformed to calculate the planned tunneling trajectory.

[0061] For example, the trajectory deviation polynomial is:

$$\mathbf{Yh(s)} = \mathbf{a_0} + \mathbf{a_1(s - s_0)} + \mathbf{a_2(s - s_0)^2} + \mathbf{a_3(s - s_0)^3} + \mathbf{a_4(s - s_0)^4} + \mathbf{a_5(s - s_0)^5}$$

$$\mathbf{Yv(s)} = \mathbf{a_6} + \mathbf{a_7(s - s_0)} + \mathbf{a_8(s - s_0)^2} + \mathbf{a_9(s - s_0)^3} + \mathbf{a_{10}(s - s_0)^4} + \mathbf{a_{11}(s - s_0)^5}$$

[0064] where, $\mathbf{s_0}$ denotes initial position, for example, expressed as initial mileage; $\mathbf{s}$ denotes driving position expressed as mileage, for example, $\mathbf{s_0 < s < s_1}$, where $\mathbf{s_1}$ denotes end position, for example, expressed as end mileage; $\mathbf{Yh(s)}$ denotes horizontal deviation between the planned tunneling trajectory and the designed axis; $\mathbf{Yv(s)}$ denotes vertical deviation between the planned tunneling trajectory and the designed axis, and $\mathbf{a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, a_{11}}$ are unknown constants of the trajectory deviation polynomial.

[0065] The first trajectory deviation, first deviation speed, and first deviation acceleration are known quantities. That is, the horizontal deviation, vertical deviation, horizontal deviation speed, vertical deviation speed, horizontal deviation acceleration, and vertical deviation acceleration of the initial mileage are all known quantities. The end mileage could be, for example, the upcoming 3rd ring to be advanced. Those skilled in the art should understand that this end mileage can be selected according to actual situations. The second trajectory deviation is determined based on the segment uplift amount and the curvature of the designed axis, while the second deviation speed and the second deviation acceleration are set to zero. That is, the horizontal deviation speed, vertical deviation speed, horizontal deviation acceleration, and vertical deviation acceleration corresponding to the end mileage are zero. The value of vertical deviation is equal to the negative of the segment uplift amount, and the value of horizontal deviation is determined according to a curvature corresponding to the designed axis, for example, 5 times the curvature. Those skilled in the art should understand that the horizontal deviation and the multiple factor of curvature can be set according to actual situations.

[0066] Taking the first-order derivative of $\mathbf{Yh(s) = a_0 + a_1(s - s_0) + a_2(s - s_0)^2 + a_3(s - s_0)^3 + a_4(s - s_0)^4 + a_5(s - s_0)^5}$ yields $\mathbf{Yh(s)' = a_1 + 2a_2(s - s_0) + 3a_3(s - s_0)^2 + 4a_4(s - s_0)^3 + 5a_5(s - s_0)^4}$. Taking the second-order derivative of $\mathbf{h(s) = a_0 + a_1(s - s_0) + a_2(s - s_0)^2 + a_3(s - s_0)^3 + a_4(s - s_0)^4 + a_5(s - s_0)^5}$ yields $\mathbf{Yh(s)'' = 2a_2 + 6a_3(s - s_0) + 12a_4(s - s_0)^2 + 20a_5(s - s_0)^3}$. Taking the first-order derivative of $\mathbf{Yv(s) = a_6 + a_7(s - s_0) + a_8(s - s_0)^2 + a_9(s - s_0)^3 + a_{10}(s - s_0)^4 + a_{11}(s - s_0)^5}$ yields $\mathbf{Yv(s)' = a_7 + 2a_8(s - s_0) + 3a_9(s - s_0)^2 + 4a_{10}(s - s_0)^3 + 5a_{11}(s - s_0)^4}$.

$s_0)^4$. Taking the second-order derivative of $\mathbf{Yv}(s) = \mathbf{a}_6 + \mathbf{a}_7(s - s_0) + \mathbf{a}_8(s - s_0)^2 + \mathbf{a}_9(s - s_0)^3 + \mathbf{a}_{10}(s - s_0)^4 + \mathbf{a}_{11}(s - s_0)^5$ yields $\mathbf{Yv}(s)'' = 2\mathbf{a}_8 + 6\mathbf{a}_9(s - s_0) + 12\mathbf{a}_{10}(s - s_0)^2 + 20\mathbf{a}_{11}(s - s_0)^3$.

[0067] By substituting the horizontal deviation, vertical deviation, horizontal deviation speed, vertical deviation speed, horizontal deviation acceleration, and vertical deviation acceleration of the initial mileage, as well as the horizontal deviation, vertical deviation, horizontal deviation speed, vertical deviation speed, horizontal deviation acceleration, and vertical deviation acceleration corresponding to the ending mileage into the above formula, $\mathbf{a}_0, \mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3, \mathbf{a}_4, \mathbf{a}_5, \mathbf{a}_6, \mathbf{a}_7, \mathbf{a}_8, \mathbf{a}_9, \mathbf{a}_{10}, \mathbf{a}_{11}$ can be derived.

[0068] Substituting the current actual mileage into the equations $\mathbf{Yh}(s) = \mathbf{a}_0 + \mathbf{a}_1(s - s_0) + \mathbf{a}_2(s - s_0)^2 + \mathbf{a}_3(s - s_0)^3 + \mathbf{a}_4(s - s_0)^4 + \mathbf{a}_5(s - s_0)^5$ and $\mathbf{Yv}(s) = \mathbf{a}_6 + \mathbf{a}_7(s - s_0) + \mathbf{a}_8(s - s_0)^2 + \mathbf{a}_9(s - s_0)^3 + \mathbf{a}_{10}(s - s_0)^4 + \mathbf{a}_{11}(s - s_0)^5$, with known variables, horizontal deviation $\mathbf{Yh}(s)$ and vertical deviation $\mathbf{Yv}(s)$ between the planned tunneling trajectory and the designed axis corresponding to the current actual mileage can be computed. Here, $\mathbf{Yh}(s)$ and $\mathbf{Yv}(s)$ represent the local tunneling trajectory in the Frenet coordinate system. The coordinates in the Cartesian coordinate system, namely the planned tunneling trajectory, can be obtained through coordinate transformation.

[0069] In step 130, at least one of an actual correction torque of a propulsion system or an actual articulation angle of an articulation system of the actively articulated tunnel boring machine is adjusted to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory.

[0070] In some embodiments, a first target correction torque of the propulsion system is adjusted to obtain a second target correction torque in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and an actual correction torque is adjusted to match the actual correction torque with the second target correction torque. The first target correction torque is a target correction torque before adjustment, and the second target correction torque is a target correction torque after adjustment. The actual correction torque is adjusted so that it reaches the adjusted target correction torque, thereby reducing the deviation between a future actual position and the planned tunneling trajectory and ensuring that the actual tunneling trajectory remains aligned with the planned tunneling trajectory.

[0071] In some embodiments, a first target articulation angle of the articulation system is adjusted to obtain a second target articulation angle in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and the actual articulation angle is adjusted to match the actual articulation angle with the second target articulation angle. The first target articulation angle is a target articulation angle before adjustment, and the second target articulation angle is a target articulation angle after adjustment. The actual articulation angle is adjusted so that it reaches the adjusted target articulation angle, thereby reducing the deviation between a future actual position and the planned tunneling trajectory and ensuring that the actual tunneling trajectory remains aligned with the planned tunneling trajectory. The articulation angle refers to the included angle between the front and rear sections of an actively articulated tunnel boring machine.

[0072] In some embodiments, the first target correction torque of the propulsion system is adjusted to obtain a third target correction torque and the first target articulation angle of the articulation system is adjusted to obtain a third target articulation angle, in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and the actual correction torque is adjusted to match the actual correction torque with the third target correction torque, and the actual articulation

angle is adjusted to match the actual articulation angle with the third target articulation angle. The first target correction torque is a target correction torque before adjustment, and the third target correction torque is a target correction torque after adjustment. The first target articulation angle is a target articulation angle before adjustment, and the third target articulation angle is a target articulation angle after adjustment. The actual correction torque is adjusted to reach the adjusted target correction torque, and the actual articulation angle is adjusted to reach the adjusted target articulation angle, thereby reducing the deviation between the future actual position and the planned tunneling trajectory, and keeping the actual tunneling trajectory on the planned tunneling trajectory.

[0073] In the above embodiments, the planned tunneling trajectory is dynamically determined based on information such as the designed axis, actual position, and segment uplift amount, and then at least one of the actual correction torque of the propulsion system of the actively articulated tunnel boring machine or the actual articulation angle of the articulation system is adjusted to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory, which enables the reduction of deviations between future actual positions and the planned tunneling trajectory, thereby safety risks associated with maintaining excavation along the designed axis in a case where navigating tunnel turns or encountering segment uplift.

[0074] Figure 3 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure.

[0075] In step 310, an actual position of an actively articulated tunnel boring machine, a designed axis, and a segment uplift amount, as well as a clearance between the shield tail of the actively articulated tunnel boring machine and a segment in a predetermined direction are obtained.

[0076] In some embodiments, a clearance between the shield tail and the segment is measured in real time by a shield tail clearance measurement module. The clearance in a predetermined direction includes, for example, a clearance between the right side of the shield tail and the segment, a clearance between the left side of the shield tail and the segment, a clearance between the upper side of the shield tail and the segment, and a clearance between the lower side of the shield tail and the segment.

[0077] In step 320, a planned tunneling trajectory is calculated based on the actual position, the designed axis, and the segment uplift amount.

[0078] In step 330, the planned tunneling trajectory is adjusted in a case where the clearance in the predetermined direction is less than a clearance threshold and the actively articulated tunnel boring machine is excavating in the predetermined direction.

[0079] In some embodiments, the trajectory deviation corresponding to the current position is taken as the second trajectory deviation in calculating the planned tunneling trajectory, and the planned tunneling trajectory is recalculated.

[0080] For example, if the clearance between the right side of the shield tail and the segment is less than a first threshold, and the horizontal deviation at the end mileage is greater than the horizontal deviation at the initial mileage, the horizontal trajectory deviation corresponding to the current actual position is taken as the horizontal deviation value at the end mileage for replanning the tunneling trajectory.

[0081] If the clearance between the left side of the shield tail and the segment is less than a second threshold, and the horizontal deviation at the end mileage is less than the horizontal deviation at the initial mileage, the horizontal trajectory deviation corresponding to the current actual position is taken as the horizontal deviation

value at the end mileage for replanning the tunneling trajectory.

[0082] If the clearance between the upper side of the shield tail and the segment is less than a third threshold, and the vertical deviation at the end mileage is greater than the vertical deviation at the initial mileage, the vertical trajectory deviation corresponding to the current actual position is taken as the vertical deviation at the end mileage for replanning the tunneling trajectory.

[0083] If the clearance between the lower side of the shield tail and the segment is less than a fourth threshold, and the vertical deviation at the end mileage is less than the vertical deviation at the initial mileage, the vertical trajectory deviation corresponding to the current actual position is taken as the vertical deviation at the end mileage for replanning the tunneling trajectory.

[0084] The first threshold, the second threshold, the third threshold, and the fourth threshold mentioned above can be the same or different, and can be set according to actual situations.

[0085] In step 340, at least one of an actual correction torque of a propulsion system or an actual articulation angle of an articulation system of the actively articulated tunnel boring machine is adjusted to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory.

[0086] In the above embodiments, during the startup or continuous excavation of the actively articulated tunnel boring machine, the planned tunneling trajectory is dynamically determined based on information such as the designed axis, actual position, and segment uplift amount. Additionally, by monitoring changes in the shield tail clearance, auxiliary adjustments are made to the planned tunneling trajectory. The actively articulated tunnel boring machine is then controlled to align its actual position with the planned tunneling trajectory, thereby reducing deviations between future actual positions and the planned tunneling trajectory. On one hand, safety risks associated with maintaining excavation along the designed axis in a case where navigating tunnel turns or encountering segment uplift is reduced. On the other hand, by taking into account the impact of attitude adjustments on the segments, it is possible to prevent segment damage and enhance operational safety.

[0087] Figure 4 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure.

[0088] In step 410, a planned attitude corresponding to the actual position on the planned tunneling trajectory is calculated, based on the actual position of the actively articulated tunnel boring machine.

[0089] In step 420, the first target correction torque is adjusted to obtain the second target correction torque, based on an attitude deviation between an actual attitude of the actively articulated tunnel boring machine and the planned attitude, .

[0090] In some embodiments, the first target correction torque and the attitude deviation are input into a correction torque adjustment model to obtain a first correction torque adjustment amount; and the first target correction torque is adjusted using the first correction torque adjustment amount to obtain the second target correction torque. The first target correction torque is a preset value, or equals a correction torque initially applied to the propulsion system. The correction torque adjustment model in this embodiment is trained based on machine learning algorithms.

[0091] In some embodiments, sample correction torques and sample attitude deviations are obtained; and the machine learning model is trained to obtain a trained correction torque adjustment model, using the sample correction torques and the sample attitude deviations as training data, with sample correction torque adjustment amounts as label values.

[0092] For example, the correction torque of the tunnel boring machine is adjusted to change the attitude of the tunnel boring machine. Correction torque and attitude information of the tunnel boring machine are collected and used as training data, with correction torque adjustment amounts as label values of the training data, output values of the machine learning model are compared with the label values, it is determined whether the comparison result meets the requirements of a loss function for constructing the correction torque adjustment model. By means of repeated iterations, parameters of the machine learning model are optimized and adjusted, ensuring that the comparison result ultimately satisfies the loss function requirements for building the correction torque adjustment model. This correction torque adjustment model is then saved.

[0093] By inputting the error between the actual horizontal attitude and the planned horizontal attitude, as well as the error between the actual vertical attitude and the planned vertical attitude, into the trained correction torque adjustment model, a first correction torque adjustment amount can be obtained. This first correction torque adjustment amount is added to the first target correction torque to yield the second target correction torque.

[0094] In some embodiments, the target correction torque includes a target horizontal correction torque and a target vertical correction torque.

[0095] Correction torque is a physical quantity that describes the rotational effect generated by multiple cylinders of the propulsion system around the horizontal and vertical axes of the tunnel boring machine. In related technologies, a resultant force point refers to a combined action point of multiple cylinders of the propulsion system.

[0096] In step 430, an actual correction torque is adjusted to match the actual correction torque with the second target correction torque.

[0097] In some embodiments, the actual correction torque is adjusted by adjusting the propulsion cylinder state of the propulsion system, to align the actual correction torque with the second target correction torque.

[0098] In some embodiments, the propulsion system enables the cylinders to operate along an axial direction. This propulsion system is arranged on a side of the tunnel boring machine, abuts against and supports the segment, and provides propulsion power for the tunnel boring machine. A correction torque of the cylinders can be determined based on the pressure value of the cylinders.

[0099] In some embodiments, the propulsion system of the actively articulated tunnel boring machine includes multiple cylinder zones spaced apart in a circumferential direction, with at least one cylinder point located within each cylinder zone. A controller obtains a target total thrust, a target horizontal correction torque, and a target vertical correction torque in the current working mode; constructs a first thrust distribution group such that the first thrust distribution group generates a unit thrust, the first thrust distribution group including first thrust values corresponding to the multiple cylinder zones; constructs a second thrust distribution group such that the second thrust distribution group generates a unit horizontal correction torque, the second thrust distribution group including second thrust values corresponding to the multiple cylinder zones; and construct a third thrust distribution group such that the third thrust distribution group generates a unit vertical correction torque, the third thrust distribution group including third thrust values corresponding to the multiple cylinder zones, the first, second, and third thrust distribution groups being linearly independent; obtains a propulsion force for each cylinder zone to control the states of the cylinders in the multiple cylinder zones accordingly based on the first thrust distribution group, the second thrust distribution group, the third thrust distribution group, as well as a target thrust, a target horizontal correction torque, and a target vertical correction torque.

[00100] In the above embodiment, by adjusting and stabilizing the actual correction torque to achieve the target correction torque, the actual tunneling trajectory is kept within an allowable range of the planned trajectory. This reduces the safety risks associated with maintaining the designed axis during tunnel turns or in the presence of segment uplift, and addresses the issue of unstable correction effects in resultant force point control schemes when the total propulsion thrust changes.

[00101] Figure 5 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure.

[00102] In step 510, a planned attitude corresponding to the actual position on the planned tunneling trajectory is calculated, based on the actual position of the actively articulated tunnel boring machine.

[00103] In step 520, the first target articulation angle is adjusted to obtain a second target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude.

[00104] In some embodiments, the first target articulation angle and the attitude deviation are input into an articulation angle adjustment model to obtain a first articulation angle adjustment amount; and the first target articulation angle is adjusted using the first articulation angle adjustment amount to obtain the second target articulation angle. The first target articulation angle is a preset value, or equals an articulation angle initially applied to the articulation system. The articulation angle adjustment model in this embodiment is trained based on machine learning algorithms.

[00105] In some embodiments, sample articulation angles and sample attitude deviations are obtained; and a machine learning model is trained to obtain a trained articulation angle adjustment model, using the sample articulation angles and the sample attitude deviations as training data, with sample articulation angle adjustment amounts as label values.

[00106] For example, the articulation angle of an articulation system is adjusted to change the attitude of the tunnel boring machine. Articulation angle and attitude information of the tunnel boring machine are collected and used as training data, with articulation angle adjustment amounts as label values of the training data, output values of the machine learning model are compared with the label values, and it is determined whether the comparison result meets the requirements of a loss function for constructing the articulation angle adjustment model. By means of repeated iterations, parameters of the machine learning model are optimized and adjusted, ensuring that the comparison result ultimately satisfies the loss function requirements for building the articulation angle adjustment model. This articulation angle adjustment model is then saved.

[00107] By inputting the error between the actual horizontal attitude and the planned horizontal attitude, as well as the error between the actual vertical attitude and the planned vertical attitude, into the trained articulation angle adjustment model, a first articulation angle adjustment amount can be obtained. This first articulation angle adjustment amount is added to a first target articulation angle to yield a second target articulation angle.

[00108] In some embodiments, the target articulation angle includes a target horizontal articulation angle and a target vertical articulation angle.

[00109] In step 530, an actual articulation angle is adjusted to match the actual articulation angle with the second target articulation angle.

[00110] In some embodiments, the actual articulation angle is adjusted by adjusting the articulation cylinder state of the articulation system, to align the actual articulation angle with the second target articulation angle.

[00111] In the above embodiment, by adjusting and stabilizing the actual articulation angle to achieve the target articulation angle, the actual tunneling trajectory is kept within an allowable range of the planned trajectory. This reduces the safety risks associated with maintaining the designed axis during tunnel turns or in the presence of segment uplift, and addresses the issue of unstable correction effects in resultant force point control schemes when the total propulsion thrust changes.

[00112] Figure 6 is a flowchart of a propulsion control method for an actively articulated tunnel boring machine according to other embodiments of the present disclosure.

[00113] In step 610, a planned attitude corresponding to the actual position on the planned tunneling trajectory is calculated, based on the actual position of the actively articulated tunnel boring machine.

[00114] In step 620, the first target correction torque is adjusted to obtain the third target correction torque, and the first target articulation angle is adjusted to obtain the third target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude.

[00115] In some embodiments, the first target correction torque, the first target articulation angle, and the attitude deviation are input into the adjustment model to obtain a second correction torque adjustment amount and a second articulation angle adjustment amount; and the first target correction torque is adjusted to obtain the third target correction torque using the second correction torque adjustment amount, and the first target articulation angle is adjusted using the second articulation angle adjustment amount to obtain the third target articulation angle.

[00116] In some embodiments, sample correction torques, sample articulation angles, and sample attitude deviations are obtained; and a machine learning model is trained to obtain a trained adjustment model, using the sample correction torques, the sample articulation angles and the sample attitude deviations as training data, with sample correction torque adjustment amounts and sample articulation angle adjustment amounts as label values.

[00117] By inputting the error between an actual horizontal attitude and a planned horizontal attitude, as well as the error between an actual vertical attitude and a planned vertical attitude, into the trained adjustment model, a second correction torque adjustment amount and a second articulation angle adjustment amount can be obtained. The second correction torque adjustment amount is added to a first target correction torque to yield a third target correction torque. The second target articulation angle is added to a first target articulation angle to obtain a third target articulation angle.

[00118] In step 630, the actual correction torque is adjusted to match the actual correction torque with the third target correction torque, and the actual articulation angle is adjusted to match the actual articulation angle with the third target articulation angle.

[00119] In the above embodiment, by adjusting and stabilizing the actual correction torque to achieve a target correction torque and the actual articulation angle to achieve a target articulation angle, the actual tunneling trajectory is kept within an allowable range of the planned trajectory. This reduces the safety risks associated with maintaining the designed axis during tunnel turns or in the presence of segment uplift, and addresses the issue of unstable correction effects in resultant force point control schemes when the total propulsion thrust changes.

[00120] In some embodiments, the current working mode of the tunnel boring machine is obtained, which includes a construction advance mode or a continuous mining mode. Based on the current working mode, the propulsion cylinder state of the propulsion system is adjusted to adjust the actual correction torque.

[00121] In the continuous mining mode, some cylinders retract during the propulsion process to enable partial segment assembly. During tunneling in the continuous mining mode, i.e., under conditions where some cylinders lack pressure due to segment assembly, the remaining active cylinders of the propulsion system are controlled to adjust and stabilize the actual correction torque until it reaches the target correction torque, thereby ensuring that the actual position during propulsion closely follows the planned trajectory.

[00122] In some embodiments of the present disclosure, based on project construction requirements, an interaction module receives a tunneling efficiency mode selected by the user. This tunneling efficiency mode includes a speed control mode and a thrust control mode.

[00123] In some embodiments, in the speed control mode, an actual propulsion speed for the tunnel boring machine is calculated; the actual propulsion speed is controlled to match the target propulsion speed, for example, keeping the actual propulsion speed within an allowable range of the target propulsion speed.

[00124] For example, the actual propulsion speed of the tunnel boring machine can be determined based on the stroke value of the propulsion cylinder. For example, the propulsion cylinder's stroke value at time t_1 is S_1 , the propulsion cylinder's stroke value at time t_2 is S_2 , and the speed $V=(S_2-S_1)/(t_2-t_1)$. This target propulsion speed is input by the user via an interaction module.

[00125] In some embodiments, in the speed control mode, the controller adjusts and stabilizes the actual propulsion speed of the propulsion system to reach the target propulsion speed when some cylinder thrusts are absent due to segment assembly.

[00126] In the above embodiment, by controlling the propulsion speed of the tunnel boring machine, construction quality and efficiency can be enhanced. Additionally, through the automatic control of the propulsion system, operator tasks during the tunneling process are reduced, thereby elevating the automation level of shield tunneling construction and minimizing the impact of human factors.

[00127] In some embodiments, an actual total thrust of the tunnel boring machine is calculated in a thrust control mode; and the actual total thrust is controlled to match a target total thrust, for example, remaining the actual total thrust within a target total thrust range. The target total thrust is input by the user via the interaction module. The actual total thrust of the tunnel boring machine is the sum of the pressures of all propulsion cylinders.

[00128] In some embodiments, in the thrust control mode, the controller controls the propulsion system to adjust and stabilize the actual total thrust to reach the target total thrust when cylinder thrust is partially absent during segment assembly.

[00129] In the above embodiment, by controlling the total thrust of the tunnel boring machine, construction quality and efficiency can be improved. Additionally, through the automatic control of the propulsion system, operator tasks during the tunneling process are reduced, which improves the automation level of shield construction and minimizes the impact of human factors.

[00130] In the embodiments of this disclosure, the tunnel boring machine can achieve propulsion along a planned axis at preset efficiency by adjusting the axial propulsion cylinders of the propulsion system and the articulation cylinders of the articulation system when operating in normal tunneling mode or continuous mining mode.

[00131] Figure 7 is a schematic structure diagram of a controller for an actively articulated tunnel boring machine according to some embodiments of the present disclosure. The controller includes a data obtaining module 710, a data processing module 720, and a control module 730.

[00132] The data obtaining module 710 is configured to obtain an actual position of the actively articulated tunnel boring machine, a designed axis, and a segment uplift amount.

[00133] In some embodiments, the data obtaining module 710 is further configured to obtain a clearance between a shield tail of the actively articulated tunnel boring machine and a segment in a predetermined direction.

5 The clearance in a predetermined direction includes, for example, a clearance between the right side of the shield tail and the segment, a clearance between the left side of the shield tail and the segment, a clearance between the upper side of the shield tail and the segment, and a clearance between the lower side of the shield tail and the segment.

[00134] In some embodiments, the data obtaining module 710 is further configured to obtain a current working mode of the actively articulated tunnel boring machine, the current working mode including a construction advance mode or a continuous mining mode.

[00135] The data processing module 720 is configured to calculate a planned tunneling trajectory based on the actual position, the designed axis, and the segment uplift amount.

15 [00136] In some embodiments, within tunnel turns, the planned tunneling trajectory is located on an inner side of designed axis bends. Under conditions of segment uplift, the planned tunneling trajectory is positioned below the designed axis.

[00137] In some embodiments, the data processing module 720 obtains a first trajectory deviation, a first deviation speed, and a first deviation acceleration corresponding to an initial position of the actively articulated tunnel boring machine, as well as a second trajectory deviation, a second deviation speed, and a second deviation acceleration corresponding to an end position of the actively articulated tunnel boring machine, where the second trajectory deviation is determined based on the segment uplift amount and a curvature of the designed axis; constructs a trajectory deviation polynomial between the planned tunneling trajectory and the designed axis based on a driving position and the initial position of the actively articulated tunnel boring machine; solves the trajectory deviation polynomial to obtain values of unknown constants of the trajectory deviation polynomial

20 based on the first trajectory deviation, the first deviation speed, the first deviation acceleration, the second trajectory deviation, the second deviation speed, and the second deviation acceleration; obtains a trajectory deviation corresponding to the actual position using the trajectory deviation polynomial; obtains the planned tunneling trajectory based on the trajectory deviation.

[00138] In some embodiments, the data processing module 720 is further configured to adjust the planned tunneling trajectory in a case where the clearance in the predetermined direction is less than a clearance threshold and the actively articulated tunnel boring machine is excavating in the predetermined direction. For example, the trajectory deviation corresponding to the current position is used as the second trajectory deviation during the calculation of the planned tunneling trajectory. Real-time monitoring of the shield tail clearance can prevent damage to the segments and enhance operational safety.

35 [00139] The control module 730 is configured to adjust at least one of the actual correction torque of the propulsion system or the actual articulation angle of the articulation system of the actively articulated tunnel boring machine, to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory.

[00140] In some embodiments, the control module 730 adjusts a first target correction torque of the propulsion system to obtain a second target correction torque in a case where there is a deviation between the actual position

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of the actively articulated tunnel boring machine and the planned tunneling trajectory; and adjusts the actual correction torque to match the actual correction torque with the second target correction torque.

[00141] In some embodiments, the control module 730 is further configured to adjust the actual correction torque by adjusting a propulsion cylinder state of the propulsion system according to the current working mode.

[00142] In some embodiments, a planned attitude corresponding to the actual position on the planned tunneling trajectory is calculated, based on the actual position of the actively articulated tunnel boring machine; and the first target correction torque is adjusted to obtain the second target correction torque, based on an attitude deviation between an actual attitude of the actively articulated tunnel boring machine and the planned attitude.

[00143] In some embodiments, the control module 730 adjusts a first target articulation angle of the articulation system to obtain a second target articulation angle in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and adjusts the actual articulation angle to match the actual articulation angle with the second target articulation angle.

[00144] In some embodiments, a planned attitude corresponding to the actual position on the planned tunneling trajectory is calculated, based on the actual position of the actively articulated tunnel boring machine; and the first target articulation angle is adjusted to obtain the second target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude.

[00145] In some embodiments, the control module 730 adjusts the first target correction torque of the propulsion system to obtain a third target correction torque and adjusts the first target articulation angle of the articulation system to obtain a third target articulation angle, in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and adjusts the actual correction torque to match the actual correction torque with the third target correction torque, and adjusts the actual articulation angle to match the actual articulation angle with the third target articulation angle.

[00146] In some embodiments, a planned attitude corresponding to the actual position on the planned tunneling trajectory is calculated, based on the actual position of the actively articulated tunnel boring machine; and the first target correction torque is adjusted to obtain the third target correction torque, and the first target articulation angle is adjusted to obtain the third target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude.

[00147] In some embodiments, as shown in Figure 8, the controller further includes a model training module 810 configured to obtain sample correction torques and sample attitude deviations; and train a machine learning model, using the sample correction torques and the sample attitude deviations as training data, with sample correction torque adjustment amounts as label values, to obtain a trained correction torque adjustment model, where the control module 730 obtains a first correction torque adjustment amount by inputting the first target correction torque and the attitude deviation into the correction torque adjustment model; and adjusts the first target correction torque using the first correction torque adjustment amount to obtain the second target correction torque.

[00148] The model training module 810 is further configured to obtain sample articulation angles and sample attitude deviations; and train a machine learning model, using the sample articulation angles and the sample attitude deviations as training data, with sample articulation angle adjustment amounts as label values, to obtain a trained articulation angle adjustment model, where the control module 730 obtain a first articulation angle adjustment amount by inputting the first target articulation angle and the attitude deviation into the articulation

angle adjustment model; and adjust the first target articulation angle using the first articulation angle adjustment amount to obtain a second target articulation angle.

[00149] The model training module 810 is further configured to obtain sample correction torques, sample articulation angles, and sample attitude deviations; and training a machine learning model, using the sample correction torques, the sample articulation angles and the sample attitude deviations as training data, with sample articulation angle adjustment amounts and sample articulation angle adjustment amounts as label values, to obtain a trained adjustment model, where the control module 730 obtains a second correction torque adjustment amount and a second articulation angle adjustment amount by inputting the first correction torque, the first target articulation angle and the attitude deviation into an adjustment model; and adjusts the first target correction torque using the second correction torque adjustment amount to obtain a third target correction torque, and adjusts the first target articulation angle using the second articulation angle adjustment amount to obtain a third target articulation angle.

[00150] In the above embodiments, the planned tunneling trajectory is dynamically determined based on information such as the designed axis, actual position, and segment uplift amount, and then the tunnel boring machine is controlled to match the actual position of the tunnel boring machine to the planned tunneling trajectory, which enables the reduction of deviations between future actual positions and the planned tunneling trajectory, thereby reducing safety risks associated with maintaining excavation along the designed axis in a case where navigating tunnel turns or encountering segment uplift.

[00151] In some embodiments of the present disclosure, the data processing module 720 is further configured to calculate the actual propulsion speed of the tunnel boring machine, and the control module 730 is further configured to control the actual propulsion speed to match the target propulsion speed.

[00152] The data processing module 720 is further configured to calculate an actual total thrust of the tunnel boring machine, and the control module 730 is further configured to control the actual total thrust to match a target total thrust.

[00153] By controlling the propulsion speed and total thrust of the tunnel boring machine, construction quality and efficiency can be improved.

[00154] Figure 9 is a schematic structure diagram of a controller for an actively articulated tunnel boring machine according to other embodiments of the present disclosure. The controller includes a memory 910 and a processor 920, where the memory 910 may be a magnetic disk, flash memory or any other non-volatile storage medium. The memory 910 is used to store instructions of the above embodiment. The processor 920 is coupled to the memory 910 and may be implemented as one or more integrated circuits, such as a microprocessor or microcontroller. The processor 920 is used to execute the instructions stored in the memory.

[00155] In some embodiments, the processor 920 is coupled to the memory 910 via a bus 930. The controller may be further connected to an external storage device 950 through a storage interface 940 to access external data, and may be further connected to a network or another computer system (not shown) through a network interface 960, the details of which will not be described herein.

[00156] In this embodiment, by storing data instructions in the memory and processing the aforementioned instructions through the processor, it is possible to reduce the safety risks associated with maintaining excavation along the designed axis in a case where navigating tunnel turns or encountering segment uplift, and address the issue of unstable correction effects in resultant force point control schemes when the total propulsion thrust

changes. Additionally, through the automatic control of the propulsion system, operator tasks during the tunneling process are reduced, thereby improving the automation level of shield tunneling construction, minimizing the impact of human factors, and improving construction quality and efficiency.

[00157] Figure 10 is a schematic structure diagram of a control system for an actively articulated tunnel boring machine according to some embodiments of the present disclosure. The control system includes a controller 1010, a guidance measurement module 1020, a propulsion system 1030 and an articulation system 1040, where the controller 1010 has been described in detail in the above embodiments and will not be repeated here. The guidance measurement module 1020, the propulsion system 1030 and the articulation system 1040 are electrically connected to the controller 1010.

[00158] The guidance measurement module 1020 is configured to measure the position and attitude of the actively articulated tunnel boring machine, and the propulsion system 1030 is configured to actuate the movement of at least some propulsion cylinders of the actively articulated tunnel boring machine. The propulsion system 1030 has its propulsion cylinders working along an axial direction, the propulsion cylinders being arranged on a side of the tunnel boring machine, and abutting against and supporting on the segments to provide propulsion power for the tunnel boring machine. For example, when the tunnel boring machine is in continuous mining mode, the propulsion system 1030 drives the movement of a portion of the cylinders. The articulation system 1040 is configured to control the movement of articulation cylinders. The articulation cylinders, arranged on the sides for connecting the front and rear sections of the tunnel boring machine, operate along the axial direction and transmit the power of the propulsion system from the rear section to the front section.

[00159] As shown in Figure 11, the propulsion system of the actively articulated tunnel boring machine includes propulsion cylinders 111, and the articulation system includes articulation cylinders 112.

[00160] In some embodiments, as shown in Figure 12, the control system further includes a shield tail clearance measurement module 1210 configured to measure a clearance between a shield tail of the actively articulated tunnel boring machine and the segment. The shield tail clearance measurement module 1210 is electrically connected to the controller 1010. The shield tail clearance measurement module is, for example, a laser detector.

[00161] In some embodiments, the control system further includes sensors 1220 configured to measure first pressure values and first stroke values of some or all of the cylinders among the at least some propulsion cylinders; and measure second pressure values and second stroke values of some or all of articulation cylinders. The sensors may include pressure sensors. Since not all cylinders are equipped with pressure sensors, it is possible to monitor only the pressure and stroke values of some cylinders. For example, the cylinders are grouped for controlling, such as Group A, Group B, Group C, and Group D. Each group contains one or more cylinders, and only one pressure sensor is configured on a specific cylinder in each group. In this case, the pressure sensor monitors the pressure of only one cylinder in each group. The sensors further include, for example, displacement sensors.

[00162] In some embodiments, the control system further includes an interaction module 1230 configured to display information and receive user input information. For example, the interaction module displays the tunneling trajectory, and receives user-input values such as segment uplift, target propulsion speed, and target total thrust. The interaction module is, for example, a user terminal such as a host computer.

[00163] In other embodiments, there is provided a computer-readable storage medium stored thereon computer program instructions that, when executed by a processor, implement the steps of the method of the above

embodiment. One skilled in the art should understand that, the embodiments of the present disclosure may be provided as a method, an apparatus, or a computer program product. Therefore, embodiments of the present disclosure can take the form of an entirely hardware embodiment, an entirely software embodiment or an embodiment containing both hardware and software elements. Moreover, the present disclosure may take the form of a computer program product embodied on one or more computer-usable non-transitory storage media (including but not limited to disk storage, CD-ROM, optical storage device, etc.) having computer-usable program code embodied therein.

[00164] According to some embodiments of the present disclosure, there is further provided a computer program, including: instructions that, when executed by a processor, cause the processor to preform the propulsion control method described above.

[00165] The present disclosure is described with reference to flowcharts and/or block diagrams of methods, apparatuses (systems) and computer program products according to embodiments of the present disclosure. It should be understood that each process and/or block in the flowcharts and/or block diagrams, and combinations of the processes and/or blocks in the flowcharts and/or block diagrams may be implemented by computer program instructions. The computer program instructions may be provided to a processor of a general purpose computer, a special purpose computer, an embedded processor, or other programmable data processing apparatus to generate a machine such that the instructions executed by a processor of a computer or other programmable data processing apparatus to generate means implementing the functions specified in one or more flows of the flowcharts and/or one or more blocks of the block diagrams.

[00166] The computer program instructions may also be stored in a computer readable storage device capable of directing a computer or other programmable data processing apparatus to operate in a specific manner such that the instructions stored in the computer readable storage device produce an article of manufacture including instruction means implementing the functions specified in one or more flows of the flowcharts and/or one or more blocks of the block diagrams.

[00167] These computer program instructions can also be loaded onto a computer or other programmable device to perform a series of operation steps on the computer or other programmable device to generate a computer-implemented process such that the instructions executed on the computer or other programmable device provide steps implementing the functions specified in one or more flows of the flowcharts and/or one or more blocks of the block diagrams.

[00168] Heretofore, the present disclosure has been described in detail. In order to avoid obscuring the concepts of the present disclosure, some details known in the art are not described. Based on the above description, those skilled in the art can understand how to implement the technical solutions disclosed herein.

[00169] The method and apparatus of the present disclosure may be implemented in many ways. For example, the method and apparatus of the present disclosure may be implemented by software, hardware, firmware, or any combination of software, hardware, and firmware. The above sequence of steps of the method is merely for the purpose of illustration, and the steps of the method of the present disclosure are not limited to the above-described specific order unless otherwise specified. In addition, in some embodiments, the present disclosure may also be implemented as programs recorded in a recording medium, which include machine-readable instructions for implementing the method according to the present disclosure. Thus, the present disclosure also covers a recording medium storing programs for executing the method according to the present disclosure.

[00170] Although some specific embodiments of the present disclosure have been described in detail by way of example, those skilled in the art should understand that the above examples are only for the purpose of illustration and are not intended to limit the scope of the present disclosure. It should be understood by those skilled in the art that the above embodiments may be modified without departing from the scope and spirit of the present disclosure. The scope of the disclosure is defined by the following claims.

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What is claimed is:

1. A propulsion control method for an actively articulated tunnel boring machine, comprising:

obtaining an actual position of the actively articulated tunnel boring machine, a designed axis, and a segment uplift amount;

calculating a planned tunneling trajectory based on the actual position, the designed axis, and the segment uplift amount; and

adjusting at least one of an actual correction torque of a propulsion system or an actual articulation angle of an articulation system of the actively articulated tunnel boring machine to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory.

2. The propulsion control method according to claim 1, further comprising:

obtaining a clearance between a shield tail of the actively articulated tunnel boring machine and a segment in a predetermined direction; and

adjusting the planned tunneling trajectory in a case where the clearance in the predetermined direction is less than a clearance threshold and the actively articulated tunnel boring machine is excavating in the predetermined direction.

3. The propulsion control method according to claim 1 or 2, wherein adjusting at least one of the actual correction torque of the propulsion system or the actual articulation angle of the articulation system of the actively articulated tunnel boring machine comprises:

adjusting a first target correction torque of the propulsion system to obtain a second target correction torque in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and

adjusting the actual correction torque to match the actual correction torque with the second target correction torque.

4. The propulsion control method according to claim 1 or 3, wherein adjusting at least one of the actual correction torque of the propulsion system or the actual articulation angle of the articulation system of the actively articulated tunnel boring machine comprises:

adjusting a first target articulation angle of the articulation system to obtain a second target articulation angle in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and

adjusting the actual articulation angle to match the actual articulation angle with the second target articulation angle.

5. The propulsion control method according to claim 1 or 2, wherein adjusting at least one of the actual correction torque of the propulsion system or the actual articulation angle of the articulation system of the actively articulated tunnel boring machine comprises:

adjusting a first target correction torque of the propulsion system to obtain a third target correction torque and adjusting a first target articulation angle of the articulation system to obtain a third target articulation angle, in a case where there is a deviation between the actual position of the actively articulated tunnel boring machine and the planned tunneling trajectory; and

adjusting the actual correction torque to match the actual correction torque with the third target correction torque, and adjusting the actual articulation angle to match the actual articulation angle with the third target articulation angle.

6. The propulsion control method according to claim 3, wherein adjusting the first target correction torque of the propulsion system to obtain the second target correction torque comprises:

calculating, based on the actual position of the actively articulated tunnel boring machine, a planned attitude corresponding to the actual position on the planned tunneling trajectory; and

adjusting, based on an attitude deviation between an actual attitude of the actively articulated tunnel boring machine and the planned attitude, the first target correction torque to obtain the second target correction torque.

7. The propulsion control method according to claim 6, further comprising:

obtaining sample correction torques and sample attitude deviations; and

training a machine learning model, using the sample correction torques and the sample attitude deviations as training data, with sample correction torque adjustment amounts as label values, to obtain a trained correction torque adjustment model, wherein adjusting, based on the attitude deviation between the actual attitude of the tunnel boring machine and the planned attitude, the first target correction torque to obtain the second target correction torque comprises:

obtaining a first correction torque adjustment amount by inputting the first target correction torque and the attitude deviation into the correction torque adjustment model; and

adjusting the first target correction torque using the first correction torque adjustment amount to obtain the second target correction torque.

8. The propulsion control method according to claim 4, wherein adjusting the first target articulation angle of the articulation system to obtain the second target articulation angle comprises:

calculating, based on the actual position of the actively articulated tunnel boring machine, a planned attitude corresponding to the actual position on the planned tunneling trajectory; and

adjusting, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude, the first target articulation angle to obtain the second target articulation angle.

9. The propulsion control method according to claim 8, further comprising:

obtaining sample articulation angles and sample attitude deviations; and

training a machine learning model, using the sample articulation angles and the sample attitude deviations as training data, with sample articulation angle adjustment amounts as label values, to obtain a trained articulation angle adjustment model, wherein adjusting, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude, the first target articulation angle to obtain the second target articulation angle comprises:

obtaining a first articulation angle adjustment amount by inputting the first target articulation angle and the attitude deviation into the articulation angle adjustment model; and

adjusting the first target articulation angle using the first articulation angle adjustment amount to obtain the second target articulation angle.

10. The propulsion control method according to claim 5, wherein adjusting the first target correction torque of the propulsion system to obtain the third target correction torque and adjusting the first target articulation angle of the articulation system to obtain the third target articulation angle comprises:

calculating, based on the actual position of the actively articulated tunnel boring machine, a planned attitude corresponding to the actual position on the planned tunneling trajectory; and

adjusting the first target correction torque to obtain the third target correction torque, and adjusting the first target articulation angle to obtain the third target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude.

11. The propulsion control method according to claim 10, further comprising:

obtaining sample correction torques, sample articulation angles, and sample attitude deviations; and

training a machine learning model, using the sample correction torques, the sample articulation angles, and the sample attitude deviations as training data, with sample correction torque adjustment amounts and sample articulation angle adjustment amounts as label values, to obtain a trained adjustment model, wherein adjusting

the first target correction torque to obtain the third target correction torque, and adjusting the first target articulation angle to obtain the third target articulation angle, based on the attitude deviation between the actual attitude of the actively articulated tunnel boring machine and the planned attitude comprises:

obtaining a second correction torque adjustment amount and a second articulation angle adjustment amount by inputting the first target correction torque, the first target articulation angle, and the attitude deviation into the adjustment model; and

adjusting the first target correction torque using the second correction torque adjustment amount to obtain the third target correction torque, and adjusting the first target articulation angle using the second articulation angle adjustment amount to obtain the third target articulation angle.

12. The propulsion control method according to any one of claims 1 to 11, wherein calculating the planned tunneling trajectory comprises:

obtaining a first trajectory deviation, a first deviation speed, and a first deviation acceleration corresponding to an initial position of the actively articulated tunnel boring machine, as well as a second trajectory deviation, a second deviation speed, and a second deviation acceleration corresponding to an end position of the actively articulated tunnel boring machine, wherein the second trajectory deviation is determined based on the segment uplift amount and a curvature of the designed axis;

constructing a trajectory deviation polynomial between the planned tunneling trajectory and the designed axis based on a driving position and the initial position of the actively articulated tunnel boring machine;

solving, based on the first trajectory deviation, the first deviation speed, the first deviation acceleration, the second trajectory deviation, the second deviation speed, and the second deviation acceleration, the trajectory deviation polynomial to obtain values of unknown constants of the trajectory deviation polynomial;

obtaining a trajectory deviation corresponding to the actual position using the trajectory deviation polynomial; and

obtaining the planned tunneling trajectory based on the trajectory deviation.

13. The propulsion control method according to claim 2, wherein:

calculating a planned tunneling trajectory comprises:

obtaining a first trajectory deviation, a first deviation speed, and a first deviation acceleration corresponding to an initial position of the actively articulated tunnel boring machine, as well as a second trajectory deviation, a second deviation speed, and a second deviation acceleration corresponding to an end position of the actively articulated tunnel boring machine, wherein the second trajectory deviation is determined based on the segment uplift amount and a curvature of the designed axis;

constructing a trajectory deviation polynomial between the planned tunneling trajectory and the

designed axis based on a driving position and the initial position of the actively articulated tunnel boring machine;

solving, based on the first trajectory deviation, the first deviation speed, the first deviation acceleration, the second trajectory deviation, the second deviation speed, and the second deviation acceleration, the trajectory deviation polynomial to obtain values of unknown constants of the trajectory deviation polynomial;

obtaining a trajectory deviation corresponding to the actual position using the trajectory deviation polynomial; and

obtaining the planned tunneling trajectory based on the trajectory deviation;

adjusting the planned tunneling trajectory comprises:

using a trajectory deviation corresponding to the current position as the second trajectory deviation during the calculation of the planned tunneling trajectory.

14. The propulsion control method according to claim 3 or 5, further comprising:

obtaining a current working mode of the actively articulated tunnel boring machine, which comprises a construction advance mode or a continuous mining mode, wherein adjusting the actual correction torque comprises:

adjusting the actual correction torque by adjusting a propulsion cylinder state of the propulsion system according to the current working mode.

15. The propulsion control method according to any one of claims 1 to 14, further comprising:

calculating an actual propulsion speed of the actively articulated tunnel boring machine; and

controlling the actual propulsion speed to match a target propulsion speed.

16. The propulsion control method according to any one of claims 1 to 15, further comprising:

calculating an actual total thrust of the actively articulated tunnel boring machine; and

controlling the actual total thrust to match the target total thrust.

17. A controller of an actively articulated tunnel boring machine, comprising:

a data obtaining module configured to obtain an actual position of the actively articulated tunnel boring machine, a designed axis, and a segment uplift amount;

a data processing module configured to calculate a planned tunneling trajectory based on the actual position, the designed axis, and the segment uplift amount; and

a control module configured to adjust at least one of an actual correction torque of a propulsion system or an actual articulation angle of an articulation system of the actively articulated tunnel boring machine to match the actual position of the actively articulated tunnel boring machine with the planned tunneling trajectory.

18. The controller according to claim 17, wherein:

the data obtaining module is further configured to obtain a clearance between a shield tail of the actively articulated tunnel boring machine and a segment in a predetermined direction; and

the data processing module is further configured to adjust the planned tunneling trajectory in a case where the clearance in the predetermined direction is less than a clearance threshold and the actively articulated tunnel boring machine is excavating in the predetermined direction.

19. A controller of an actively articulated tunnel boring machine, comprising:

a memory; and

a processor coupled to the memory, the processor configured to, based on instructions stored in the memory, carry out the propulsion control method according to any one of claims 1 to 16.

20. A control system for an actively articulated tunnel boring machine, comprising:

the controller according to any one of claims 17 to 19;

a guidance measurement module configured to measure the position and attitude of the actively articulated tunnel boring machine;

a propulsion system configured to actuate movement of at least some propulsion cylinders of the actively articulated tunnel boring machine; and

an articulation system configured to control movement of articulation cylinders.

21. The control system according to claim 20, further comprising:

a shield tail clearance measurement module configured to measure a clearance between a shield tail of the actively articulated tunnel boring machine and a segment.

22. The control system according to claim 20, further comprising:

sensors configured to measure a first pressure value and a first stroke value of some or all of the cylinders among the at least some propulsion cylinders; and measure a second pressure value and a second stroke value of some or all of articulation cylinders.

23. The control system according to any one of claims 20 to 22, further comprising:

an interaction module configured to display information and receive user input information.

24. A computer-readable storage medium stored thereon computer program instructions that, when executed by a processor, implement the propulsion control method according to any one of claims 1 to 16.

25. A computer program, comprising:

instructions that, when executed by a processor, cause the processor to perform the propulsion control method according to any one of claims 1 to 16.