STABILITY ANALYSIS AND CONTROL FOR A WHEEL-LEGGED ROBOT

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This paper introduces a novel robot with six wheel-legs. The robot is a combination of two frames, two rear wheel-legs and four front wheel-legs with 7 DOF (degree of freedom). In order to analyze the stability of the robot, kinematic model of the robot is established.

Stability pyramid technique is applied as the theoretical criterion of the system. Based on the criterion, stability algorithm rules and control strategy are designed to keep the stability of the robot. In order to prove the accuracy of the control system, two types of slope on the roads are applied in the simulation under the ADAMS/MATLAB environment. Stability criterion value, trim angles and roll angles of the robot are obtained through the simulation.

The final result shows that through the control system the average stability criterion values are 38.13 which is increased 22.02% compared with that without control on the longitudinal slope, and 35.59 which is increased 6.5% compared with that without control on the side slope. It is clear that the stability criterion value have changed gently after stability control.

Keywords: Stability criterion, Kinematic analysis, Wheel-legged robot, control strategy.

1. Introduction

In recent years, there has been a strong demand for the mobile robots operating on uneven surface [1]. According to different traveling mechanism, the mobile robot can be divided into three types: wheeled robot, tracked robot and legged robot [2-4]. With the development of the technology, hybrid robot, for instance, wheel-legged robots are invented [5-8]. Such equipments have found numerous applications in a wide variety of arenas such as exploration of extraterrestrial, rough unprepared and sharp slope environments[9-10].Wheel-Legged locomotion system is a preferred solution for maneuvering on such rough terrain, e.g. Chariot III[11],HyLoS series(four-legged robot)[12], NOROS series

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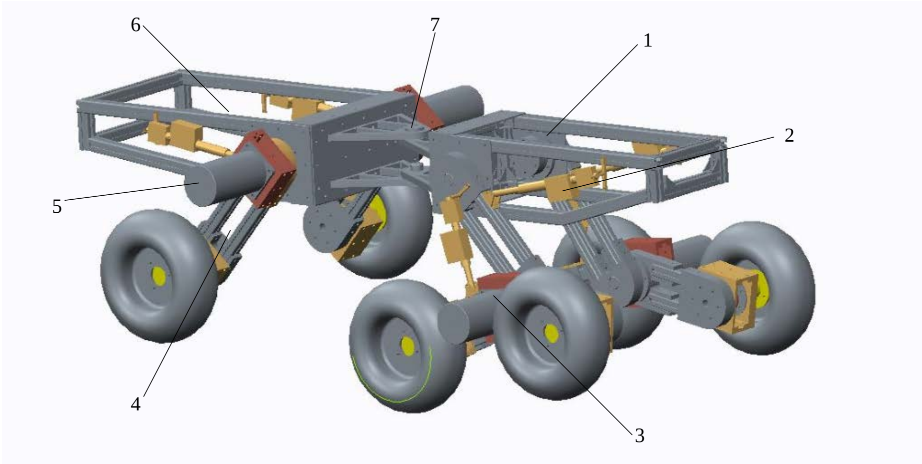
[13]and ATHLETE (six-legged robot)[14-16].Compared with the traditional wheeled machines, high mobility, obstacle-surmounting capability and maneuverability are the major merits of the wheel-leg locomotion system.

With the development of the technology, a large number of theoretical studies and simulation technology of the virtual prototype are applied to the stability analysis. Amount of academic achievements about the stability of the chassis are obtained based on the stable test of the vehicle, and the methods of the stability analysis are also developed. The major stability analysis methods such as: center of pressure method [17] (COP), effective mass center [18] (EMC), tumble stability margin[19] (TSM), force-angle stability measure [20](FASM), stability pyramid technique [21-22](SPT), normalized dynamic energy stability margin [23](NDESM), dynamic energy stability pyramid method (DESPM) are developed and applied to the stability control system.

In this paper, a novel six wheel-legged robot is presented. Kinematic model of the robot is established. Based on the kinematic model and stability pyramid technique, a special stability algorithm is applied to the control strategy for enhancing the stability of the robot. In order to prove the accuracy of the stability algorithm, simulations of the robot walking on the slope are taken in ADAMS/MATLAB environment.

2. Structure of the wheel-legged robot

This mobile robot is an equipment designed to surmount obstacles actively on forest road. As shown in Fig.1, the presented robot is a combination of two frames, two rear wheel-legs and four front wheel-legs. The two frames are connected by an articulated shaft. Wheel-legs are attached to the frames and distributed in both sides symmetrically, each with a wheel in the end. The rear wheel-leg with one degree of freedom (DOF) is independently actuated by 1 motor (for wheel driving) and 1 linear actuator (for leg lifting). The front wheel-legs are divided into two parts. Each part is a modular with 2 DOF and actuated by 1 motor and 2 linear actuators. In order to enhance the stability of the robot, the wheel-legs can change the position of the wheel legs when the robot moves on the rough surface.



1. Front frame 2. Linear actuator 3. Front wheel-leg 4. Rear wheel-leg 5. Motor 6. Rear frame 7. Articulated shaft

Fig. 1 Structure of the wheel-legged robot

3. Algorithm for the stability criterion value of the robot

3.1 Stability pyramid technique for the robot

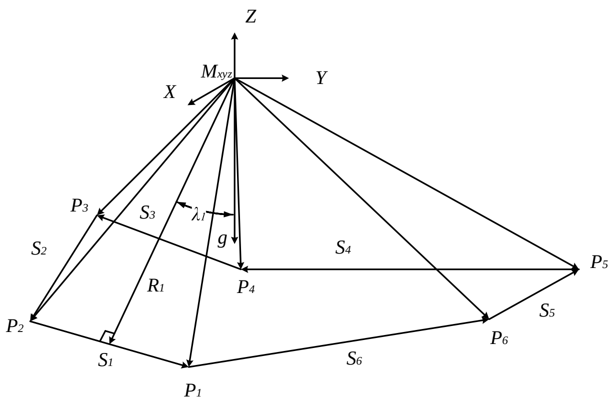


Fig.2 Stability pyramid technique model of the robot

Space model of the robot stability pyramid technique is established. It is assumed that the contacts between the wheels and the ground are dot contact, and the bottom surface of the stability pyramid is the dot contact connection polygon. As can be seen in fig.2, the i-th support contact is expressed as points pi, and the polygon of the stability pyramid can be expressed as

$$\begin{cases} S_i = P_{i+1} - P_i & 1 \le i \le 6 \\ S_i = P_1 - P_i & i = 6 \end{cases} \quad (1)$$

where P_i is the wheel-ground point and the S_i is the line vector between the wheel-ground points Coordinate of the weight points on the robot is marked as Mxyz, and vertical line between Mxyz and tumble margin can be calculated as

$$\boldsymbol{R}_i = \left(\boldsymbol{I} - \boldsymbol{s}_i \cdot \boldsymbol{s}_i^T \right) \boldsymbol{P}_{i+1} - \boldsymbol{M}_{xyz} \quad (2)$$

Where si is the unit vector of the support margin, which is $\boldsymbol{s}_i = \boldsymbol{S}_i / \left| \boldsymbol{S}_i \right|$, the stability criterion method is to calculate the angle between the vector of the gravity and the vertical R_i. Tumble criterion is related to the included angle and the minimum means the most possible tumble margin of the robot. The minimum angle is marked λ_i, which can be calculated as

$$\lambda_i = a\cos\left(\frac{\boldsymbol{R}_i \boldsymbol{g}}{|R_i| \cdot |g|} \right) \quad (3)$$

3.2 Control strategy of the stability system

Based on the output velocities of the electric actuators are controlled by the PID controller. The control strategy is shown in fig.3.

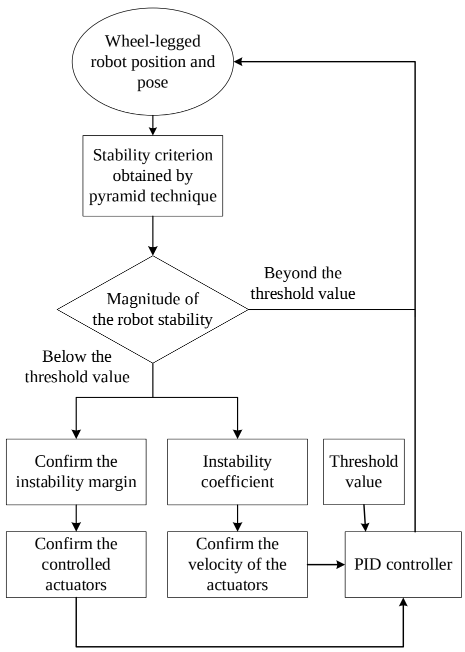
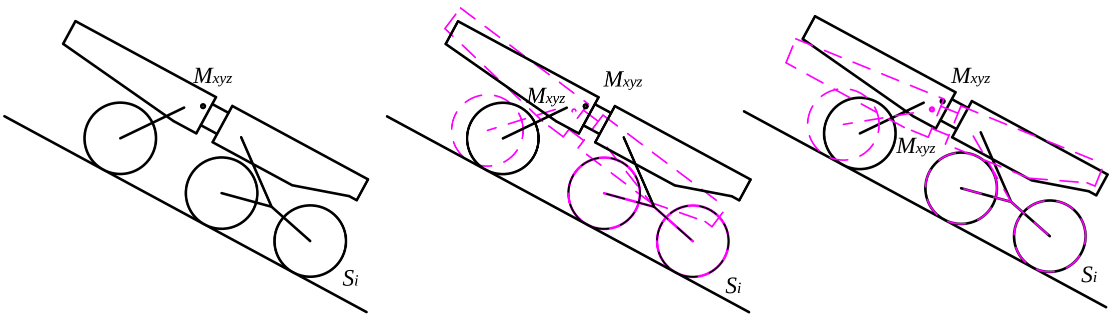


Fig.3 Control strategy of the robot stability control system

As shown in fig.3, wheel-legged position is obtained by the tilt sensors on the frames and the angle sensors between the swing legs. Based on the method of the pyramid technique, stability criterion is achieved. Magnitude of the robot stability is judged by comparing the calculated criterion with the threshold value. If the calculated criterion is beyond the threshold value, the robot will keep moving on its way. If the calculated criterion is below the threshold value, the robot will make some changes to adjust its position and pose in two ways, one is to confirm the controlled actuators, and another is to adjust the velocity of the controlled actuators. After adjustment, the robot will get a new position and pose.

3.3 Stability algorithm rules of the stability control system

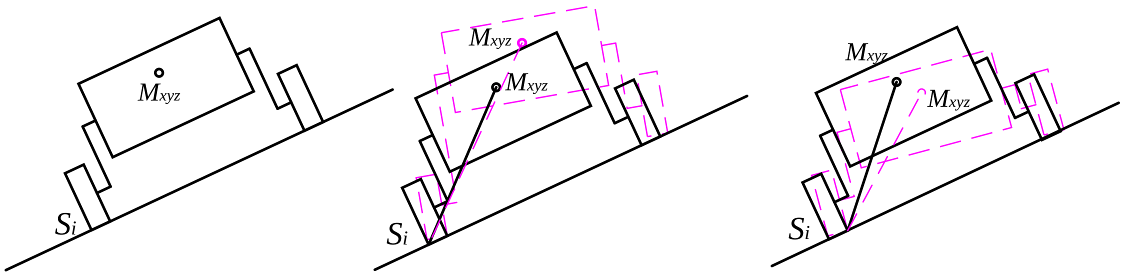
The tumble of the robot can be divided into two types: roll over and trim over. Velocities of the extension and retraction of the actuators are decided by the main instability margin in roll over and trim over. Fig4 shows the sketch of the longitudinal slope walking of the robot, and the tendency of the tumble is roll over. As can be seen in fig4 (b), when the robot lifts the front leg, the position of the weight point is changed and the stability criterion value can be improved at the same time. As can be seen in fig4(c), when the robot lifts the rear leg, the position of the weight point is changed and the stability criterion value can be improved also.



a) Initial pose and position b) When the front wheel-leg lift c) When the rear wheel-leg lift

Fig.4 pose and position of the robot on the longitudinal slope

Fig5 shows the sketch of the side slope walking of the robot, and the tendency of the tumble is trim over. As can be seen in fig5 (b), when the robot lifts the left leg, the position of the weight point is changed, and the stability criterion value can be improved. As can be seen in fig5 (c), when the robot shortens the right leg, the position of the weight point is changed, and the stability criterion value can be improved also.



a) Initial pose and position b) When the left wheel-leg lift shorten c) When the right wheel-leg

Fig.5 pose and position of the robot on the side slope

Slope stability analysis shows that when the robot on the longitudinal slope, the main factor effected the stability is the height of the robot weight point. On the side slope, the main factor is the levelness of the robot body. The stability algorithm rules is presented in tab.1.

Table1. Stability algorithm rules of the stability control system

	S1	S2	S3	S4	S5	S6
FLUA	+	-	-	-	-	+
FRUA	-	-	+	+	-	-
FLLA	-	0	0	0	0	+
FRLA	0	0	-	+	0	0
RLA	+	-	-	-	-	+
RRA	-	-	+	+	-	-

As can be seen in table1, Si stands for the instability margin shown in the fig 2. In this table, FLUA (front left upper actuator) FRUA (front right upper actuator) FLLA (front left lower actuator) FRLA (front right lower actuator) RLA (rear left actuator) and RRA (rear right actuator) are controlled by the stability system. “+” means extension of the actuators, and “-” means retraction of the actuators. The weightiness matrix of the FLUA, FRUA, RLA and RRA can be obtained as

$$\begin{cases} Q_1 = 1 + \dfrac{\tau_r}{\tau_t}, Q_2 = 1, Q_3 = -1 + \dfrac{\tau_r}{\tau_t}, Q_4 = -1 & \tau_r < \tau_t \\ Q_1 = 1 + \dfrac{\tau_t}{\tau_r}, Q_2 = 1, Q_3 = -1 + \dfrac{\tau_t}{\tau_r}, Q_4 = -1 & \tau_t < \tau_r \end{cases} \tag{4}$$

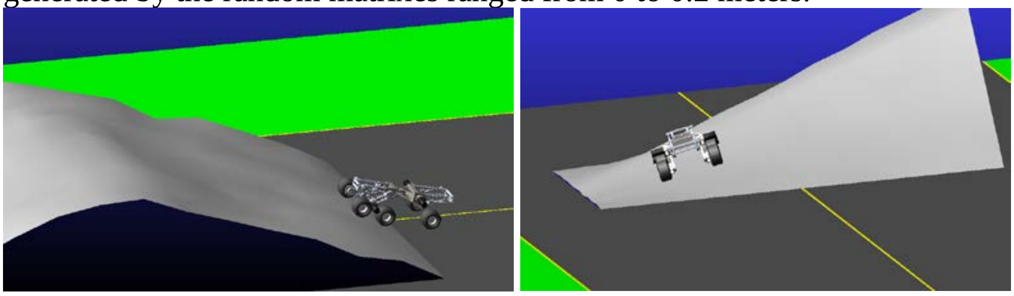
where τr means the criterion value of the main instability margin in roll over, and τt means the criterion value of the main instability margin in trim over, Q_1, Q_2, Q_3 and Q_4 are the adjustment weightiness of the main actuators FLUA, FRUA, RLA and RRA. Q_1 takes the largest proportion of the weightiness, the extension of the corresponding actuator can enhance stability in both aspects of the robot body. Q_2, Q_3 and Q_4 are assigned to the corresponding actuators respectively.

Weightiness of FLLA and FRLA are as 0.3 time as that of FLUA and FRUA, because of the stroke and effect relationship.

4 Simulation of the system through adams/matlab

4.1 Establishment of the simulation

Virtual prototype of the robot is established by Solidworks. In ADAMS environment as can be seen in fig6, virtual prototype of the robot is imported. The initial position of the robot is set as: $\theta_1=\theta_2=51°$, $\theta_3=\theta_4=35°$, $\theta_5=\theta_6=48.5°$. The initial velocity of the robot is 0.25m/s. Fiala model is chosen as the tires model of the robot in ADAMS. Based on the product parameters, the main parameters of the tires are set as follow in ADAMS: the radius of the tire is 0.208m, the width is 0.18m, the vertical stiffness is 1.9E+6. Two types of slopes are established for the simulation. One is 30° longitudinal slope and the other is 25° side slope. Both of the slopes are 7.5 meters long and 8 meters wide. The roads on the slopes are generated by the random matrixes ranged from 0 to 0.2 meters.



a) on the longitudinal slope b) on the side slope

Fig 6. Virtual prototype imported in ADAMS environment

Based on the combination of Simulink and Adams, the model in ADAMS is imported into the MATLAB/Simulink environment. As shown in fig.7, the inputs of the ADAMS_sub include the velocities of the electric actuators and velocities of both side wheels of the robot. ADAMS_sub is a module which represents the whole model of the simulation in ADAMS. The outputs of the ADAMS_sub are angle θ_1, θ_2, θ_3, θ_4, θ_5, θ_6 and γ, the function block which changes the included angle to the weightiness of the actuators and stability criterion value of the robot is connect to the ADAMS_sub. The D-value between ideal stability criterion value and output stability criterion value and the weightiness of the actuators are the input of the next function block judging the weightiness for the corresponding actuators, and the outputs of the block are the input of the PID controller which controls the velocity of the actuators for the ADAMS_sub. The threshold value of the system is 35.

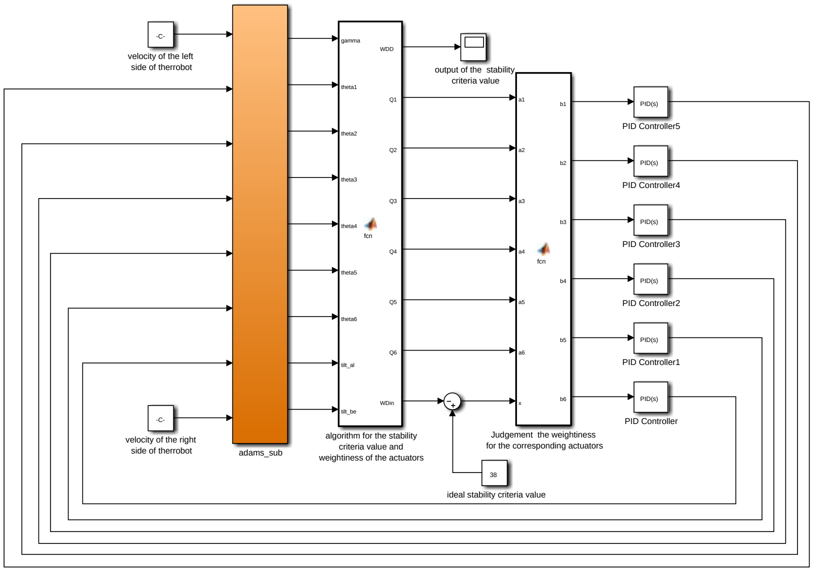
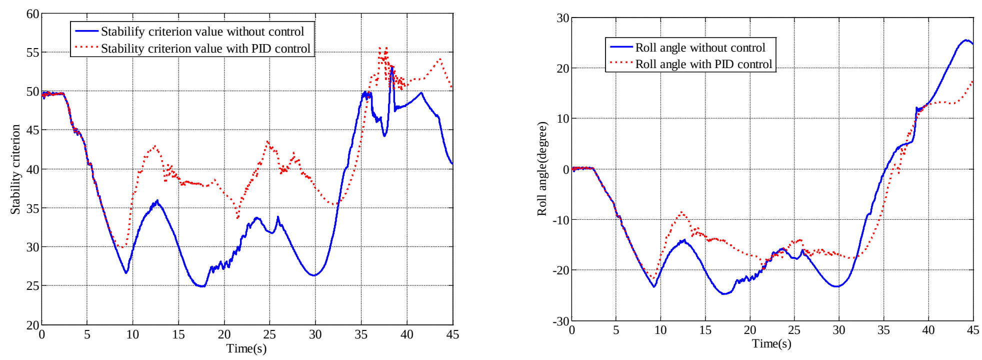


Fig 7. simulation model combined ADAMS with MATLAB

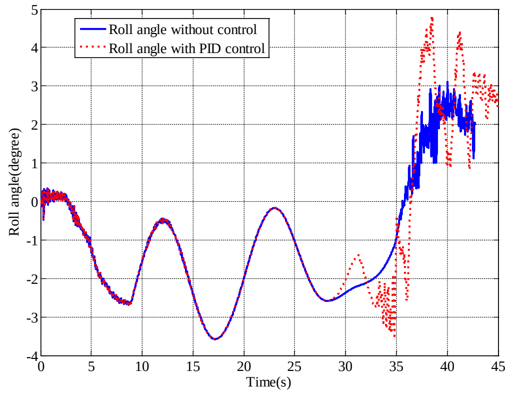
4.2 Results analysis of the simulation

The simulations are divided into 2 groups: one is with the stability control, the other is without control. Each group contains the two situations: longitudinal slope simulation and side slope simulation. Through the simulation, stability criterion value, roll angle, and trim angle are obtained. Fig 8 shows the simulation results when the robot is on the longitudinal slope, and Fig11 shows that when the robot is on the side slope.



a) stability criterion value

b) Roll angle



c) Roll angle

Fig 9. Simulation results when the robot is on the side slope

As can be seen in fig.9a), on the side slope the stability criterion value with PID control is significantly enhanced by the improved stability control system. The control system starts to work at 27.3 second, when the stability criterion value is below 35. At 37.5 sencond, the stability criterion value without control drops to the lowest point through the simulation. The robot is on the inclined slope at the same time. During this period, the average of the stability criterion value with control system is 35.59, that without control is 33.40. The stability criterion value is increased 6.5%. In the simulation, variation tendency of the trim angle is the same as that of stability criterion value, as can be seen in fig.9b). Trim angle starts to increase after the 27.3 second, because the stability algorithm intends to keep the body level when the robot went on the side slope. The roll angle of the robot changes a little heavily with the stability control, as can be seen in fig9 c), which is due to the vibration of the body when the wheel-legs swing. The range of the roll angle is from -3.5° to 4.7° during the period. It is clear that the trim angle and stability criterion value have changed gently after stability control.

5. Conclusion

1) In this paper, a novel six-wheel-legged robot is presented. Kinematic model of the robot is established. Coordinates of the wheel/ground contact points, weight point position and vector of the gravity are solved by the screw theory method.

2) Based on the stability pyramid technique, stability criterion value is as the criterion judgement of the robot stability system. After analyzing the position change of the robot on the longitudinal slope and side slope, stability algorithm rules and control strategy are designed to the robot stability control system.

3) To prove the accuracy of the control system, simulation of the robot is conducted under ADAMS/MATLAB environment. Two types of slope on the roads are applied in the simulation. The result of the simulation shows that through the control system the average stability criterion values are 38.13 which is increased 22.02% compared with that without control on the longitudinal slope, and 35.59 which is increased 6.5% compared with that without control on the side slope. It is clear that the stability criterion value has changed gently after stability control.

6. Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this article.

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