Automation in Construction xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Automation in Construction

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

Electro-hydraulic control of high-speed segment erection processes

Lintao Wang [a,b], Wei Sun [a], Guofang Gong [b,*], Huayong Yang [b]

[a] School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China
[b] State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 12 August 2015
Received in revised form 15 July 2016
Accepted 22 August 2016
Available online xxxx

Keywords:
Shield tunneling machine
Segment erector
Electro-hydraulic control
Speed and position compound control

ABSTRACT

To improve the efficiency of constructing a tunnel lining, an effective high-speed segment erection system is desired. Due to the excessive positioning errors and large joint forces caused by high speed and large inertia loads, a conventional segment erector is unable to achieve a high-speed erection process. To reduce the steady-state positioning error of a segment erector under high-speed working conditions, this work presents a speed and position compound control system (SPCS) based on the electro-hydraulic proportional control technology. A combined motion law with a smooth and continuous changing speed is adopted for the erecting motion to reduce joint force. Experiments are carried out on a Φ2.2 m segment erector test rig to evaluate the performances of the designed control system. Experimental results show that the SPCS is superior to the position feedback control system (PFCS) in terms of accuracy and joint force under high-speed working conditions. The maximum rotation speed of the erector with the SPCS can reach up to thrice that of the conventional segment erection system without decreasing the positioning precision and increasing the joint force. To further increase the segment erecting efficiency, a parallel speed and position compound control system (PSPCS) with multi-axis simultaneous movements is proposed. The coupling effects of the three positioning motions are analyzed. According to the experimental results, the time consumed by the erection system with PSPCS on the segment positioning process is further reduced to approximate one third of that by the erection system with SPCS.

1. Introduction

The shield tunneling machine (STM) is a typical modern construction machinery that is widely applied in excavating tunnels in soft ground [1,2]. Using the shield construction method, the tunnel lining is built with prefabricated concrete segments to support the free face behind the STM. Segments are placed on the right positions by a robotic manipulator which is referred as the segment erector, and then manually connected with bolts to form the segment ring and the tunnel lining [3]. The main process of the tunnel lining construction is shown in Fig. 1.

The main structure of a typical segment erector is shown in Fig. 2. The installation process of a segment consists of two procedures: segment positioning and attitude adjusting [4]. Lifting (LFT), sliding (SLD), and rotating (ROT) are the three positioning motions in three different directions. Two lifting cylinders are utilized to lift the segment in the radial direction. A sliding cylinder is used to drive the clamping head moving in the axial direction. A hydraulic motor drives the erector to rotate around the central axis of the tunnel through a gear reducer. The primary functions of the clamping head are to grip the segment and to perform attitude adjusting motions. The time spent on the segment positioning is significantly longer than that on attitude adjusting. The segment positioning process is thus the focus of this stud.

Segment erection is a time-consuming process. On one hand, a large number of segments need to be assembled to construct a tunnel. For example, to construct a 10-km-long tunnel, over 60 000 segments need to be installed. On the other hand, the time spent to build one ring of segments is longer than that to excavate a distance with the same width as the segment. Therefore, increasing the segment erection speed can directly improve the efficiency of the tunnel lining construction.

Automating the segment positioning and increasing the speed of positioning motions are effective means to improve the efficiency of the tunnel lining construction. In the past decades, several automatic segment assembly systems have been applied in practice for STMs [5,6]. However, most of these systems are position-controlled devices. An inevitable problem for these large-inertia erection systems controlled by direction control valves is the contradiction between speed and precision. If a high positioning speed is not handled appropriately, it may lead to big positioning error and joint force. Because of these limitations, the maximum rotation speed of a practical segment erector is 1.5 rpm, which cannot satisfy the requirement of highly efficient shield tunneling [7]. In addition, all the existing segment erectors perform the three positioning motions sequentially (termed as sequential mode), i.e., the erector initially lifts the segment, rotates, and finally slides the segment into the target position. Therefore, the time spent on segment

* Corresponding author.
E-mail address: gfgong@zju.edu.cn (G. Gong).

http://dx.doi.org/10.1016/j.autcon.2016.08.037
0926-5805/© 2016 Published by Elsevier B.V.

Nomenclature

b	compensating voltage of position control system
b_v	compensating voltage of speed control system
D_m	volumetric displacement of hydraulic motor
E_θ	steady-state error of erector rotation angle
G_s	gravity of segment
i	gear ratio of the rotation drive
I_v	valve input current
J	rotary inertia of ROT motion
k_i	integral gain for position control
k_{iv}	integral gain for speed control
k_p	proportional gain for position control
k_{pv}	proportional gain for speed control
K_{au}	acceleration feedback coefficient
K_h	gain of the valve control motor system
K_{ui}	gain of the proportional valve amplifier
K_v	gain of the valve
l_1	initial distance from O_A to $O_{C'}$ along the y_B-axis
l_2	perpendicular distance from $O_{C'}$ to the axis of the sliding guide
l_3	perpendicular distance from K_3 to the axis of the sliding guide
l_4	perpendicular distance from O_A to the axis of the lifting guide
l_5	initial perpendicular distance from K_3 to the axis of the lifting guide
T_r	duration of the reference signal
x_l, x_s	displacements of the lifting and sliding cylinders
v_l, v_s	practical speed of the lifting and sliding cylinders
v_{Tl}, v_{Ts}	theoretical speed of lifting and sliding cylinders
V_0	total compressed volume
ω	rotation speed of hydraulic motor
ω_T	theoretical rotation speed of hydraulic motor
ω_m	hydraulic natural frequency of the ROT driving system
ω_h, ζ_h	hydraulic natural frequency and hydraulic damping ratio
ω_v, ζ_v	natural frequency and damping ratio of the valve
φ	output angle of the hydraulic motor
θ	rotation angle of the erector
$\dot{\theta}_d$	desired rotation speed of the erector
ε	angular acceleration of the erector
β_e	equivalent bulk modulus
ζ	theoretical maximum rotation speed of hydraulic motor

positioning is always longer than the total time to complete the three positioning motions. Hence, an appropriate segment erector control system must be designed and used to improve the efficiency of the tunnel lining construction.

In this study, a novel parallel speed and position compound control system was designed, and proportional direction control valves are used. Distinct from the high-speed segment erection system in the previous work [8], this novel system can perform the three segment erection motions simultaneously, which is significant to improve the segment erection efficiency. This new system was developed through two steps. To reduce the positioning error and joint force of the conventional position feedback control system caused by large inertia and high motion speed, a speed and position compound control system was designed and used in the erection motion control. A combined motion law with smooth and continuous changing speed was adopted for the erecting motion so as to reduce the joint force. To further increase the segment erecting efficiency, a novel parallel speed and position compound control system with multi-axis simultaneous movements was proposed. Experiments were then performed on a Φ2.2 m segment erector test rig to evaluate the performance of each designed control system.

2. Mathematical modeling

2.1. Kinematic analysis of the positioning process

In controlling a segment erector to place the segment in the appropriate location, the target displacements of the corresponding actuators must be initially determined. To describe the position of the segment in space, the coordinate systems are established as shown in Fig. 3. A global coordinate system $\{A\}$ is attached to the STM. Its origin is in point O_A which is located at the center of the erector. Plane O_A-x_Ay_A is perpendicular to the tunnel axis. The local coordinate system $\{B\}$ is attached to the rotating frame, and its original point O_B is also located at the center of the erector. The z_B-axis coincides with the rotation axis of the erector. Points K_1, K_2, and K_3 denote the centroids of the rotating frame, the lifting frame, and the segment, respectively. In this work, the coordinate of point K_3 is used to represent the position of the segment. To describe the positions of points K_1, K_2, and K_3, the vectors from point O_A to points K_1, K_2, and K_3 with respect to coordinate system $\{A\}$ are written as

$$\begin{cases} {}^A\boldsymbol{r}_{K_1} = {}^A\boldsymbol{r}_{O_B} + {}^A_B\boldsymbol{R}\cdot{}^B\boldsymbol{O}_B\boldsymbol{K}_1 \\ {}^A\boldsymbol{r}_{K_2} = {}^A\boldsymbol{r}_{O_B} + {}^A_B\boldsymbol{R}\cdot\left({}^B\boldsymbol{r}_{O_{B'}} + {}^B\boldsymbol{O}_B\boldsymbol{O}_{C'} + {}^B\boldsymbol{O}_{C'}\boldsymbol{K}_2\right) \\ {}^A\boldsymbol{r}_{K_3} = {}^A\boldsymbol{r}_{O_B} + {}^A_B\boldsymbol{R}\cdot\left({}^B\boldsymbol{r}_{O_{B'}} + {}^B\boldsymbol{O}_{B'}\boldsymbol{O}_C + {}^B\boldsymbol{O}_C\boldsymbol{O}_D + {}^B\boldsymbol{O}_D\boldsymbol{K}_3\right) \end{cases}, \tag{1}$$

where ${}^A_B\boldsymbol{R}$ is the rotation transformation matrix from coordinate system$\{B\}$ to $\{A\}$. In this paper, the left superscript letter of a vector indicates that this vector is described in the corresponding coordinate system.

The target position of the segment is supposed at point K_{3T} (x_T, y_T, z_T). Based on Eq. (1), the target displacement of each actuator to place the segment onto the target position can be determined as

$$\begin{cases} \varphi = i\theta = \tan^{-1}(x_T/y_T) \\ x_l = {}^B\boldsymbol{\tau}_2\cdot\left[{}^A_B\boldsymbol{R}^T\left({}^A\boldsymbol{r}_{k_3} - {}^A\boldsymbol{r}_{O_B}\right)\right] - l_1 - l_2 - l_3 \\ x_s = {}^B\boldsymbol{\tau}_3\cdot\left[{}^A_B\boldsymbol{R}^T\left({}^A\boldsymbol{r}_{k_3} - {}^A\boldsymbol{r}_{O_B}\right)\right] - l_4 - l_5 \end{cases}, \tag{2}$$

where ${}^B\boldsymbol{\tau}_2$is the unit direction vector of the y_B-axis, ${}^B\boldsymbol{\tau}_3$is the unit direction vector of the z_B-axis. The rotation transformation matrix ${}^A_B\boldsymbol{R}$ is equivalent to $\boldsymbol{Rot}(z_A,\theta)$.

To evaluate the coupling effects between the positioning motions in the subsequent sections, the acceleration vectors of the centroid points K_1, K_2, and K_3 are derived by differentiating Eq. (1) twice as follows:

$${}^A\boldsymbol{a}_{k_1} = \hat{\boldsymbol{\varepsilon}}\left({}^A_B\boldsymbol{R}{}^B\boldsymbol{O}_B\boldsymbol{K}_1\right) + \hat{\boldsymbol{\omega}}\left(\hat{\boldsymbol{\omega}}{}^A_B\boldsymbol{R}{}^B\boldsymbol{O}_B\boldsymbol{K}_1\right), \tag{3}$$

$$\begin{aligned} {}^A\boldsymbol{a}_{k_2} = {} & \hat{\boldsymbol{\varepsilon}}{}^A_B\boldsymbol{R}\left[{}^B\boldsymbol{\tau}_2(l_{C'} + x_l) + {}^B\boldsymbol{\tau}_3(l_3 + l_{k2})\right] \\ & + \hat{\boldsymbol{\omega}}\left\{\hat{\boldsymbol{\omega}}{}^A_B\boldsymbol{R}\left[{}^B\boldsymbol{\tau}_2(l_{C'} + x_l) + {}^B\boldsymbol{\tau}_3(l_3 + l_{k2})\right]\right\} + 2\hat{\boldsymbol{\omega}}{}^A_B\boldsymbol{R}{}^B\boldsymbol{\tau}_2\dot{x}_l \\ & + {}^A_B\boldsymbol{R}{}^B\boldsymbol{\tau}_2\ddot{x}_l, \end{aligned} \tag{4}$$

$$\begin{aligned} {}^A\boldsymbol{a}_{k_3} = {} & \hat{\boldsymbol{\varepsilon}}{}^A_B\boldsymbol{R}\left[{}^B\boldsymbol{\tau}_2(l_1 + x_l) + {}^B\boldsymbol{\tau}_3(l_3 + l_4 + x_s)\right] \\ & + \hat{\boldsymbol{\omega}}\left\{\hat{\boldsymbol{\omega}}{}^A_B\boldsymbol{R}\left[{}^B\boldsymbol{\tau}_2(l_1 + x_l) + {}^B\boldsymbol{\tau}_3(l_3 + l_4 + x_s)\right]\right\}, \\ & + 2\hat{\boldsymbol{\omega}}{}^A_B\boldsymbol{R}\left({}^B\boldsymbol{\tau}_2\dot{x}_l + {}^B\boldsymbol{\tau}_3\dot{x}_s\right) + {}^A_B\boldsymbol{R}\left({}^B\boldsymbol{\tau}_2\ddot{x}_l + {}^B\boldsymbol{\tau}_3\ddot{x}_s\right) \end{aligned} \tag{5}$$

where $\boldsymbol{\omega}$ is the vector of the rotation speed of coordinate system $\{B\}$, and $\boldsymbol{\varepsilon}$ is the vector of the angular acceleration of coordinate system $\{B\}$. In this case, $\hat{\boldsymbol{\omega}}$ denotes $\boldsymbol{\omega}\times$ and $\hat{\boldsymbol{\varepsilon}}$ denotes $\boldsymbol{\varepsilon}\times$.

Please cite this article as: L. Wang, et al., Electro-hydraulic control of high-speed segment erection processes, Automation in Construction (2016), http://dx.doi.org/10.1016/j.autcon.2016.08.037