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A Cable-driven Seat Pedal Mechanism Motion Simulation for Climbing Stair Wheelchair

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Abstract. A seat posture is tilted when the wheelchair robot climbs stairs, in which it is possible for the pedal of wheelchair to collide with the steps. In this paper, a port-based ontology model is described to obtain the outline of the pedal mechanism of wheelchair, and a cable-driven method is adopted to drive the motion of pedal mechanism of wheelchair seat to avoid the collision with the steps. Active posture of the wheelchair is changed to fit the wheelchair robot climbing stair motion on the basis of modeling the pedal mechanism. The simulation results show its validity of the model of the pedal mechanism.

Introduction

With the aging of the society, the demand for human-interactive robotic wheelchair that can help people with disabilities and elderly people is increasing [1]. At present, millions of young disabled and elderly people rely on wheelchair in their daily lives. Although wheelchairs provide them more mobility with less effort, especially electric powered wheelchairs improve the mobility of people with physical disabilities, they can only work on flat or the small slope of the ground, and it appears powerless when faced the obstacles such as steps, trench and stairs [1-3].

An advance in mobility assistance came with the development of wheelchair with negotiating architectural barriers, therefore, the wheelchair climbing-stair can avoid the difficulties. However most of the current wheelchair climbing the stairs in the reversing or backwards way, this is different from the way we normally walk forward for wheelchair motion [4]. This not only reduces the vision of the rider, increases the complexity of the wheelchair operation, but also decreases the security. In order to overcome the shortcomings of the existing wheelchair climbing-stair, this paper designed a wheel-leg compound electric wheelchair which can climb the stairs in the forwards way. An adjustable pedal mechanism that is of the wheelchair climbing-stairs is designed to make easily realizing the way to climb the stairs [5]. This paper applies port-based ontology for wheelchair robot and mainly focus on the design of the adjustable pedal mechanism of the wheelchair with stair-climbing]6]. The metamorphic mechanism model is built to describe the feasibility of the system. By the analysis of the simulation curve, the foot pedal mechanism is very good to safely avoid interference with the stairs when the wheelchair robot climbs the stairs, and it will not brings secondary damage to the lower limbs of human body[7-8].

Modling Pedal Mechanism

Port-based Ontology for Describing Pedal Mechanism

Port-based ontology (PBO) has been successfully used as an effective means for describing component functional semantics by making sense of port definition[2]. Also it is used to modeling the pedal mechanism of the wheelchair climbing stairs. Figure 1 represents the outline of the wheelchair climbing stairs. According to port-based ontology, one-level ports of the wheelchair robot, and it has three one-level connectors (CON). Therefore, robot wheelchair (RW) is represented as follows.

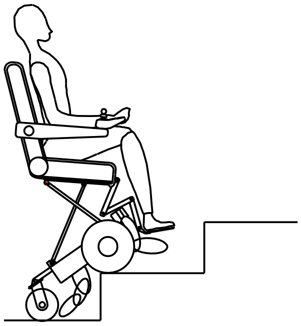

Figure 1. Outline of wheelchair climbing stair.

$$\mathrm{RW} = \sum_{i=1}^{3}\sum_{j=1}^{3}\mathrm{P}_{i}\,\mathrm{CON}_{j} \tag{1}$$

$$\mathrm{CON}=\mathrm{INT}\,(\mathrm{G}_{k},\ \mathrm{G}_{l})$$

Where, each one-level port can be extended into two-level, three-level, ... Also each connector can be considered as two-level, three-level, ... The basic connectors are usual used standard or common components[6,9].

The Pedal Mechanism Freedom Analysis

Assume that the pedal mechanism of wheelchair consists of three degree freedom, it includes the seat, the rod l1, l2, l3, and the pedal. When the wheelchair walks on the ground, the rod l3 is located in the slideway. And the rod l3 is off the slideway when it climbs down stairs, otherwise, the rod l3 runs in the slideway as shown in figure 2. By topological analysis of mechanism, the number of rods and mechanical joints can be used to calculate the freedom as follows.

$$F=3n-(2P_{\mathrm{L}}+P_{\mathrm{H}}) \tag{2}$$

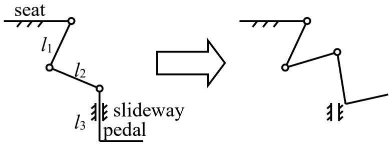

Figure 2. The pedal mechanism.

Where, n stands for the number of moving rod, PL and PH mean low and high slide movement, respectively [10].

In order to fit up and down stair motion, it is necessary for the pedal to avoid interference with steps. And shown in table 1.

Table 1. The activity freedom of pedal.

	Ground	***Upstair***	***Downstair***
Freedom	1[a]	2	3
Motion mode	Up-and down movement	Forward movement	Backward movement

a. Only vertical motion of the pedal

Motion Status of Metamorphic Mechanism

The pedal mechanism runs in three ways, that is, vertical motion, forward motion, and backward motion. Each need to be metamorphic mechanism. At first, the pedal needs to work at up and down motion process in order that the wheelchair is raised and lowered. It is necessary for the pedal to work at crank-slider mode, then leaves the slideway. Secondly, the pedal works in forward movement, in which it always runs in the slideway. Thirdly, the pedal works in backward movement, and it needs to leave the slideway, then realize backward movement as shown in figure 3. Point A is located at the seat, and its trajectory affects the pedal mechanism motion. Therefore, it needs to know the activity space of A point.

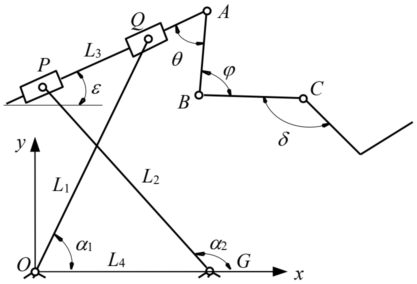

Figure 3. The pedal backward status graph.

According to the vector polygon method, a vector graph of the four rod mechanism is shown in figure 3 below.

OG+GP=OQ+QP (3)

Two projection axis equations is listed as follows.

$$\begin{cases} x_{op}=L_1\cos\alpha_1+(L_3-2s)\cos\varepsilon \\ y_{op}=L_1\sin\alpha_1+(L_3-2s)\sin\varepsilon \end{cases}$$

The above formula is simplified below.

$$a\cdot\sin\alpha_1+b\cdot\cos\alpha_1+c=0 \tag{4}$$

where, $\begin{cases} a=2L_1(L_3-2s) \\ b=2L_1[(L_3-2s)\cos\varepsilon-L_1] \\ c=(L_3-2s)^2+L_1-2L_1(L_3-2s)\cos\varepsilon \end{cases}$

Further, α1, α2 can be solved in the following.

$$\begin{cases} \alpha_1=2\arctan(\frac{a\pm\sqrt{a^2+b^2-c^2}}{b-c}) \\ \alpha_2=\alpha_1-\varepsilon+180° \end{cases} \tag{5}$$

Assuming that K represents the gradient of seat as follows.

$$K=\frac{y_Q-y_P}{x_Q-x_P}=\frac{L_1\sin\alpha_1-L_1\sin\alpha_2}{L_1\cos\alpha_1-(L_2+L_1\cos\alpha_2)}$$

Thus, $y_A=K(x_A-x_Q)+y_Q$

Then the angle ε of seat in the following.

$$\varepsilon=\arctan(K)=\frac{\pi}{2}-\arctan\left(\frac{L_1\sin\alpha_1+L_2\sin\alpha_2}{L_1}\right)$$

Thus, A point coordinate is represented as follows.

$$\begin{cases} x_A = \dfrac{s}{\sqrt{K^2+1}} + L_1 \cos\alpha_1 \\ y_A = \dfrac{K \cdot s}{\sqrt{K^2+1}} + L_1 \sin\alpha_1 \end{cases} \tag{6}$$

The activity space of A point decides the pedal mechanism work region. The wheelchair robot climbing-stair runs in different stairs, and it's work region is different. The region of A point is given in figure 4. The total activity space of A point includes three subspaces: one is up and down motion space, the second is forward motion space, and the third is backward motion space. The lowest point coordinate is (461.2, 48.23), the right most point coordinate is (476.6, 177.7), and the left most point coordinate is (445.7, 264.1).

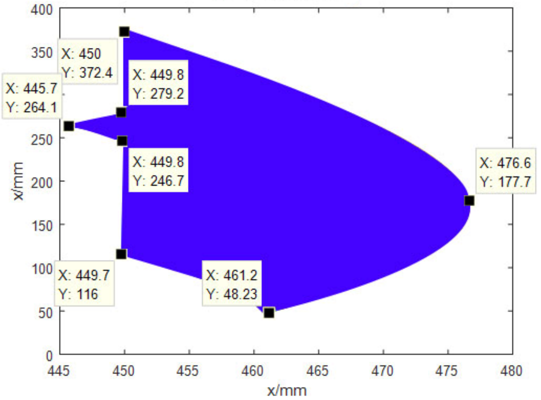

Figure 4. Activity space of a point.

Cable-Driven Modling PeDal Mechanism G

Closed Vector Model for Lower Limbs

The pedal mechanism is of a multi-freedom. According to metamorphic mechanism theories, the number of rod and freedom depends on the classification of different metamorphic mechanism[10]. The objective of cable-drive is to obtain different size θ, φ, δ shown in figure 3.

According to vector polygon method, a vector equation of lower limbs is as follows.

$$\boldsymbol{JF}+\boldsymbol{FE}=\boldsymbol{JE} \tag{7}$$

Equation (7) is projected to the coordinate as follows.

$$\begin{cases} l_6 \cos\theta_6 + l_5 \cos\theta_5 = l_7 \cos\theta_7 \\ l_6 \sin\theta_6 + l_5 \sin\theta_5 = l_7 \sin\theta_7 \end{cases}$$

Assuming that A point as the coordinate origin, E point coordinate is represented in the following.

$$\begin{cases} \mathrm{x_E} = l_6 \cos\theta_6 + l_5 \cos\theta_5 - w_0 \\ \mathrm{y_E} = l_6 \sin\theta_6 + l_5 \sin\theta_5 - h_0 \end{cases}$$

Where, w0, h0 mean the parmeters of the seat structure.

In addition, E point trajectory is known, and A point works in an effective region. Path planning algorithm is adopted to obtain B point coordinate, that is, the values of the θ1, θ2, θ3.

$$\theta_1 = 2arctan\ (\frac{(A \pm \sqrt{A^2+B^2-C^2})}{B-C})$$

Where, $A = -2l_1(y_E\text{-}l_{CE}\sin\alpha)$, $B = -2l_1(x_E\text{-}l_{CE}\cos\alpha)$,
$C = l_1^2+(x_E\text{-}l_{CE}\cos\alpha)^2+(y_E\text{-}l_{CE}\sin\alpha)^2- l_2^2$

$$\theta_2 = \arcsin\left(\frac{y_E - l_{CE}\sin\alpha - l_1\sin\theta_1}{l_2}\right) - \theta_1$$

$$\theta_3 = \alpha - \theta_1 - \theta_2$$

Therefore, the values of the θ, φ, δ can be obtained.

Cable-driven Modeling for Pedal Mechanism

Cable-driven can be simplified two ends as revolute joint, and the mid as translational joint [11]. The joints can be seen as a connector both rods, and a reasonable joint is situated on the place with more less cable-driven force. In this paper, one third location of each rod is fixed as cable-driven support joint shown in figure 5.

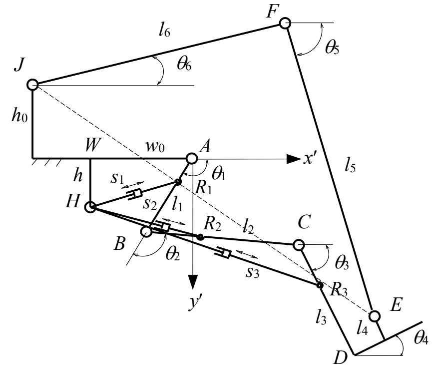

Figure 5. The vector graph of pedal mechanism.

The other end of cable-driven is fixed on the seat, and its movable end is fixed on one third rod. As A point coordinate is known, the coordinate of a cable-driven end can be solved on the basis of vector polygon as follows.

$$\begin{cases} HW + WA = HR_1 + AR_1 \\ HR_2 = HA + AR_2 \\ HR_3 = HA + AR_3 \end{cases} \tag{8}$$

Where, H is fixed on the seat, and it is the fixed end of cable-driven force output. Cable driven length can be calculated according to equation (8), that is, HR1, HR2, and HR3 respectively represent cable length s1, s2, and s3.

As AR1=1/3· l1, AR2 and AR3 are represented as foolows.

AR2 =sqrt[l12+ (l2/3)2–2/3· l1 l2·cosφ]

AR3= sqrt[l12+ (l2+ l2/3·cos δ)2–2l1 (l2+ l2/3·cos δ)·cos(φ-δ)]

Therefore, the cable length is represented as follows.

s1=sqrt[(l1/3)2+h2+w2–2 l1/3 $\sqrt{h^2+w^2}$ cos(θ1-arctan(h/w))]

s2=sqrt[AR22+h2+w2–2 AR2 $\sqrt{h^2+w^2}$ cos(θ1-arctan(h/w)-∠A)]

s3=sqrt[AR23+h2+w2–2 AR3 $\sqrt{h^2+w^2}$ cos(θ1-arctan(h/w)-∠A′)]

Where, ∠A, ∠A′ mean A angle of triangle AHR2 and AHR3.

Simulation Results and Analysis

Angle, angle veocity, and angle acceleration change of the pedal mechanism paremeter θ, φ, δ are shown in figure 6, figure 7 and figure 8. If the wheelchair robot runs up, or forward motion, the angle change is reverse, that is, when the angle θ is increasing, φ and δ are decreasing shown in figure 6.

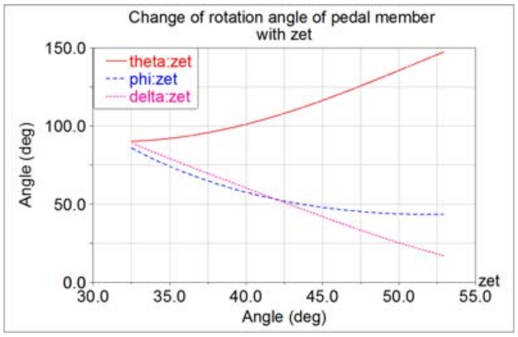

Figure 6. The angle change of pedal.

Otherwise, it is the opposite. When the seat runs in the backward motion, the range of θ change is from 90° to 147°. In so doing, cable-driven can easily obtain tilt angle range from –35° to 35°.

In addition, an angle velocity of rod l1 is increasing, and the angle velocities of rod l2 and rod l3 are decreasing. Figure 7 and figure 8 respectively give the cure of angle velocity and acceleration change about θ, φ, and δ with the ε change. Figure 7 shows the angle velocity is always decreasing until zero, at the same time, the acceleration gradually decreases to zero, then there is a small boost, as shown in figure 8. This keeps the acceleration stable. When the wheelchair robot begins to climb up, the angle θ quickly increases, as at the beginning location, the acceleration of θ is the biggest, then slow down.

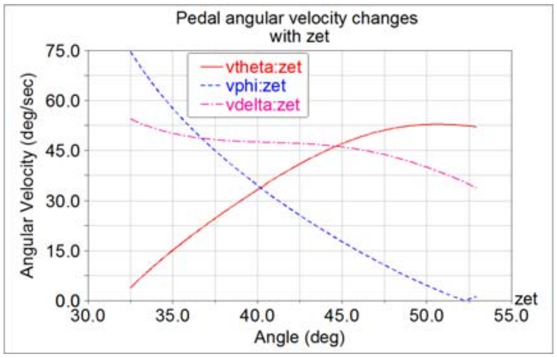

Figure 7. The angle velocity change of pedal.

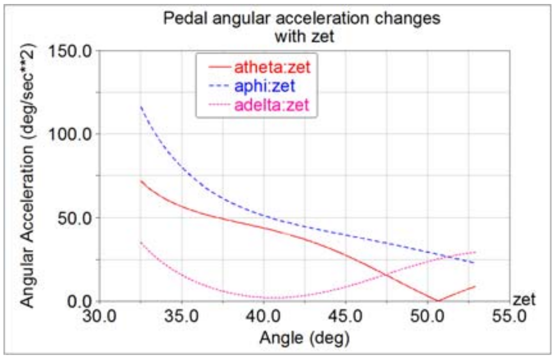

Figure 8. The angle acceleration change of pedal.

The angle velocity of φ has a bigger change range, and its angle acceleration is the same as that of angle θ. Also, the change still becomes from big to small. And the trend of change is more prominent. In the otherwise, the angle velocity of δ is the gradual change, and it is the smallest. However, its acceleration change becomes from big to small, furthermore keep the angle velocity stable, and there is no big shock.

Conclusion

The paper presents a cable-driven pedal mechanism motion simulation. We have established a prototype system for realizing the pedal mechanism motion when the wheelchair robot climbs stairs. A fruitful work is only used for motion modeling and simulation As the limit of length, some modeling process of about different size stairs, trench, structural obstacle, etc. don't give the description in detail. In addition, the force analysis doesn't implement. We are extending the work to including to dynamic system analysis. Current research is expanding them towards describing wheelchair robot system. We will further research port-based approach to mechanotronics system for control cable-driven, which provides the port modeling to effectively present for multi domain problems.

Acknowledgments

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