Simulation analysis on motion stability of smart wheelchair

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Abstract. Electric wheelchairs sometimes are used in complex terrain, such as slopes, stairs, ravines, etc. If there is no rapid and accurate judgment and decision-making for the current situation, the wheelchair may lose control and become unstable, which may will lead to serious consequences. The intelligent electric wheelchair studied in this paper can conduct stability analysis when moving on different terrains based on its own motion state. This paper uses ADAMS simulation software to build a wheelchair model according to the size of an existing wheelchair. The stability pyramid technique used in this paper has a good judgment on the tip-over stability of the object. This paper also has a more comprehensive judgment for slippage instability. In the simulation and experiment, the slippage and tip-over instability are verified. Theoretical analysis and actual simulation demonstrated that the developed smart wheelchair has high reliability for stability analysis in different environments.

1. Introduction

With the development of science and technology, the functions of electric wheelchairs continue to be enriched. The increasingly safe, high-performance, and multifunctional wheelchair has become a development objective [1-3]. In real life, when an ordinary electric wheelchair goes up and down the slope, the tilt of the chair surface will give people an uncomfortable feeling, especially on a steep slope. It is necessary to make timely and accurate judgments to ensure safety. Therefore, the stability of the wheelchair and its ability to resist tipping are very important [4]. When driving on different types of complex terrain, the factors and mechanisms that affect the stability of the wheelchair are different, and the types of instability that occur are also different. When traveling on a low-friction terrain, the electric wheelchair is prone to slip due to the very small friction between the wheels and the ground, causing the slippage and deflection of the fuselage, which is called slippage instability [5]. When moving on an uneven terrain, the contact force between wheelchair's wheels and ground is unevenly distributed, the supporting area is small, and thereby the horizontal components of inertial forces and gravity are large. Since the projection position of the center of gravity (COG) of the wheelchair along the direction of gravity is not in the overall supporting surface of the wheelchair, it will cause pitching or lateral tip-over of the fuselage, resulting in overturing instability. The discussion about the instability of the wheelchair robot mainly lies in two aspects: static stability and dynamic stability.

Among the current research methods, the static stability criterion methods mainly include: Center of gravity Projection (CGP) method [6], Static Stability Margin (SSM) method [7], Longitudinal Stability Margin (LSM) method [8], Crab Longitudinal Stability Margin (CLSM) method, Energy Stability Margin (ESM) method [9-10], etc. Dynamic stability criterion methods include: Effective Mass Center (EMC) method [11], Zero Moment Point (ZMP) method [12], and Dynamic Stability Margin (DSM) method [13-14], etc. This paper uses ADAMS software to build a wheelchair model according to an
existing electric wheelchair model, and conduct dynamic simulation of the movement on a slope terrain. This paper analyzes the motion state according to the coordinate position trajectory of the COG of the wheelchair, and judges the tip-over state and motion stability. Based on the summary and analysis of traditional stability theories, this paper uses a stability analysis method based on stability pyramid suitable for the smart wheelchair model.

2. Stable pyramid technique

The wheelchair model in this paper is a four-wheel drive robot system [15]. The common principle of the above-mentioned criteria for judging the stability of wheelchairs is the stable pyramid technique. The principle of the static stability judgment method is that the distance between the projection of the COG on the wheelchair support polygon and the tipping edge line is used as the judgment criterion of the stability margin [16].

2.1. The stable pyramid technique establishment

The coordinates of the vertex in Cartesian coordinate system can be calculated by [17]:

\[ x_c = \frac{\sum_{i=1}^{n} m_i x_i}{\sum_{i=1}^{n} m_i}, \]
\[ y_c = \frac{\sum_{i=1}^{n} m_i y_i}{\sum_{i=1}^{n} m_i}, \]
\[ z_c = \frac{\sum_{i=1}^{n} m_i z_i}{\sum_{i=1}^{n} m_i}, \]

where \( x_c, y_c, z_c \) is the coordinates of the COG of each part of the wheelchair, \( m_i \) corresponds to the mass of each part, \( x_i, y_i, z_i \) is the coordinates of each part, and \( n \) is the number of parts.

The process of constructing the convex polygon of the stable pyramid base is actually a process of finding the convex hull. Define set \( A \) as the set of all the contact points between the wheels and the ground, and its convex hull is the smallest convex polygon formed by these points, which is denoted as \( P \). The basic principle of finding the convex hull is to add vertices in a certain direction (clockwise and counterclockwise) near the points in the convex hull, to ensure that the internal angle of the polygon is less than 180° [18]. If the angle formed by three consecutive vertices is greater than 180°, the intermediate points are deleted, and the polygon formed by these points is a convex polygon.

2.2. Stability identification based on stability pyramid technique

Regarding the analysis of wheelchair stability, two performance indicators is proposed, namely slippage stability and tip-over stability [19]. Two indicators, the maximum slippage angle and the maximum tilt angle of the wheelchair on a slope, are used to verify the model.

![Figure 1](image-url)

Figure 1. (a) Stability pyramid of wheelchair model with slope. (b) Stability pyramid of wheelchair model. (c) Support domain of wheelchair model.

The calculation method of the maximum slippage angle index [20] is as:

According to the wheelchair model, the established stability pyramid is shown in the Figure 1 (a). The wheelchair which is at an azimuth angle of \( \theta \) degrees is stationary on a slope with an angle of \( \alpha \) degrees. The adhesion coefficient is the ratio of the adhesion force to the pressure in the normal direction of the wheel (vertical to the road surface), which is equivalent to the static friction factor between the tire and the road surface. The attachment coefficient \( \varphi \) of the tire is:

\[ \varphi = \sqrt{(\varphi_a \cos \theta)^2 + (\varphi_b \sin \theta)^2} \]  

(2), where \( \varphi_a \) and \( \varphi_b \) are the longitudinal and horizontal components of. The condition that the wheelchair does not slip on the slope is:

\[ G \sin \alpha \leq \varphi \sum_{i=1}^{n} N_i = \varphi G \cos \alpha \]  

(3),
where $N_i$ is the normal force exerted by the tire on the inclined plane ($i = 1,2,3,4$), $G$ is the gravity received by the wheelchair. When the wheelchair does not slip on the slope, the relationship between $\alpha$ and $\varphi$ can be obtained by solving (3), which is: $\alpha \leq \arctan \varphi$ (4).

The calculation method of the maximum tilt angle is as follows:

The stability pyramid of the wheelchair model is composed of the contact points $C$ and $D$ of the front wheel and the inclined plane, the contact points $A$ and $B$ of the rear wheel and the inclined plane, and the COG $O$ of the model. Point $O'$ is the projection of the COG within the convex polygon of the stable pyramid. In order to keep the wheelchair stable, the point $O'$ needs to be always within the convex polygon. The principle of stability margin is as follows: Taking $\theta = 0^\circ$ as an example, the points $O_1$, $O'$ and $F$ are collinear. As the slope angle $\alpha$ increases, the point $O'$ coincides with the point $O_1$ from $\alpha = 0^\circ$. When the critical angle is reached, point $O'$ coincides with point $F$. Because $OO'$ is perpendicular to the horizontal ground, the sum of the angles of $\angle OF(O') O_1$ and the inclined plane is $90^\circ$. According to the internal angle relationship of the triangle $OF(O')O_1$, it is easy to get that the inclined plane angle is equal to $\angle F(O') O_1$. Set $OO_1 = H$, $\eta_{AB} = \arctg (O_1 S/H)$, then $\eta_{AB}$ is the stable margin angle of the supporting boundary $AB$.

Figure 1 (b) and (c) are detailed diagrams of the stability pyramid, and $A$, $B$, $C$, and $D$ are the four contact points between the wheelchair tires and the inclined surface. For the boundary $AB$, the stability margin angle is $\eta_{AB} = \arctg (SO_1/H)$, and the calculated result is the limit angle of the slope when the wheelchair does not tip over. Similarly, the stability margin angles of other boundaries can be calculated as $\eta_{BC} = \arctg (NO_1/H)$, $\eta_{CD} = \arctg (TO_1/H)$, $\eta_{DA} = \arctg (MO_1/H)$. For point $B$, the stability margin angle is $\eta_B = \arctg (BO_1/H)$. It can be known through geometric knowledge that there is $\eta_B > \eta_{AB}$. The margin angle is: $\eta = \min\{\eta_{AB}, \eta_{BC}, \eta_{CD}, \eta_{DA}\} = \min\{\arctg (SO_1/H), \arctg (NO_1/H), \arctg (TO_1/H), \arctg (MO_1/H)\}$ (5).

Therefore, the judgment basis for wheelchair stability is:

1. when $\alpha < \arctg \varphi$, the wheelchair does not slip or tip over; 2. when $\arctg \varphi < \alpha < \eta$, the wheelchair slips but does not tip over; 3. when $\alpha > \eta$, the wheelchair tips over.

3. Model establishment

This paper uses ADAMS for modeling and simulation, which can establish system dynamics equations and analyze the kinematic and static mechanical systems. It can also display the motion track parameters and the movement trajectories of various important parameters such as the position of the COG, displacement, velocity, acceleration and force during the simulation process.

In this paper, the size of the wheelchair is used as the standard as shown in Figure 2. Add the same torque to set the motion constraints, set the contact force and friction force between the tire and the road, reduce the rigidity between objects to reduce the collision effect between objects, and avoid excessive interaction force causing bounce. After setting various parameters according to the actual situation, the whole motion state conforms to the actual situation. In the Cartesian coordinate system, the wheelchair model walks on the XOZ plane, and the Y axis is the height direction. When the wheelchair moves stably, the coordinate position of the Z axis in the lateral direction does not change.

Figure 2. Wheelchair model and ground model.
4. Experiment and results
This section simulates two cases of moving on slopes of the wheelchair in ADAMS software, and compares it with the stability results calculated by the stability theory described above.

4.1. Validation of the maximum slippage angle index
Both the longitudinal and horizontal components of the adhesion coefficient are set to be 0.3, which is equivalent to the static friction coefficient. According to (2) - (4), the maximum angle at which the wheelchair does not slip in this case is 16.7°. In this software, the X-axis position of the COG of the wheelchair is measured with time to determine the stability of the wheelchair. Continue to increase the inclination angle of the inclined plane from 0°. When the inclination angle of the bottom surface is 12.7°, the wheelchair will not slip and lose stability. The X-axis position is shown in Figure 3 (a).

![Figure 3](image)

Figure 3. (a) The X-axis position of the wheelchair model when slope’s angle is from 0° to 12.6°. (b) The X-axis position of the wheelchair model when slope’s angle is at 12.7°.

When the inclination angle of the inclined plane increases to 12.7°, the Z-axis position of COG is obviously deviated, as shown in Figure 3 (b). The wheelchair model deviates from the motion track of the ground model seriously during the traveling process, resulting in instability. This shows that the maximum slippage angle of the wheelchair in this simulation environment is 12.7°, which is 3.9° different from the calculated theoretical value. The result can prove the applicability of the established simulation model to a certain extent.

4.2. Validation of the maximum tipping angle
For driving up a slope, we can verify another stability index: the maximum tilt angle. Select the straight line formed by the contact points between the two front wheels of the wheelchair and the bottom surface as the tipping line. The calculation method of the COG coordinates of the wheelchair is shown in (1), and the coordinates of each small part can be measured by the ADAMS View measuring tool. The coordinates of the wheelchair’s COG are calculated via MATLAB as shown in Table 1. After combining the various parts into a whole through the Boolean operation in the software, the displayed value of the COG of the whole module is equal, as shown in Table 2.

| Object       | Part 1       | Part 2       | Part 3       | Part 4       | Part 5       | Part 6       | Whole        |
|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| X-axis position (mm) | 1428.284     | 1428.284     | 728.284      | 728.284      | 1047.444     | 1079.289     | 1110.803     |
| Y-axis position (mm) | 1890.000     | 1890.000     | 1780.000     | 1780.000     | 1860.849     | 2384.353     | 2172.697     |
| Z-axis position (mm) | 350.000      | 1000.000     | 350.000      | 1000.000     | 674.995      | 680.000      | 678.000      |
| Mass (kg)    | 10.000       | 10.000       | 5.000        | 5.000        | 10.000       | 60.000       | 100.000      |

Table 1. Whole COG of the wheelchair model calculated in MATLAB software.

| Object       | Whole        |
|--------------|--------------|
| X-axis position (mm) | 1110.803     |
| Y-axis position (mm) | 2172.697     |

Table 2. COG position and whole mass of the wheelchair displayed in ADAMS software.
By calculating the overall centroid of the wheelchair model, as shown in Figure 4, the height of the centroid from the support domain can be obtained as $H = 51.3cm$. Calculate the maximum tilt angle in this simulation situation. The calculation formula of the stability margin angle is $\eta = \arctg(SO_1/H)$. Calculated by MATLAB, we get $\eta_{AB} = 32.6^\circ$.

In the simulation software, the angle between the uphill road surface and the horizontal direction is continuously adjusted from $0^\circ$ to $35^\circ$, and the wheelchair can run stably along the desired route. When the slope is $36^\circ$, the wheelchair will tip over and cannot operate stably, as shown in Figure 5. It can be determined that the maximum tipping angle is $35^\circ$, which is $2.4^\circ$ different from the calculated theoretical value of $32.6^\circ$. The suitability of the wheelchair model can be proved within a certain range.

Therefore, the stability condition of the wheelchair in this experiment is:
1) when $\alpha < 12.6^\circ$, the wheelchair does not slip or tip;
2) when $12.6^\circ < \alpha < 35^\circ$, the wheelchair slips but does not tip;
3) when $\alpha > 35^\circ$, the wheelchair tips over.

5. Conclusion
In this paper, a simulation model of a wheelchair is established by ADAMS, and two stability indicators using stability theory are verified, laying a good foundation for the subsequent analysis of motion stability on more complex ground. The test process in the software simulation yields the same experimental results as the theory, which can illustrate the applicability of the stability theory and the reliability of the simulation environment within the allowable range of error. In the future work, we will promote the research and application of more dynamic and complex stability theories. Besides, after adding the function of terrain identification and analysis, the motion stability of the wheelchair can be analyzed combined with the its own parameters and running status.
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