Study on Interactional Characteristics of WT Wheelchair Robot with Stairs during Stair-Climbing Process

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Abstract. The characteristics of interaction between WT wheelchair robot and stair environments is analyzed and possible patterns of WT wheelchair robot during the stairs climbing are summarized, and then the criterion to determine the pattern of the wheelchair robot is proposed. STATEFLOW module in MATLAB is used to simulating the whole stair-climbing of WT wheelchair robot, and an entire analytical procedure about how to determine the pattern by using the simulation curves is given.

Introduction

Wheelchair robot, as a very important mobile service robot for some aged and physical disabled persons, is attracted by more and more domestic and foreign research institutions in recent decades. Traditional wheelchairs move flexibly on the flat ground, but when they encounter obstacles, especially the need to climb up or down the stairs they will be greatly restricted. Therefore, developing new wheelchair robots with low cost, simple structure and operation is a work of social values.

This paper takes WT wheelchair robot [1] developed by Ting Wang in Chinese Academy of Sciences, Shenyang Institute of automation as the experimental platform, which uses a deformable wheel-tracked obstacle-surmounting mechanism. This structure not only has the advantage of a wheeled mobile mechanism that running flexibly in the ground, but also gives full play to the characteristics of carrying ability of crawler mechanism [2] by deforming during stair-climbing.

However, this kind of moving mechanism is so complicated that the interaction between robot and stairs environment should be taken fully account into during wheelchair robot's stair-climbing, and the pattern which the wheelchair is in during stair-climbing should be determined.

The pattern of WT wheelchair robot during stair-climbing alternatively changing, which brings difficulty to the path planning of the robot. Path planning in the traditional sense is the ideas of inverse kinematics solution, which plans the path curve in the joint's space of robot [3]. This paper puts forward an idea that the seat plane of the wheelchair should be maintained horizontal to determine each joint's generalized coordinate variable.

Robot Description

Experiment Platform of WT Wheelchair Robot

WT wheelchair robot, as shown in Fig. 1, is mainly composed of a body, two front flippers, two driving wheels, a back flipper and two tracks installed symmetrically. The body AB consists of a supporting frame and a seat connected together, and there are guide wheels A, carrier wheels B, and the belt pressing wheels F and G symmetrically arranged at both sides of the supporting frame; The
back flipper $BE$ can be controlled by a motor which can rotate around the axis $B$ of the supporting frame; The driving wheels $E$ and $E'$, which equip driving motors controlling movements, are arranged symmetrically at the end of the back flipper; The left front flipper $CD$ and the right front flipper $C'D'$ are controlled by motors respectively, which can rotate around the axis $CC'$ of the supporting frame to adjust the track tension, and there are the belt pressing wheels $D$ and $D'$ arranged at the end of each front flipper; There are two same tracks arranged at the two sides of WT wheelchair robot. WT wheelchair robot has 5 driving motors, a potentiometric sensor installed in the axis $B$ for detecting the swing angle of the back flipper $BE$, and a two-dimensional tilt sensor for detecting changes of the pitch angle and the roll angle.

![WT wheelchair robot](image)

**Stair-Climbing Process**

Stair-climbing can be defined as the process that WT wheelchair robot transfers from the horizontal ground to the stairs' slope. Experiments show that the process is so short that the influence of turning direction can be ignored, and the process can be simplified into the vertical plane.

WT wheelchair robot's process of stair-climbing is shown in Fig. 2. First, the back flipper rotates counterclockwise so that the tension force of track increases, and then rotate the front flippers clockwise or counterclockwise to keep track tension constant. Finally, the seat plane angle relative to the horizontal plane can be controlled by swing the back flipper to different angles simultaneously driving the wheelchair robot backwards.

![Stair-climbing process of WT wheelchair robot](image)

**Generalized Coordinates of the Robot**

The relative coordinate system, as shown in Fig. 1 (b), can be established. Its origin is located at the axis of wheel $A$, $u$ axis is parallel to the plane of wheelchair's seat, and its $v$ axis is vertical. $q_1$ can be defined as the angle rotated counterclockwise from $BA$ to $BE$, $q_2$ and $q_3$ can be defined as the angles of the left and the right front flippers rotated clockwise from $CA$ to $CD$ and to $C'D'$ respectively, $q_4$ and...
$q_5$ can be defined as the angles of the left or the right driving wheels rotated clockwise around the back flipper $BE$ respectively. The above can be seen as the WT wheelchair robot's generalized coordinate variables. $q_6$ and $q_7$ can also be defined as the angles measured by the two-dimensional tilt sensor installed on WT wheelchair robot. The rest are structural parameters that can be measured.

Analysis and Determination of WT Wheelchair Robot's Pattern during Stair-Climbing Process

Locating Wheelchair Robot on the Stairs

A single stair's height is $h=0.15$ m, width is $b=0.32$ m, and stairs' slope angle can be defined as

$\Lambda = \arctan \left( \frac{h}{b} \right)$. If connecting the stair vertex, we can get the stair slope line, as shown in Fig. 3. We can draw straight lines through stair vertex perpendicular to stair slope line, and then we can label the stair from bottom to up in turn. When the driving wheel's center is located in between two certain straight lines, we can use the smaller number of stair to calibrate the robot. A complete process of stair-climbing can be decomposed into a number of segments, from the $E$ wheel's center running after a calibration line to the $E$ wheel's center running after the next calibration line. Meanwhile we introduce a parameter $l = |EH|$ to calculate the numerical of calibration, where $|EH|$ is the length of the line $EH$ where $H$ is the point crossed by the line $EH$ which is parallel to the stair slope line and the line $AH$ which is parallel to the level ground.

The criterion expressed by $l$ for calibrating a stair can be deducted as:

$$i \sqrt{h^2 + b^2} + r_e b - r_e \sqrt{h^2 + b^2} \frac{b}{h} \leq l < (i + 1) \sqrt{h^2 + b^2} + r_e b - r_e \sqrt{h^2 + b^2} \frac{b}{h}.$$

The stair's calibration number $i$ can be deducted as:

$$i = \text{floor} \left( \frac{hl + r_e \sqrt{h^2 + b^2} - r_e b}{h \sqrt{h^2 + b^2}} \right).$$

where $\text{floor}(*)$ is rounding function.

Pattern Classification

As stair's horizontal surface is tangential to the bottom surface of the driving wheel as shown in Fig. 4, can be used as a primary classification of the patterns. When the driving wheel moving in the horizontal plane as shown in Fig. 4, the parameter $l$ keeps unchanged, and the relationship can be obtained as:
\[ \frac{i\sqrt{h^2 + b^2} + (r_E - r_A)\sqrt{h^2 + b^2}}{h} = l. \] (3)

Fig. 4 Primary classification of the patterns

**Analysis and determination between pattern I and Pattern II**

When \( i\sqrt{h^2 + b^2} + \frac{(r_E - r_A)\sqrt{h^2 + b^2}}{h} > l \), there are two patterns, as shown in Fig. 5.

Pattern I: The stair vertex with the smaller label shown as the left subfigure's \( i \) in Fig. 5 exerts a force on the track and then on the driving wheel. The criterion of pattern I can be obtained as:

\[
\begin{align*}
&\left\{ \frac{i\sqrt{h^2 + b^2} + (r_E - r_A)\sqrt{h^2 + b^2}}{h} > l \\
&\gamma \leq \gamma_{cr}
\end{align*}
\]

(4)

where \( \gamma \) is the angle formed by the line crossing from stair vertex to driving wheel's center and the line perpendicular to stair slope line, and \( \gamma_{cr} \) is the angle formed by the line crossing from the tangent point of track and driving wheel to driving wheel's center and the line perpendicular to stair slope line.

Pattern II: The stair vertex with the smaller label shown as right subfigure's \( i \) in Fig. 5 exert a force on the track while not on the driving wheel directly. The criterion of pattern II can be obtained as:

\[
\begin{align*}
&\left\{ \frac{i\sqrt{h^2 + b^2} + (r_E - r_A)\sqrt{h^2 + b^2}}{h} > l \\
&\gamma > \gamma_{cr}
\end{align*}
\]

(5)

**Analysis and determination between pattern III and Pattern IV**

When \( i\sqrt{h^2 + b^2} + \frac{(r_E - r_A)\sqrt{h^2 + b^2}}{h} \leq l \), there are also two patterns, as shown in Fig. 6.

Pattern III: The stair vertex with the larger label shown as the left subfigure's \( i+1 \) in Fig. 6 keeps in no contact with the track, and exerts no force on the driving wheel directly. While the stair vertex with the smaller label shown as the left subfigure's \( i \) in Fig. 6 exerts a force on the track while not on the driving wheel directly. The criterion of pattern III can be obtained as:
where $\eta$ is the distance from driving wheel's center to stair vertex with the larger label, and $\zeta$ is the angle formed by stair slope line and the line crossing from driving wheel's center to stair vertex with the larger label.

Pattern IV: The stair vertex with the larger label shown as the right subfigure's $i+1$ in Fig. 6 keeps in contact with the track, and exerts a force on the driving wheel. While the stair vertex with the smaller label shown as the right subfigure's $i$ in Fig. 6 keeps in no contact with the track. The criterion of pattern IV can be obtained as:

$$\begin{cases}
i\sqrt{h^2 + b^2} + \frac{(r_E - r_i)h}{h} + \frac{(h^2 + b^2)^{1/2}}{2} \leq l \\
\eta > r_E \quad \text{and} \quad \zeta < \frac{\pi}{2}
\end{cases}$$

(7)

If the expression $\zeta < \frac{\pi}{2}$ is not satisfied simultaneously for the criterion of pattern III, as is shown in Fig. 7, pattern IV might be mistaken for pattern III.

**Analysis of Simulation by STATEFLOW**

STATEFLOW [4] module in MATLAB is used to simulate the whole process of WT wheelchair robot' stair-climbing, as is shown in Fig. 8, which can realize the function similar to a finite state machine and make a determination for wheelchair's pattern in the stair-climbing process.
All the abscissa of the curves in Fig. 8 is time $t$. The ordinate of subfigure a in Fig. 8 is $\gamma_{cr}$, and the left of the black line at about $t=16$ (s) means stair-climbing process while the right of the black line means it finished. The ordinate of subfigure b in Fig. 8 is $i$ without unit, as shown in formula (2), $i=1$, $i=2$ and $i=3$ denote the stairs' section where wheelchair robot climbs. The ordinate of subfigure c in Fig. 8 is the sign of $i\sqrt{h^2+b^2+(r_\eta-r_\gamma)\sqrt{h^2+b^2}}/h - l$ without unit, as described in section 3. A value of 0 represents the wheelchair robot' climbing between the starting and the first stair in pattern IV, a value of 1 indicates the wheelchair robot in pattern I or in pattern II, a value of -1 indicates the wheelchair robot in pattern III or in pattern IV. The ordinate of subfigure d in Fig. 8 is the sign of $\gamma - \gamma_{cr}$ without unit. Combined with subfigure c in Fig. 8 a value of 1 indicates the range of pattern I, and a value of -1 indicates the range of pattern II, as shown as the subfigure d's annotation in Fig. 8. The ordinate of subfigure e in Fig. 8 is $\eta - r_\eta$, and the ordinate of subfigure f in Fig. 8 is $\zeta - \frac{\pi}{2}$. According to the equations 3 and 4, we can determine the range of pattern III and the range of pattern IV, as shown as the subfigures c and d's annotations in Fig. 8.

**Conclusion**

Different patterns of WT robot during stair-climbing are inducted and analyzed.

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