Track Tension Optimization for Stair-Climbing of a Wheelchair Robot with Variable Geometry Single Tracked Mechanism

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Abstract—This paper introduces an originally designed wheelchair robot. This robot is equipped with a novel type of Variable Geometry Single Tracked Mechanism (VGSTM) that can actively control the robot shape and the track tension. So it becomes possible to improve the obstacle clearing capability of the robot by adapting the robot shape for the obstacle. The track tension is closely related to the performance of this original wheelchair robot, so with the aim of stair-climbing, which is the most fundamental obstacle clearing performance of the wheelchair robot, the optimization model of the track tension is established based on the geometric model and the static model of the robot. Then the simulation is performed, and the optimal track tension values of the robot for different phases of stair-climbing are obtained. Finally, these track tension values are verified through the experiment.

I. INTRODUCTION

The traditional wheelchair, as a very important mobility assistance device for some aged and physically disabled persons, has high mobility on even terrain. However, when facing some obstacles such as stairs, the locomotion of the wheelchair will be seriously limited, which brings great discommodity to the user. For the purpose of improving the obstacle clearing capability, especially the capability of stair-climbing, many researchers have tried to equip the traditional wheelchair with locomotion mechanisms of mobile robots to construct a wheelchair robot.

To the authors’ knowledge, there are mostly three types of locomotion mechanisms applied in mobile robots that are appropriate for stair-climbing, and they are wheeled type mechanisms, legged type mechanisms, and tracked type mechanisms. Wheelchair robots equipped with wheeled type mechanisms, which are usually in the form of wheel cluster, can perform stair-climbing movement [1], but the climbing process may be uncomfortable for passengers because of the orbiting motion of the wheel cluster, and the security cannot be guaranteed without appropriate assistance. Legged type mechanisms can bring high capability of stair-climbing to wheelchair robots, but the structure of the mechanisms is excessively complex [2-3]. Compared to these two types of mechanisms, wheelchair robots equipped with tracked type mechanisms have better stationarity because of the larger contact area with the stairs, and the structure of the mechanisms is compact enough [4-5]. However, when climbing to the peak of the stairs, if the tracked mechanism is in the form of single-section, the robot will have difficulty in stable transformation of its posture, and even if the tracked mechanism is in the form of multi-section, the moving process of the robot will still not be smooth enough.

To improve the terrain adaptability of common tracked type wheelchair robots for the peak of the stairs, we have proposed a wheelchair robot equipped with a novel type of Variable Geometry Single Tracked Mechanism (VGSTM) [6]. Different from general VGSTMs [7-8], this mechanism can actively control the robot shape and the track tension to adapt the robot shape for the obstacles. Thus, the wheelchair robot equipped with this mechanism will have better capability of stair-climbing.

The track tension plays a significant role in the stair-climbing performance of this wheelchair robot. If the track tension is too low, the tractive force between the track and the stairs may be insufficient, and the skip between the track and the driving wheel may happen. If the track tension is too high, excessive load will be generated on the track and the mechanism system to reduce the power efficiency and the component life. In order to maintain the optimal track tension during stair-climbing, the track tension optimization of the wheelchair robot is indispensable. In this paper, first, the design of our wheelchair robot and its stair-climbing performance are introduced. Then the geometric model that describes the relative position to the stairs and the shape of the robot is presented, and the static model including the track tension is established. Following that, the optimization model of the track tension is established and the simulation is performed to obtain the optimal track tension values for different climbing phases. Finally, the stair-climbing experiment is conducted to verify these track tension values.

II. ROBOT DESCRIPTION

A. Mechanism and Control System

The mechanism of the wheelchair robot consists of a chassis with a chair on the top and two VGSTMs installed symmetrically at the flanks of the chassis, as shown in Fig. 1. In the VGSTMs, two back flippers can be driven synchronously to control the robot shape, and two front flippers can be driven synchronously to control the track
tension. Two pairs of planetary wheels are attached at the tip of the flippers, and the two back planetary wheels are also used as the driving wheels that can be driven independently to realize moving and steering of the robot. Some road wheels, guide wheels, and idlers are also installed to assist the mechanism to work.

The wheelchair robot is equipped with an inclinometer on the chair to read its pitch angle and a torque sensor at the revolute joint of the front flippers to detect the received torque. With a standard joystick and the information acquired from the sensors, the robot can perform stair-climbing in the tele-controlling mode or the semiautomatic mode.

B. Stair-Climbing Performance

The stair-climbing procedure of the wheelchair robot can be divided into four phases. In phase 1, the back and the front flippers of the robot rotate counter-clockwise to definite angles to make the chair retroverted, as shown in Fig. 2(a). In phase 2, the robot starts to climb the first several stairs backward. When the pitch angle of the chair reaches a definite value, as the robot moves on, the back and the front flippers rotate counter-clockwise sequentially to keep the expected chair obliquity, as shown in Fig. 2(b)~(d). In phase 3, the robot has climbed onto the stairs completely and goes on moving on the nose line of the stairs with the back flipper keeping at the terminal position, as shown in Fig. 2(e). In phase 4, when the back flipper passes over the nose of the last stair completely, the robot stops moving and the back flipper rotates clockwise to make the robot shape adapt for the peak of the stairs until the back planetary wheel has supported on the upper floor, as shown in Fig. 2(f). Then the robot keeps on climbing with the back and the front flippers rotating clockwise until the robot loads on the upper floor completely, as shown in Fig. 2(g)~(h).

In this paper, the analysis will focus on phase 2, phase 3, and the late stage of phase 4 of the stair-climbing procedure when the wheelchair robot is moving on the stairs and the track tension required for the robot is more strictly. According to different contact conditions between the robot and the stairs, we have defined several motion states for these phases.

1) Phase 2: State 2a and 2b indicates the conditions that only the driving wheel or the bottom track segment supports on the nose of the stairs separately. State 2a is shown in Fig. 2(b), and state 2b is an ideal state only happens when the track tension increases to an unacceptable high value. State 2c and 2d indicate the conditions that the bottom track segment supports on the nose of the stairs, and at the same time, the driving wheel also supports on the tread or the nose of the stairs separately, as shown in Fig. 2(c) and Fig. 2(d).

2) Phase 3: State 3a indicates the condition that there are three contact points between the bottom track segment and the stairs. State 3b and 3c indicate the conditions that there are four contact points between the bottom track segment and the stairs, and at the same time, the driving wheel supports or does not support on the stairs separately.

3) Phase 4: State 4a, 4b, and 4c indicate the conditions that there are three contact points, two contact points, or only one contact point between the bottom track segment and the stairs separately.

III. GEOMETRIC MODEL

A. Coordinate system

In the symmetry plane of the robot mechanism, the coordinate system is defined as follows: frame $o_{xy}z_{W}$ is fixed on the lower floor of the stairs; frame $A-x_0y_0z_4$ is attached to the chassis of the robot to represent the position of the front road wheels and the chair obliquity; frames $B-x_0y_0z_B$ and $C-x_0y_0z_C$ are attached to the front and the back flippers separately to represent their rotations, as shown in Fig. 3.

In the coordinate system, some points are defined to denote the significant positions of the robot mechanism and the stairs, as shown in Fig. 3. When the design parameters of the robot and the stairs are determined, these points can all be expressed in the corresponding frames [6], and the relative position to the stairs and the shape of the robot can be described by the vector $\tilde{q}$:

$$\tilde{q} = \begin{bmatrix} x^w_i \\ z^w_i \\ \theta \\ \alpha \\ \beta \end{bmatrix}$$

where $(x^W_i, z^W_i)$ is the coordinates of point $A$ in plane $x_0y_0z_4$; $\theta$ is the rotation angle from frame $o_{xy}z_{W}$ to frame $o_{xy}x_0y_0z_4$ that can represent the chair obliquity; $\alpha$ and $\beta$ are the rotation angles from frame $A-x_0y_0z_4$ to frames $B-x_0y_0z_B$ and $C-x_0y_0z_C$ separately that can represent the rotations of the front and the back flippers.

B. Equations of the Back Flipper

During stair-climbing, the wheelchair robot needs to keep appropriate chair obliquity by rotating the back flipper. According to the position of the back planetary wheel subjected to the stairs, the equations of the back flipper that represent the variations of the pitch angle of the chair and the rotation angle of the back flipper are derived as follows:

1) Phase 2:

State 2a, 2d:

$$f_{2a}(\tilde{q}) = (x^w_i - x^w_0) + (z^w_i - z^w_0) - r^2 = 0 \quad (1)$$

State 2b (assuming the bottom track segment is straight)
Fig. 2. Stair-climbing procedure of the wheelchair robot. (a) Transforming on the lower floor. (b)–(d) Climbing the first several stairs. (e) Moving on the nose line of the stairs. (f) Adapting for the peak of the stairs. (g)–(h) Loading on the upper floor.

Fig. 3. Coordinate system of the wheelchair robot.

\[
f_{s_{22}}(\hat{q}) = \left[ \tan(\kappa_{621}^w) x_{22}^w + z_{22}^w - \tan(\kappa_{621}^w) x_{32}^w - z_{32}^w \right] - r_1 = 0 \quad (2)
\]

State 2c:

\[
f_{s_{22}}(\hat{q}) = z_{32}^w - z_{30}^w - r_1 = 0 \quad (3)
\]

2) Phase 3:

\[
f_{s_{22}}(\hat{q}) = \left[ \tan(\varphi) x_{23}^w + z_{23}^w - h \right] - r_1 = 0 \quad (4)
\]

3) Phase 4:

\[
f_{s_{22}}(\hat{q}) = z_{33}^w - (z_{30}^w + r_1) = 0 \quad (5)
\]

where \( r_1 \) is the radius of the back planetary wheel; \( \kappa_{621}^w \) is the direction angle from point \( N_1 \) to point \( A' \) in plane \( x_{20}^w-y_{20}^w-z_{20}^w \); \( h \) and \( \varphi \) are the riser height and the incline angle of the stairs.

C. Equations of the Front Flipper

The wheelchair robot needs to keep appropriate track tension by rotating the front flipper. According to the position of the front planetary wheel subjected to the track length, the equations of the front flipper that represent the variation of the rotation angle of the front flipper are derived as follows:

1) Straight bottom track segment (state 2a, 2b, phase 3):

\[
f_{f_{11}} = L - \angle A \times r_2 - L_{230} - \angle D \times r_1 - L_{123} - \angle F \times r_1
- \angle C \times r_2 - L_{231} - \angle E \times r_1 - L_{121} = 0
\]

\[
f_{f_{12}} = L - \angle A \times r_2 - L_{230} - \angle D \times r_2 - L_{120} - \angle F \times r_1
- \angle G \times r_1 - L_{120} - \angle E \times r_1 - L_{121} = 0
\]

\[
f_{f_{12}}(\hat{q}) = \left\{ \begin{array}{l}
f_{f_{11}} = L - \angle A \times r_2 - L_{230} - \angle D \times r_1 - L_{123} - \angle F \times r_1
- \angle C \times r_2 - L_{231} - \angle E \times r_1 - L_{121} = 0

f_{f_{12}} = L - \angle A \times r_2 - L_{230} - \angle D \times r_2 - L_{120} - \angle F \times r_1
- \angle G \times r_1 - L_{120} - \angle E \times r_1 - L_{121} = 0
\end{array} \right\} (6)
\]

2) Folded bottom track segment (State 2c, 2d, phase 4):

\[
f_{f_{12}}(\hat{q}) = \left\{ \begin{array}{l}
f_{f_{11}} = L - \angle A \times r_2 - L_{230} - \angle D \times r_1 - L_{123} - \angle F \times r_1
- \angle C \times r_2 - L_{231} - \angle E \times r_1 - L_{121} = 0

f_{f_{12}} = L - \angle A \times r_2 - L_{230} - \angle D \times r_2 - L_{120} - \angle F \times r_1
- \angle G \times r_1 - L_{120} - \angle E \times r_1 - L_{121} = 0
\end{array} \right\} (7)
\]

where \( L \) is the length of the track; \( r_2 \) is the radius of the front planetary wheel, the front road wheel, and the idler; \( r_1 \) is the radius of the guide wheel; \( \angle I \) is the radius angle faced by the track segment surrounding component \( i \) and \( J \). The two expressions in (6) and (7) are corresponding to the two conditions that the idler \( C \) or the guide wheel \( G \) work when the back flippers rotate to different positions.

IV. Static Model

A. Forces Applied to the Robot

Since the wheelchair robot must have enough security and comfort, the movement velocity of the robot cannot be too large. So in this section, the wheelchair robot is assumed to be a static balance system during stair-climbing, and the forces applied to the robot that are considered are the gravity, the forces work when the robotic parts, and the track tension around the driving wheel.

First we divide the wheelchair into the parts of the main body (including the chassis and the passenger), the back flipper, the front flipper, the back planetary wheel, and the front planetary wheel. Then the gravity of each part \( \vec{G} \) can all be expressed by the mechanical parameters of the robot and the variable \( \hat{q} \).

The external forces applied by the stairs, which are shown in Fig. 2, can be classified into two types: the tangential and the normal forces applied by the noses of the stairs \( \vec{F}_n \) and \( \vec{N}_n \); the tangential and the normal forces applied by the treads of the stairs \( \vec{F}_t \) and \( \vec{N}_t \), and the forces can be represented with the vector \( \vec{F}_m \).
\[ \mathbf{F}_e = [\mathbf{F}_e^0, \mathbf{N}_S, \mathbf{N}_e, \mathbf{N}_e, \mathbf{F}_e]^{\top} \]

The track tension around the driving wheel \( \mathbf{T}_{e1} \) and \( \mathbf{T}_{e2} \), which are shown in Fig. 4, can be represented by the vector \( \mathbf{T}_e \): \[ \mathbf{T}_e = [\mathbf{T}_{e1}, \mathbf{T}_{e2}]^{\top} \]

In this paper, the mass effect of the track and the inertial effect of the track wheels are neglected, so \( T_{e2} \) can also be assumed equal to the controlled track tension around the front planetary wheel [9].

B. Statics of the Robot Whole Body

The static balance equations of the robot whole body in plane \( x_{0y-o_{0y-z_{0y}}} \) can be derived as:

\[
f_{ex}(\mathbf{q}, \mathbf{T}_e) = \begin{bmatrix} f_{e1} \\ f_{e2} \end{bmatrix} = \mathbf{0} \]

\[
\begin{align*}
\mathbf{T}_{e1} & = \mathbf{0} \\
\mathbf{T}_{e2} & = \mathbf{0}
\end{align*}
\]

where \( I_{10} \) is the vector from point \( I \) to point \( J; \), \( Q \) is the mass center of each part of the robot; \( n \) is the quantity of the stairs, and in the static equations of this paper, the external forces applied by the noses and the treads of the stairs that do not contact with the robot will be set as zero.

The relationship between the driving force of the driving wheel and the external forces applied by the stairs can be expressed by

\[
f_{e1x}(\mathbf{F}_e) = F_{e1} - \sum_{i=1}^{n} F_{a1} - \sum_{i=1}^{n} F_{t1} = 0 \tag{9}
\]

where \( F_{e1} \) is the driving force of the driving wheel.

C. Statics of the Driving Wheel

The forces applied at the rim of the driving wheel including the track segment around it are shown as Fig. 4. With the aim of the driving wheel, by making the resultant moment around the wheel center in plane \( x_{0y-o_{0y-z_{0y}}} \) to be zero, the relationship between the driving force of the driving wheel and the track tension around the driving wheel can be described by

\[
f_{e2x}(\mathbf{F}_e, \mathbf{T}_e) = \begin{cases} 
F_{e1} - (T_{e2} - T_{e1}) = 0 & \text{or} \\ F_{e1} - (T_{e2} - T_{e1}) - F_{a1} = 0 & \text{or} \\ F_{e1} - (T_{e2} - T_{e1}) - F_{t1} = 0
\end{cases} \tag{10}
\]

According to the Euler formula in [10], when the driving wheel and the track segment around it are in the critical skid condition, the track tension around the driving wheel \( T_{e1} \) and \( T_{e2} \) will meet the equations

\[
(f_e, T_e) = 0
\]

where \( \rho \) and \( K \) are the weight factor and the magnitude factor of the variables separately, and in this paper we assign them as \( \rho = 0.5 \) and \( K = 10^3 \).

3) Constrain Equations: According to (1)-(10), (12), and the physical condition that the external forces should satisfy, the constraint equations, which the optimization variables are subjected to, can be established as:

\[
g_1(\mathbf{q}, F_e) = f_1(\mathbf{F}_e) = F_e = 0, \quad g_2(\mathbf{q}, F_e) = f_2(\mathbf{F}_e, F_e) = 0, \quad g_3(\mathbf{F}_e) = f_3(\mathbf{F}_e, \mathbf{T}_e, F_e) = T_{e2} - T_{e1} = 0
\]
where $\mu_e$ is the maximal attachment coefficient between the track and the tread of the stairs.

**B. Optimization Simulation Parameters**

First the parameters of the stairs are set as $\phi = 27^\circ$, $h = 0.15m$, and $\mu_t = 0.3$ (the same to those of the stairs in our laboratory building with standard dimension in civil engineering). For the wheelchair robot, the mass center of the main body is set at (0.4m,0.3m) in plane $x_A$, and the mass centers of the other parts are set at their figure centers. According to the structure of the tooth of the driving wheel, we assign $\mu_t = 3.5$. The other design parameters of the wheelchair robot are listed in Table 1, where $m_i$ are the mass of each part of the robot (The mass of the main body is halved for optimizing the one-sided track tension.), and $\lambda$ is the established angle of the chair as shown in Fig. 3.

| Structure ($m_i^*$) | Mass (kg) |
|-------------------|-----------|
| $l_{wa}$ | 0.94 | 0.04 | 55.0 |
| $l_{ec}$ | 0.69 | 0.07 | 2.5 |
| $l_{be}$ | 0.37 | 0.20 | 15.0 |
| $l_{cd}$ | 0.53 | 3.65 | 2.0 |
| $l_{bc}$ | 0.59 | 32.0 | 1.0 |

**C. Optimization Simulation Flow**

In phase 2, first a constant rotation angle of the back flipper for the early stage and a constant pitch angle of the chair for the late stage need be given. Then the simulation flow can be given as follows:

1) Let $\begin{bmatrix} x^w_n \\ z^w_n \end{bmatrix} = \begin{bmatrix} x_{n0} - s \\ r_2 \end{bmatrix}$. Assign an initial $x_{n0}$ and let $s = 0$ to make the robot in state 2a (nose $N_1$).

2) Increase $s$. If the driving wheel has not crossed $N_1$, carry out the optimization with state 2a, and then return to 2, otherwise go to 3).

3) Increase $s$. Assume that the robot is in state 2c (tread $T_1$). If the driving wheel has not supported on $N_{i+1}$, carry out the optimization with state 2c, and then return to 2), otherwise go to 4).

4) Increase $s$. Assume that the robot is in state 2b. If the driving wheel has not crossed $N_{i+1}$, carry out the optimization with state 2d, and then return to 2), otherwise finish the optimization.

In phase 3, the back flipper is kept at the terminal position. Then the simulation flow can be given as follows:

1) Let $\begin{bmatrix} x^w_s \\ z^w_s \end{bmatrix} = \begin{bmatrix} x^w_n + r_2 \sin \phi - s \cos \phi \\ z^w_n + r_2 \cos \phi + s \sin \phi \end{bmatrix}$ and $s = 0$ to make the robot in state 3b (nose $N_i$).

2) Increase $s$. If the driving wheel has not crossed $N_{i+1}$, carry out the optimization with state 3a, and then return to 2), otherwise carry out the optimization with state 3c, and go to 3).

3) Increase $s$. If the front road wheel has not crossed $N_{i+1}$, carry out the optimization with state 2b, and then return to 3), otherwise finish the optimization.

In the late stage of phase 4, the chair obliquity is kept the same to that obtained from phase 3. Then the simulation flow can be given as follows:

1) Let $\begin{bmatrix} x^w_s \\ z^w_s \end{bmatrix} = \begin{bmatrix} x^w_n + r_2 \sin \phi - (ht \cot \phi)/2 \cos \phi \\ z^w_n + r_2 \cos \phi - h/2 + s \sin \phi \end{bmatrix}$ and $s = 0$ to make the robot in state 4a (nose $N_{i-1}$).

2) Increase $s$. If the front road wheel has not crossed $N_i$, carry out the optimization with state 4a, and then return to 2), otherwise go to 3).

3) Increase $s$. If the front road wheel has not crossed $N_{i+1}$, carry out the optimization with state 4b, and then return to 3), otherwise go to 4).

4) Increase $s$. If the front road wheel has not crossed $N_{i+2}$, carry out the optimization with state 4c, and then return to 4), otherwise finish the optimization.

**D. Optimization Simulation Results**

The Simulation of track tension optimization is performed as the simulation flow. In the early stage of phase 2, we keep $\beta = 100^\circ$ and assign $x_{n0} = 1.35m$ to make the robot start from $N_1$. In the late stage of phase 2, we keep $\theta = 0^\circ$ and assign $x_{d0} = 0.75m$ to make the robot start from $N_3$. In phase 3, we keep $\beta = 141^\circ$ and let $i = 1$ to make the robot start from $N_1$. In the late stage of phase 4, we keep $\theta = 5^\circ$ that is obtained from phase 3 and let $i = 2$ to make the robot start from $N_2$. Then the simulation results are obtained as shown in Fig 5.

![Fig 5 Simulation results. (a) Early stage of phase 2. (b) Late stage of phase 2. (c) Phase 3. (d) Late stage of phase 4.](image-url)
cannot be less than these values during each phase to make sure the robot can complete the stair-climbing successfully.

VI. EXPERIMENT FOR STAIR-CLIMBING

In the stair-climbing experiment conducted in our laboratory building, the movement of the wheelchair robot and the rotation of the back flipper are controlled manually by the operator with the guidance of the information acquired from the inclinometer, and the rotation of the front flipper is controlled automatically according to the information acquired from the torque sensor. The relationship between the controlled track tension around the front planetary wheel and the torque received by the front flipper can be easily derived and will not be stated in this paper.

According to the simulation results, the one-sided track tension around the front planetary wheel is controlled as follows: for phase 1 and phase 2, the track tension is controlled at the value 150 N; for phase 3, the track tension is controlled at the value 400 N; for the early stage of phase 4, the track tension is controlled at the value 150 N because in this stage the robot does not move but only transforms; for the late stage of phase 4, the track tension is controlled at the value 300 N.

The snapshots of the experiment are shown in Fig 6. In the experiment, the wheelchair robot completes the stair-climbing performance successfully, and the clearance of the peak of the stair is very smooth. The experiment result can give a preliminary verification to the obstacle clearing capability of the robot and the optimal track tension values obtained from the above analysis.

VII. CONCLUSION

In this paper, an original wheelchair robot equipped with a novel type of VGSTM has been presented. This mechanism that can actively control the robot shape and the track tension has been proved to have great interest in improving the obstacle clearing capability of the wheelchair robot by adapting the robot shape for the obstacle. An optimization model of the track tension for stair-climbing has been established thanks to the geometric model and the static model. The optimal track tension values for each phase of stair-climbing have been obtained by the simulation of the track tension optimization and have been verified by the stair-climbing experiment of the robot.

Future works will focus on the autonomy of the wheelchair robot. More sensors will be added on the robot to increase its capability of terrain perception and to enable the autonomous stair-climbing.

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