Mountain Rescue Mobile Platform based on Anti-saturation Strategy Proportional Integral Control

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Abstract: Rugged terrain and inconvenient transportation in the rural areas of southwest China, lead to difficulties in transporting power equipments such as electric poles, transmission lines and small transformers in time of power grid upgrading and emergencies. In particular, when there is no road in the last few kilometers, the transportation relies totally on manpower. In this paper, the dynamics of the power equipment mobile platform is analyzed, and then its stability is analyzed using the proportional-integral control method with anti-saturation strategy. Combined with the control rate characteristics and anti-saturation strategy, the stable operation conditions of the mobile platform are obtained, making it possible for the platform to drive in mountains, hills and farmlands. This creates an efficient mechanical operation mode under no-road conditions during construction.

1. Introduction
Intelligent mobile platform for mountain emergency rescue based on All Terrain Vehicle(ATV) is helpful to solve problems of transporting equipments during transformation and upgrading of rural power grids and emergency response. It can move on terrains where ordinary vehicles are difficult to drive, such as inland rivers, lakes, waterways. Special purpose vehicles are assembled by carrying different modules. At present, one representative example is the BV202 crawler ATV developed by Sweden. Its main characteristics are that the ratio of grounding pressure is much lower than that of wheeled vehicles, and the turning radius and longitudinal passing radius are much better compared with other vehicles of the same size. In reference [1], a kind of crawler walking mechanism passively adapted to terrains with flexible suspension was proposed, and tests were carried out on convex platform and continuous steps. Since it can passively adapt to rugged terrains, it shows good ability to pass terrains with stability. However, due to soft characteristics of the track itself, it seriously restricts the height that the chassis can climb. In reference [2], a kinematic and dynamic model of in-situ steering of articulated crawler vehicle is established by mathematical modeling. The formulas of steering radius and steering angle of articulated tracked vehicles in-situ steering are derived theoretically, which provides theoretical basis for structural design of articulated tracked vehicles. Reference [3] applies advanced wireless control to explore and transport goods in complex terrains or areas with safety concerns. In reference [4-5], the design of overall structure and front suspension system of ATV is studied from the aspects of operation stability and structure simplification. In reference [6], in order to ensure that large-scale power equipment can control its tilt angle during transportation, a multi-sensor tilt angle measurement system is proposed. Reference [7] introduces that under the harsh transportation conditions, when traditional transportation cannot fully meet the needs
of construction, the use of crawler vehicle can effectively solve the transportation problems of engineering materials, construction tools and equipments, so that the project can be constructed smoothly, and provide reference for transmission line construction in the future.

Aiming at the lack of stability analysis of mobile platform in emergencies, this paper proposes a method of stability control based on proportional-integral control with anti-saturation strategy. Firstly, the dynamic analysis of mobile platform is carried out to analyze its motion characteristics. Based on the characteristics, the role of control rate in maintaining system stability is analyzed. Finally, combined with the characteristics of control rate and anti-saturation strategy, the stable operation conditions of the mobile platform are obtained.

2. Dynamic Analysis

![Figure 1 Analysis of forces applied to the vehicle](image)

The driving force of the whole vehicle satisfies the balance equation of force when vehicle driving in straight line, that is

$$ F_i = F_f + F_r + F_w + F_j $$

Expanded as follows:

$$ \frac{T_{mi}i_{ph}}{r} = mgf \cos \alpha + mg \sin \alpha + \frac{CdA}{21.15}v^2 + \delta m \frac{dv}{dt} $$

(2)

Where $F_i$ is traction force, $F_f$ is rolling resistance, $F_r$ is uphill resistance, $F_w$ is air resistance, $F_j$ is acceleration resistance, $m$ is vehicle mass, $g$ is gravity acceleration, $f$ is rolling resistance coefficient, $\alpha$ is ramp angle, $Cd$ is air resistance coefficient, $A$ is windward area, $v$ is speed, $\delta$ is mass increase factor, $t$ is time, $T_m$ is motor torque, $r$ is wheel rolling radius, $i_{ph}$ is the mechanical transmission efficiency, $i$ is the total transmission ratio.

At the same time, the driving force $F_i$ is limited by the maximum adhesion of the ground $F_{\varphi}$, and the expression of $F_{\varphi}$ is:

$$ F_i \leq F_{\varphi} $$

(3)

$$ F_{\varphi} = \mu mg \cos \alpha $$

(4)

Where the ground adhesion coefficient $\mu$ is 0.8.

2.1 Maximum Speed

Let us ignore the limit of power for the time being, when the vehicle runs smoothly on the horizontal surface and the driving motor reaches its maximum speed, the vehicle can reach the theoretical maximum speed of:

$$ V_{max} = \frac{n_{m_{max}} \times 0.377 \times r}{i} $$

(5)

where $n_{m_{max}}$ is the maximum speed of the driving motor, $r$ is the radius of the wheel, and $i$ is total transmission ratio.
2.2 Maximum climb
Because only one-side motor is used to provide power for the vehicle, there is no need to consider axial load transfer in the process of climbing and accelerating, and all adhesion can be converted into driving force. Because the climbing speed is low and the wind resistance is negligible, the climbing slope can be calculated directly by balance equation of forces. The dynamic equilibrium equation of forces during climbing is:

\[
\frac{T_m \eta_{ch}}{r} = mg \cos \alpha + mg \sin \alpha
\]  

(6)

where \( T_m \) is driving motor torque, \( i \) is transmission ratio, \( \eta_{ch} \) is mechanical transmission efficiency, \( r \) is rolling radius, \( m \) is vehicle mass, \( g \) is gravity acceleration, \( \alpha \) is slope, \( f \) is rolling resistance coefficient.

The torque of driving motor should be less than the peak torque of driving motor, and the adhesion of slope surface should be taken into account when calculating performance of climbing, and the adhesion coefficient \( \mu \) is set as 0.8 for calculation. At this time, the maximum slope of vehicle climbing should satisfy:

\[
mg \cos \alpha + mg \sin \alpha \leq \mu mg \cos \alpha
\]  

(7)

2.3 Maximum driving slope

![Figure 2 Analysis of forces on vehicle on the side slope](image)

The state of the vehicle on the side slope is shown in figure 2. The critical state of tipping is:

\[
\frac{B}{2} G \cos \alpha - h G \sin \alpha = 0
\]  

(8)

Where \( h \) is height, set as 716 mm, \( B \) is distance between wheels, set as 1425 mm, then:

\[
tg \alpha = \frac{B}{2h} \approx 1.00
\]  

(9)

In the critical state of side slip, we have:

\[
\varphi G \cos \alpha - G \sin \alpha = 0
\]  

(10)

\[
tg \alpha = \varphi = 0.75
\]  

(11)

3. System stability
From the above dynamic analysis, it can be seen that when the platform is moving, if its speed, climbing gradient or driving side slope exceed the critical value, sideslip may occur. At this time, the control rate is needed to prevent the track side slip. The control of mobile platform is proportional-integral control with anti-saturation strategy, i.e. the controller is only a proportional-integral controller when saturation does not occur. However, due to the change of system parameters, external disturbance and imprecise modeling and other factors, the stability of the system will be affected. If the system cannot be stabilized for a long time, the integral term will continue to
increase, which will lead to premature saturation of the actuator and damage the transient response and even stability of the system. The anti-saturation strategy can ensure that the system can be stabilized after the actuator saturation. The stability analysis of the control is given below.

### 3.1 Stability analysis

The controller saturation $s$ is introduced to indicate the stability of the system, where $s$ satisfies:

$$s = \bar{X} + k_\mu \varepsilon$$

where $s$ is the controller saturation, $\varepsilon$ is the error, $\bar{X}$ is the error integral and $k_\mu$ is the slope.

When $|S| < \theta_u$ the system is stable, otherwise the system is unstable. At this time, as long as the parameters of the designed controller meet certain conditions, it can ensure that the controller converges to the range $(0, \theta_u)$ in finite time, and then the system is stable.

Let $M_s$ be error and error integral manifold, that is:

$$M_s = \{(e, \bar{x}) \mid s = |\bar{x} + k_\mu \varepsilon| \leq \theta_u, |\varepsilon(t_0)| \leq \theta_u / k_\mu\}$$

Its geometric meaning is as follows:

![Figure .3 Error and error integral manifold](image)

Let $M_e$ be a set of error integral, that is:

$$M_e = \{\varepsilon \mid |\varepsilon| \leq \theta_u / k_\mu\}$$

Then, as long as $\varepsilon(t_0) \leq \theta_u / k_\mu$, as derived from (14), For any $t \geq t_0$, the following formula holds:

$$|\varepsilon(t)| \leq \theta_u / k_\mu$$

### 3.2 Stability control

(1) Controller saturation

$M_s$ is an invariant set. The motion of the system state is defined between two parallel lines of AC and BD: the range of motion is $S \geq \theta_u$ (line segment AB above) and $S \leq -\theta_u$ (line segment CD below), set $\bar{\alpha} = [K_u \quad 1]$ to a vector perpendicular to the line segment and pointing to the manifold other than $M_s$.

Above the line segment AB, $s$ moves toward the manifold $M_s$, as long as (16) is satisfied:
\[
\begin{bmatrix}
\dot{\epsilon} \\
\dot{\tilde{x}}
\end{bmatrix}
= \begin{bmatrix}
k_u
1
\end{bmatrix}
< 0
\] (16)

Expand (16), we have:
\[
\begin{bmatrix}
\dot{\epsilon} \\
\dot{\tilde{x}}
\end{bmatrix}
= k_u \dot{\epsilon} + \tilde{x}
\]
\[
= k_u \left( -k_u \epsilon + \theta_u \text{sat} \left( \frac{s}{\theta_u} \right) \right) + \tilde{f} (\tilde{x}) - K_u \text{sat} \left( \frac{s}{\theta_u} \right)
\]
\[
= -k_u^2 \epsilon + k_u \theta_u + \tilde{f} (\tilde{x}) - K_u
\] (17)

Therefore, from (17), \( K_u \) needs to meet the following condition:
\[
K_u > 2k_u \theta_u + \tilde{f} (\tilde{x})
\] (18)

Below the line segment CD, \( s \) moves toward the manifold \( M_s \), similarly, as long as \( K_u \) satisfies the following condition:
\[
K_u > 2k_u \theta_u - \tilde{f} (\tilde{x})
\] (19)

Combine (18) and (19), we have:
\[
K_u > \max \left\{ 2k_u \theta_u \pm \tilde{f} (\tilde{x}) \right\}
\] (20)

When the controller is saturated, the system is unstable, and when \( K_u \) in (20) is satisfied, the system returns to stability.

(2) Unsaturation of the controller

When \( S < 0 \) the control law is proportional-integral control, the state of the system \( \bar{X} \) can be stabilized to the origin and the system converges asymptotically. The error system can be transformed into:
\[
\dot{\tilde{x}} = \left( \frac{\tilde{f} (\tilde{x})}{\tilde{x}} - K_u \frac{\theta_u}{\theta_u} \right) \tilde{x} - K_u k_u \epsilon + p(t)
\]
\[
\dot{\epsilon} = \tilde{x}
\] (21)

Clearly, the above system equation is a typical VanderPol equation, which can be regarded as a mass-spring-damping system. Therefore, as long as the system satisfies (21), the system must be asymptotically stable.
\[
\frac{K_u}{\theta_u} > \left| \frac{\tilde{f} (\tilde{x})}{\tilde{x}} \right| = \left| \frac{f(x) - f(x_c)}{x - x_c} \right|
\] (22)

4. Results & Discussion
The known conditions for dynamic calculation as listed in Table 1.

| Marking | Meaning                      | Value   | Marking | Meaning                      | Value   |
|---------|------------------------------|---------|---------|------------------------------|---------|
| \( g \) | Gravity acceleration         | 9.8 m/s² | \( f \) | Rolling resistance coefficient | 0.035   |
| \( \mu \) | Ground adhesion coefficient  | 0.8     | \( \delta \) | Quality increase factor       | 1.05    |
| CD      | Air drag coefficient         | 0.6     | \( \eta_m \) | Mechanical                   | 0.91    |
The results of the dynamic calculations are shown in Table 2:

| Marking | Meaning | Value  | Marking | Meaning | Value     |
|---------|---------|--------|---------|---------|-----------|
| $A$     | Windward area | 2.5 m$^2$ | $i$     | Total transmission ratio | 15.208 |
| $m$     | Truckload  | 3000 kg | $r$     | Rolling radius | 0.375 |
|         | Truck     | 1500 kg |         |         |           |
|         | Full load | 4500 kg | $n_{m \_ \text{max}}$ | Maximum speed of drive motor | rpm 8000 |

| $\eta_m$ | Drive motor high speed efficiency | 0.82 |
|          | Drive motor low speed efficiency  | 0.90 |

Due to the different rolling radius of no-load and full load, the theoretical maximum speed is 8 km/h with no load and 6 km/h with full load.

To ensure that the model vehicle does not tip over or sideslip when driving on the side slope, the maximum driving side slope should be taken as the minimum value of $\alpha_1$ and $\alpha_2$, so the maximum driving side slope of the vehicle can be 75% theoretically, but the maximum angle of the oil suction port of the engine oil bottom shell is 26.5°.
5. Conclusions
In this paper, in order to prevent the mobile platform from side-slipping during driving, system stability is simulated through the control rate based on the proportional-integral control with anti-saturation strategy. When saturation occurs, the transient response and even the stability of the system will be damaged. Through the anti-saturation strategy optimization, the system can still stabilize and converge after actuator saturation, which effectively improves the safety of the mobile platform when driving in different terrains. Combined with the control rate characteristics and anti-saturation strategy, the stable operation conditions of the mobile platform are obtained. Based on this, a prototype of mountain emergency mobile platform is developed.

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