Design of high precision mechatronic-hydraulic leveling system for vehicle-mounted radar

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Abstract: In order to improve the control performance of vehicle-mounted radar, a high precision leveling control system is designed through mechatronic-hydraulic integration technology. A leveling method combining angle error leveling method and height error leveling method is designed, and inclinometers are set in the front and rear of the vehicle body platform to effectively eliminate the virtual outrigger phenomenon in the leveling process. The mathematical model of hydraulic system is developed, the fuzzy PID control method is introduced, and the four-point support hydraulic leveling control system is developed by using STM32 microcontroller as the control core. The field test proves that the control system has good control performance, high leveling accuracy, short time, and meets the control requirements of the radar vehicle.

1. Introduction
In modern information warfare, radar plays an important role as a clairvoyant on the battlefield. The work of vehicle-mounted radar requires a high level of car body, so a high precision car body leveling control scheme needs to be designed. Liao Yide et al from Huazhong University of Science and Technology designed a set of fast leveling device controlled by high-speed on-off valve [1]. Xia Xin et al. from Southwest Jiaotong University designed a set of 4-point electro-hydraulic leveling system with PLVC as the control core, with a precision of 2.5° [2]. In this context, to improve the leveling control performance of a radar vehicle, the original control system is improved, a set of high-precision automatic leveling control system is designed, and virtual outrigger phenomenon is effectively dealt with. In this control system with ARM STM32F407 as control core, fuzzy PID control method is adopted to develop a four-point support hydraulic leveling control system, and the system is tested in the field. Under the premise that the initial angle is close to 3°, the final leveling accuracy reaches 0.015°. The adjustment time is less than 400s (including the time of outrigger synchronous pre-support), which proves the control performance of the system is better than that of the same type of vehicle.

2. Leveling system modeling

2.1. Introduction to leveling System
The 3D model of radar vehicle platform is shown in figure 1. It is necessary to control the movement of four hydraulic outriggers to adjust the platform to the level, and the inclination angle of the platform is measured by the inclinometer installed at the bottom of the platform. Among them, the hydraulic leveling outrigger is driven by the proportional directional control valve, and the inclinometer signal is processed by STM32 microcontroller, and the control signal in the form of current is input to the
proportional directional control valve to control the opening of the proportional directional control valve and then control the movement speed of the outrigger. The block diagram of the radar vehicle leveling control system is shown in figure 2.

![Figure 1. 3D model of radar vehicle platform](image)

Figure 1. 3D model of radar vehicle platform

![Figure 2. Block diagram of leveling control system](image)

Figure 2. Block diagram of leveling control system

2.2. Mathematical modeling of hydraulic outrigger

In this system, the outrigger movement speed $v_1$ is directly controlled by the oil flow $Q_v$, and the proportional valve spool displacement $X_v$ and the external load size $P_l$ are the direct factors affecting the oil flow $Q_v$, in which the control plate controls the proportional valve spool displacement $X_v$ through the current signal $I$. The system transfer function and its derivation are shown below.

$$v_l = \frac{4Q}{\pi d^2}$$  \hspace{1cm} (1)

$$Q_v = K_q X_v - K_p P_l$$  \hspace{1cm} (2)

$$X_v = \frac{IK_q}{\omega_v^2 + 2\zeta_v \omega_v + 1}$$  \hspace{1cm} (3)

By combining equations (1), (2) and (3), we can obtain:

$$v_l(s) = \frac{4K_q^2 I(s)}{\left(\frac{s^2}{\omega_v^2} + \frac{2\zeta_v s}{\omega_v} + 1\right)\pi d^2} - \frac{K_p P_l(s)}{\pi d^2}$$  \hspace{1cm} (4)
Where, $K_q$ is the flow gain of the proportional valve near the steady-state operating point, $m^2/s$; $K_p$ is the flow-pressure coefficient of the proportional valve near the steady-state operating point, $m^3/MPa/s$; $\omega_v$ is the equivalent undamped natural frequency of the proportional valve, $rad/s$; $\zeta_v$ is the equivalent damping coefficient of proportional valve, dimensionless; $d$ is the rodless cavity diameter of hydraulic outrigger, $m$.

3. Control strategy design and simulation

3.1. Design of leveling method

Automatic leveling system is a negative feedback control system. According to the error type, leveling methods can be divided into angle error control method and height error control method[3]. Angle error control method, according to the platform dip angle controls outriggers to move. The control method is relatively simple, and can control the movement of two outriggers at the same time, fast but with low precision. Height error control method, according to the platform dip angle calculates the needed stroke of the outriggers, and then control the corresponding outriggers to extend the corresponding stroke, can control the three outriggers at the same time with high precision[4].

Leveling method of design need to consider to the processing of virtual outrigger phenomenon. Virtual outrigger phenomenon is that one outrigger does not force or stress is small in the process of leveling. Because of the large platform span, when a virtual outrigger, the four outrigger uneven bearing will inevitably lead to deformation of the platform, at this point does not obtain in angle accurate leveling needed for each outrigger movement, thus height error control method can't process the virtual outrigger phenomenon. The angle error leveling method can directly adjust the inclination angle of the platform. When inclinometers are set on the front and rear of the vehicle platform, it can control the angle difference of vehicle platform in a small range and the virtual outrigger can be accurately excluded. The sensor layout is shown in figure 3.

After comparing the two leveling methods, a leveling method combining angle error control and height error control is designed. Specifically, the angle error control method is used to conduct rough adjustment, adjust the platform inclination to a certain angle threshold value, and then adjust the angle to the final demand angle by position error control method.

![Figure 3. Schematic diagram of inclinometer layout](image)

3.2 Fuzzy PID control principle

Fuzzy control is a modern intelligent control algorithm based on fuzzy mathematics, which can be used to simplify the solution of complex systems. As an intelligent PID, fuzzy PID control can solve the problems of poor parameter setting and poor performance while retaining the strong robustness of conventional PID[5], its control principle diagram is shown in figure 4.

![Figure 4. Control principle of fuzzy PID control](image)
The fuzzy PID control process is as follows[6]:

- Input the deviation and deviation change rate into the fuzzy controller after fuzzy processing.
- The fuzzy controller queries the fuzzy control rule table according to the membership function of the input parameter and obtains the corresponding fuzzy value output.
- Fuzzy processing of output parameters of fuzzy controller.
- Input the value of the fuzzy solution to the PID controller for system control.

### 3.3 Fuzzy PID controller design

Let’s take the deviation $E$ and the rate of change $E_c$ as input, and variables, and PID parameter change \( \Delta K_p/\Delta K_i/\Delta K_d \) are the output. The continuous variables were discretized into NB (negative large), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive middle), And PB (positive large). Among them, PB is the s-type membership function, NB is the Z-type membership function, and the others are triangular membership functions. The domain of $E$ and $E_c$ is [-3,3], the domain of variable $\Delta K_p/\Delta K_i$ is [-0.3,0.3], and the domain of variable $\Delta K_d$ is [-0.06,0.06].

The formulation of fuzzy control rules is shown in the table 1.

#### Table 1. Table of fuzzy control rules

| $\Delta K_p/\Delta K_i/\Delta K_d$ | EC          |
|-----------------------------------|-------------|
| NB  | PM/NM/NS  | PS/NS/PS   |
| NM  | PS/NM/NS  | NS/Ps/Ps   |
| NS  | ZO/ZO/NS  | NM/PM/PS   |
| E   | PS/NS/NS  | NS/Ps/Ps   |
| PS  | ZO/ZO/NS  | NM/PM/PS   |
| PM  | ZO/ZO/NS  | NM/PM/PS   |
| PB  | ZO/P/PS   | NB/PB/PB   |

The output of fuzzy controller needs to be defuzzified to get the accurate output value, so as to correct PID parameters. The centre of gravity method is commonly used to defuzzify[7], as shown in the equation (5).

$$\sum_{i=1}^{j} x_i \mu_i(x_i)$$

Where, $j$ is the number of fuzzy set elements; $x_i$ is the element value in the fuzzy set; $\mu_i$ is the weighting coefficient of membership degree.

Input the value of the fuzzy solution to the PID controller for parameter $K_p/K_i/K_d$ in order to meet the requirements of different error and error rate on the control system.
4. Control system design

4.1 Hardware Structure
The control principle of leveling system is shown in figure 5. The main control chip is STM32F407, which receives input signals from all sides and generates corresponding output signals to control the action of the hydraulic system. The inclinometers through the RS485 communication mode input platform dip angle into levelling control circuit board which communicates other system through the RS485 communication mode and display real-time control status on the OLED display platform. Operators can control body automatic leveling or leg separate action, etc. via buttons on the panel.

4.2 Software Design
The software of the control system is developed on the Keil5 platform, and the control program is written in C language. It is mainly composed of solenoid valve control module, button input module, digital sensor input module, analog sensor input module, RS485 communication module, OLED display module, timer module and logic control module. The functions of the system include automatic movement of the extension arm and outrigger, detection of outrigger landing, automatic leveling of the body, synchronous recovery of outrigger and display of the control status. The automatic leveling program is mainly divided into two parts, coarse and fine, respectively using different leveling strategies, angle error leveling method and position error leveling method[8], the leveling flow chart is shown in figure 6.

Figure 5. Control principle diagram of leveling system
5. System test verification

5.1. Test system
The design scheme and theoretical research of the automatic leveling control system have been successfully applied to a radar vehicle, and the system has been verified by field test. In this radar vehicle leveling system, the software is developed on Keil5 platform, and the control program is established by C language. LIQZO-L-503 /L4 proportional valve of ATOS company is used for outrigger control, and HCA546T of RION Company is used for inclinometer, which has high stability, high precision and strong anti-interference. As mentioned above, in order to exclude virtual outriggers, inclinometers are set in front and back of the vehicle body respectively.

5.2. Experimental Results
After outrigger to support of synchronous control system according to the control logic and algorithm for automatic leveling, in order to verify the validity of the leveling strategy and control algorithm, has carried out many experiments, the car body initial angle adjustment for different values, the following will be data graph from two trials, as shown in figure 7.
In Figure 7(a), the initial longitudinal inclination is about 1.43° and the transverse inclination is about 0.1° on average. Combined with the actual observation, the body outriggers all landed in about 105 seconds, the complete leveling process was less than 200 seconds, and the final leveling accuracy reached 0.015°. In Figure 7(b), the initial longitudinal inclination is about 3.09°, and the transverse inclination is about 0.15° on average. Combined with the actual observation, the body outriggers all landed in about 180 seconds, the complete leveling process was less than 370 seconds, and the final leveling accuracy reached 0.015°. In the whole leveling process, there is only little difference between the front transverse angle and rear transverse angle, which indicates that this leveling strategy can effectively eliminate the virtual outrigger. When the initial angle reaches 3°, the leveling time is within 400s, and the leveling accuracy reaches 0.015°, which can fully meet the requirements of accuracy and time. The test results verify that the leveling control system has excellent performance, its control method has good repeatability, and the inclination angle change process is almost the same in the two leveling tests.

6. Conclusion

- Through the test, the hydraulic leveling control system applying the leveling method combining angle error control and height error control, and fuzzy PID control method, has good control performance, whose leveling precision can reach 0.015°, and even though on the premise of the initial angle 3°, can complete the leveling process (including preliminary support phase) in the 400 s, which fully meets the radar vehicle leveling requirements.
- In this leveling system, inclinometers are arranged on the front and rear horizontal sides, which can effectively avoid the occurrence of virtual outriggers in the leveling process. And the system has the characteristics of high leveling precision, short time, easy operation and universality, and combined with the actual engineering improvement, can be extended to other vehicle-mounted platform leveling occasions.

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