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Attitude stability Control for Multi-Agent Six Wheel-Legged Robot

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Abstract: Multi wheeled-legged robot systems are MIMO complex systems with multi information fusion. In this paper, a multi-sensor information fusion based wheeled-legged cooperative control strategy is proposed to solve the problem of attitude stability control for the six wheeled-legged robot-BIT-NAZA-II. First, when the robot is wheel motion, the overall attitude of the robot is adjusted by controlling the vertical degree of freedom(DOF) for the Stewart platform. Second, when the wheel movement is on uneven road, the foot end is easy to be suspended or raised. The impedance control method based on the position inner loop is used to solve the problem of leg suspension or raised. Third, in order to ensure the maximum motion space of single leg, the central height controller is designed. Moreover, the control strategy is mainly completed by the central CPU and six bottom CPUs. Six bottom CPUs receive the force information of each leg, and calculate the position of each leg by combining the impedance controller. Meanwhile, the central CPU receives the attitude angle information, calculates the position of each leg by using the attitude controller, takes two different position commands as the input of the central height controller, outputs the calculated position of the central height controller to six bottom CPUs through UPD communication, and the bottom CPU is used to calculate the variation of Stewart platform DOF. Finally, the experimental results of the control strategy in the six wheeled-legged robot system are given, and the feasibility and effectiveness of the control strategy are verified.

Keywords: wheeled-legged robot, cooperative control, attitude stability control, CPU, controller design.

1. INTRODUCTION

In recent years, the research of wheel-legged robot seems to be an active research field [1]. Compared with the pure foot robot or the pure wheel robot, the wheel- legged robot not only has the fast locomotion of the former, but also has the possibility of the latter through the complex environment. Moreover, most wheel-legged robots, such as [2] - [8], basically adopt a series structure, which can't achieve large load. This paper presents a large load electric parallel six wheel-legged robot BIT-NAZA-II as shown in Fig. 1, and BIT-NAZA-II was designed on the basis of BIT-NAZA-I [13] in May 2019. Compared with BIT-NAZA-I, BIT-NAZA-II has the following advantages: first, foot gait has many types, fast movement speed and high stability. Second, the four wheel-legged support surface is too large, the stability is high, and the load capacity is stronger. Therefore, how to plan and cooperatively control attitude for BIT-NAZA-II , to achieve the dynamic traversing of complex terrain, which can be used in material transportation, resource exploration, emergency rescue and other fields in the future.

At present, the research of wheel-legged robot is still insufficient, which also causes a wide range of researchers to invest in it. The wheeled Quadrupedal Robots ANYmal shows high robust and dynamic locomotion while walking on flat and inclined terrains, which relies on a zero-moment point based motion optimization strategies [1], [9]. The four-wheel drive wheel-legged robot [10] drives and overcomes the obstacles through the kinematic method to realize the complex terrain crossing. Robot [11]-[12] shows static stability and slow walking speed when passing through raised stones and stairs. However, these researches are only focused on the motion control of the serial wheel leg robot, which has low load capacity.

In terms of parallel wheel-legged robots. Peng Hui [13], research of the first generation wheel-legged robot BIT-NAZA-I. This robot uses cooperative control framework to overcome obstacles like slope. However, the attitude adjustment algorithm in the cooperative control method is not suitable for BIT-NAZA-II. The wheeled-quadruped Robot BIT-NAZA-I shows stability motion while walking on stairs, which relies on COG trajectory planning [14].

The six wheel-legged robot has the characteristics of strong coupling and redundant DOF, and there is still an obvious gap in the research of attitude stability control. This paper shows overall design and cooperative control for large load electric parallel six wheel-legged robot which combine the flexibility of legs with the efficiency of driving. Our main contribution of this work are as follows:

1) Cooperative control strategy is proposed as shown in Fig. 2. Six legs can be regarded as six multi-agent. The cooperative control of the central CPU and the six bottom CPU is the basis of the stable motion of the robot.

2) An impedance controller based on the position inner loop is proposed to solve the problem of robot leg suspension.

3) The central height controller is proposed to ensure the robot leg has the maximum motion space. The ideal central height should be the average height of six legs.

Finally, ADRC is used for single leg position control [13]. Six leg coordinated control is the key to ensure the body posture stability.

2. SYSTEM DESCRIPTION

In this Section, the structure and stability control of the robot will be described. In Section II.A, the basic functions of each component for the robot are introduced. In Section II.B, the factors that affect the cooperative control of robot fuselage are introduced.

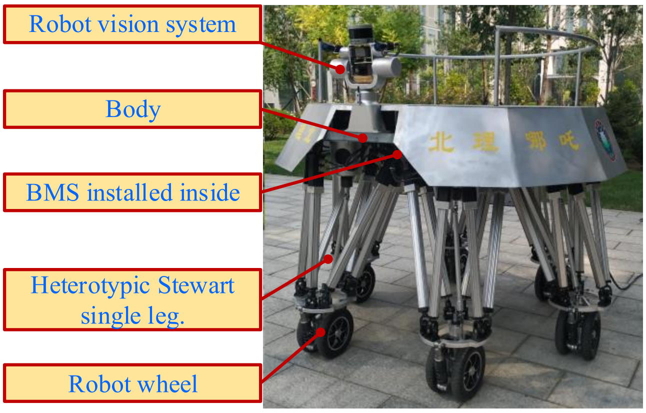

Fig. 1. Electric parallel six wheel-legged robot – BITNAZA3.

2.1 Basic structure of robot

The presented BIT-NAZA-II robot (As shown in Fig.1), which consists of the following five parts:

Robot vision system: It includes LIDAR used to measure the location and size of obstacles. Charge coupled device (CCD) camera used to acquire the image information of the external environment. Infrared light used to feel the reflection of the surrounding environment and realize the night vision function.

Body: The robot body is used to carry people, transport materials, or install some special equipment. The driver and other electrical equipment of multi-agent legs are mainly installed inside the body.

BMS installed inside: Battery management system (BMS) is the power source of robot, which is mainly powered by lithium battery. The system can effectively monitor the state of charge (SOC) of the battery pack and maintain the reliability and efficiency of the battery operation.

Six legs: Each leg of the robot is composed of an inverted abnormal shape Stewart platform, which is distributed around the body in a hexagon shape. Each leg can be regarded as a multi-agent. The abnormal shape Stewart platform is composed of six electric cylinders, which endows the robot with super load capacity and flexibility. In this paper, we only discuss the stability control of robot wheel motion. When the robot is in wheel motion, we only need to control the degree of freedom of Stewart platform in the vertical direction, that is $p_i (i=1,2,3,4,5,6)$.

Six wheel: The wheels are mounted at the end of the Stewart platform and have a diameter of 28 cm. Springs are installed on both sides of the wheel to achieve passive damping. The wheel power is driven by a wheel independent motor, and transmitted to the wheel through a transmission link.

2.2 Cooperative control problem

Each leg can be regarded as an agent when the BIT-NAZA-II robot moves in wheeled motion, and the cooperative control of six wheeled-legs is the key to ensure the stable attitude control of the robot. As shown in Fig. 2, it represents the topology of robot multi wheeled-legged cooperative control. The attitude sensor is installed in the middle part of the body, which can measure the roll angle α and pitch angle β of the body. Robot leg position and force information can be measured by sensors. Six single leg CPUs include impedance controller and force position controller. Central CPU includes attitude controller and central height controller. The single leg CPU communicates with the central CPU through UDP. When the robot is walking on the uneven road, how to improve the stable control of robot attitude needs to solve the following four problems:

1) Attitude adjustment: The initial target attitude angle of the robot is $\alpha=0,\beta=0$. When the body attitude angle of the robot is near zero, it can be regarded as the body level. The desired attitude angle and the actual measured attitude angle are input into the attitude controller to achieve closed-loop attitude control.

2) The six wheels must always be in contact with the ground. Because six legs are driven independently, and every wheel works in the torque mode. Once the robot wheel is in the suspension state, it is easy to cause the wheel to accelerate all the time, even overspeed and make the motor in the locked state. At this time, the dangling state of the leg can be solved by the impedance controller.

3) The central height of the robot is determined by the degree of freedom of Stewart platform in the vertical direction. When the robot is kept in the central height position, it can maximize the single leg space.

4) ADRC is used for single leg position control. Six leg coordinated control is the key to ensure the body posture stability.

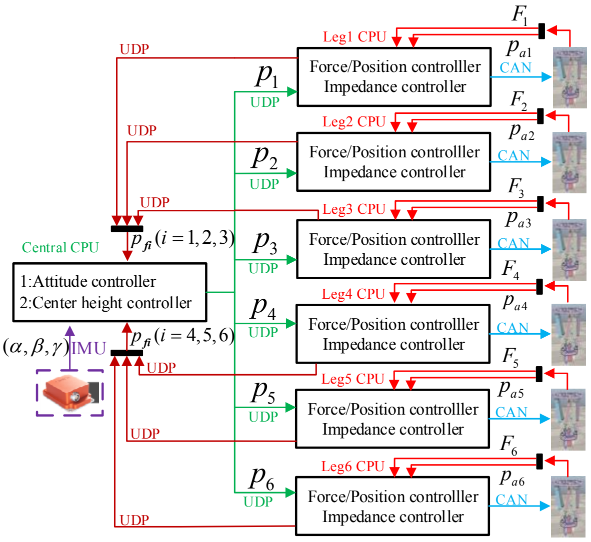

Fig. 2. Cooperative control block diagram of single leg based on Multi-Agent.

3. OVERALL CONTROL STRATEGY

The cooperative control problem of the BIT-NAZA-II robot has been discussed in Section 2.2. For the method of overall attitude stability control, this section introduces the multi controller fusion control strategy (Fig.3), which is suitable for wheel motion and wheeled-legged compound motion, so that the robot can pass through the complex terrain autonomously and maintain attitude stability. The control strategy consists of four controllers: attitude controller, impedance controller, robot central height controller, and multi-agent single leg position controller.

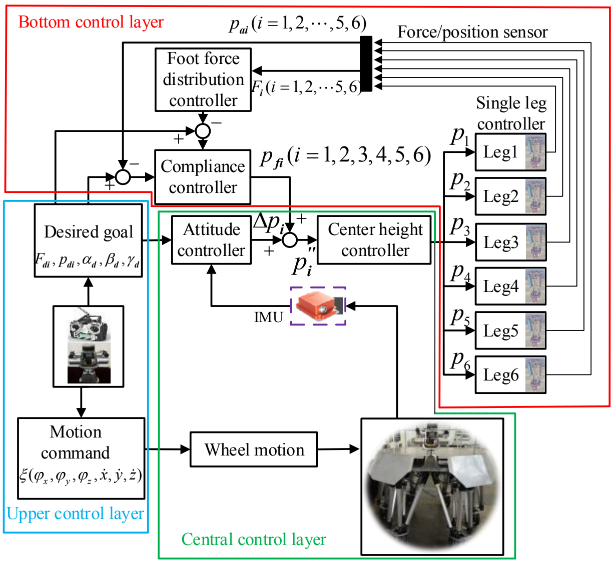

Fig. 3. Overall attitude stability control strategy.

3.1 Attitude controller

Fig. 4 shows the schematic diagram of wheel motion fuselage attitude adjustment when the BIT-NAZA-II robot passes over the obstacle. Fig. 4(a) is a 3D model diagram of the robot. The forward direction of the robot is the X-axis direction, the roll direction of the robot is the direction of rotation around the X-axis, and the pitch direction is the direction of rotation around the Y-axis. Although Liu et al. [15] uses coordinate transformation equation to adjust the attitude of the first generation BIT-NAZA-II robot, the effect is very general. This section presents more convenient and fast attitude adjustment method for the second generation BIT-NAZA-II robot.

Fig. 4(b) shows the situation when the $leg1,2$ for the robot passes through the obstacle at the same time, and the fuselage attitude changes ($\beta \neq 0$). Where, l represents the length of the robot, and k represents the width of the robot. In order to adjust the pitch angle β to 0, $leg1,2$ need to shorten Δp_β or $leg4,5$ need to extend Δp_β

$$\Delta p_\beta = l\sin(|\beta|) \tag{1}$$

In order to adjust the robot's attitude to horizontal stability, equation (1) can make $leg1,2$ shorten Δp_β or $leg4,5$ extend Δp_β. However, if $leg1,2$ is shortened by $\Delta p_{1,2} = \Delta p_\beta / 2$ and $leg4,5$ is extended by $\Delta p_{4,5} = \Delta p_\beta / 2$ as shown in Fig. 4(c), the fuselage posture can also be releveled and the adjustment time can be reduced by half. If $\alpha \neq 0$, the change height Δp_α required for roll angle level is

$$\Delta p_\alpha = k\sin(|\alpha|) \tag{2}$$

The whole attitude adjustment strategy of the robot is shown in **Algorithm 1**.

Algorithm 1 Input (α,β) and output $\Delta p_{i,i}$

```
Acquire IMU attitude angle $(\alpha,\beta)$;
Send $(\alpha,\beta)$ to formula (1) and (2);
If $\alpha > 0 \& \beta > 0$ then
    $\Delta p_1 = \Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_2 = -\Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_3 = -\Delta p_\alpha / 2$
    $\Delta p_4 = -\Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_5 = \Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_6 = \Delta p_\alpha / 2$
end
If $\alpha > 0 \& \beta < 0$ then
    $\Delta p_1 = \Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_2 = -\Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_3 = -\Delta p_\alpha / 2$
    $\Delta p_4 = -\Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_5 = \Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_6 = \Delta p_\alpha / 2$
end
If $\alpha < 0 \& \beta < 0$ then
    $\Delta p_1 = -\Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_2 = \Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_3 = \Delta p_\alpha / 2$
    $\Delta p_4 = \Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_5 = -\Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_6 = -\Delta p_\alpha / 2$
end
If $\alpha < 0 \& \beta > 0$ then
    $\Delta p_1 = -\Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_2 = -\Delta p_\alpha / 2 - \Delta p_\beta / 2,\ \Delta p_3 = \Delta p_\alpha / 2$
    $\Delta p_4 = \Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_5 = -\Delta p_\alpha / 2 + \Delta p_\beta / 2,\ \Delta p_6 = -\Delta p_\alpha / 2$
end
return $\Delta p_i (i=1,2,3,4,5,6)$
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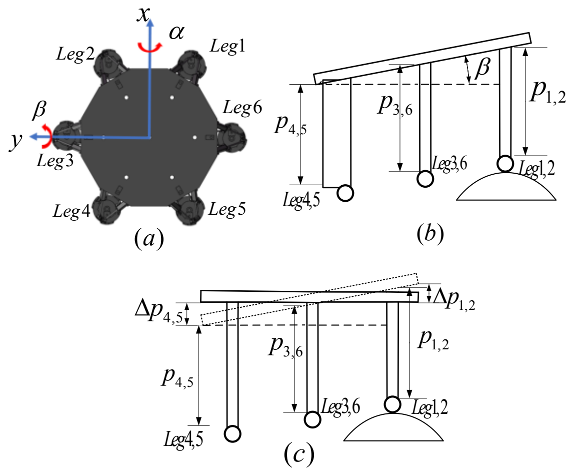

Fig. 4. Schematic diagram of attitude adjustment.

3.2 Impedance controller

When the robot adopts wheel motion, the wheels of six legs contact with the ground respectively. Six legs can be regarded as multi-agent cooperative motion to ensure the level of the fuselage. As shown in Fig. 5(a), Leg1 and Leg2 of the robot respectively run on the surface of raised obstacles, Leg3 and Leg6 are suspended, and Leg4 and Leg5 are in contact with the ground, but the robot can maintain stability. But the robot body inclines, and Leg3 and Leg6 are in suspension state, so they will idle because of torque control, even speeding and make the motor in the locked state. Therefore, in the torque control mode, in order to ensure the horizontal stability of the fuselage, the impedance control algorithm based on the position inner loop is adopted. The controller needs to solve two problems: First, to keep the legs in the air in contact with the ground all the time. Second, if the legs of the robot run to the raised obstacles, the height of the legs is shortened to ensure the level of the fuselage. Fig. 5(b) shows the control effect brought by the impedance controller. It is necessary to ensure the level of the fuselage and the contact between each leg and the ground.

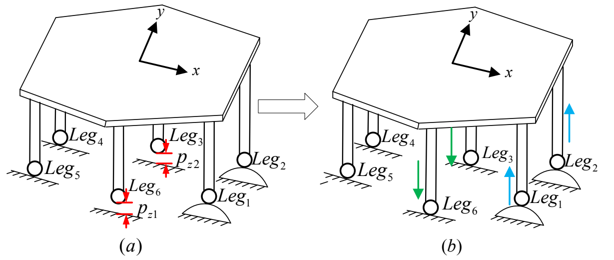

Fig. 5. Schematic diagram of impedance control when one or more legs of the robot are suspended.

After Hogan proposed the impedance control model, the traditional impedance model is as follows:

$$M(\ddot{X}_d-\ddot{X})+B(\dot{X}_d-\dot{X})+K(X_d-X)=F_e \qquad (3)$$

where, M is the target impedance inertia coefficient, B is the damping coefficient, K is the stiffness coefficient, F_e is the environmental contact force, X_d is the expected position, X is the actual position.

As shown in Fig. 3, the expected force F_d and the environmental force F_e are subtracted as the input of the impedance model. Formula (3) can be simplified as follows:

$$M(\ddot{X}_d-\ddot{X})+B(\dot{X}_d-\dot{X})+K(X_d-X)=F_\zeta \qquad (4)$$

where, $F_\zeta=F_d-F_e$ is the deviation of the force, $F_e=F_i(i=1,2,3,4,5,6)$ is the measured value of each leg force sensor. The transfer function of (4) is presented as:

$$\frac{F_\zeta(s)}{p_{fi}(s)}=Ms^2+Bs+K \qquad (5)$$

Therefore, $p_{fi}(s)$ can be obtained from formula(5) and expressed as follows:

$$p_{fi}(s)=\frac{1}{Ms^2+Bs+K}F_\zeta(s) \qquad (6)$$

In addition, the impedance controller based on the position inner ring is related to the control accuracy of the position inner ring, it is necessary to improve the position control accuracy of the electric cylinder, which can reference [13].

3.3 Central height controller

In order to make the six legs of the robot keep the largest motion space, the robot central height controller plays a decisive role. The principle is that the central height controller must always control the average height of six legs in the initial middle position. See Peng Hui et al. [13], as shown in Fig. 3, the input of the central height controller is

$$p_i''=\Delta p_i+p_{fi}(i=1,2,3,4,5,6) \qquad (7)$$

The average height of six legs in the initial middle position is

$$\bar{p}''=(p_1''+p_2''+p_3''+p_4''+p_5''+p_6'')/6 \qquad (8)$$

Therefore, the position input signal of the single leg controller is

$$p_i=p_i''-\bar{p}'' \qquad (9)$$

The input to output of the central controller is shown in algorithm 2.

Algorithm 2 Input $(\Delta p_i', p_{fi})$ and output p_i

```
Accept $\Delta p_i$ from **Algorithm 1** ;
Accept $p_{fi}$ from formula (6) ;
$p_i''$ is obtained by sending $\Delta p_i$ and $p_{fi}$ to formula (7) ;
$\bar{p}''$ is obtained from formula (9) ;
$p_i = p_i'' - \bar{p}''$ ;
return $p_i = p_i'' - \bar{p}''$
```

4. EXPERIMENTS

This experiment is mainly aimed at the attitude stability control of the robot body in different terrain, such as uneven road, soft terrain, pit terrain, slope terrain, etc. All the experiments are carried out indoors and outdoors to verify the effectiveness of the body attitude stability control strategy of the wheel motion of the BIT-NAZA-II. The experimental results can be reflected in the attachment video.

4.1 Stability control of wheel-legged robot in different terrain

Fig. 6 shows the multi-sensor information fusion based wheeled-legged overall attitude control strategy is used to solve the problem of attitude stability control for the six wheeled-legged robot BIT-NAZA-II in different terrain, such as uneven road surface, soft terrain, pit terrain, slope terrain, etc. The overall attitude control strategy includes: Attitude control **Algorithm 1**, impedance control algorithm by using equation (6), central height controller **Algorithm 2**. In addition, in order to verify the effectiveness of the overall attitude control strategy, the experimental results of attitude stabilization control for slope terrain are given in Section 4.2.

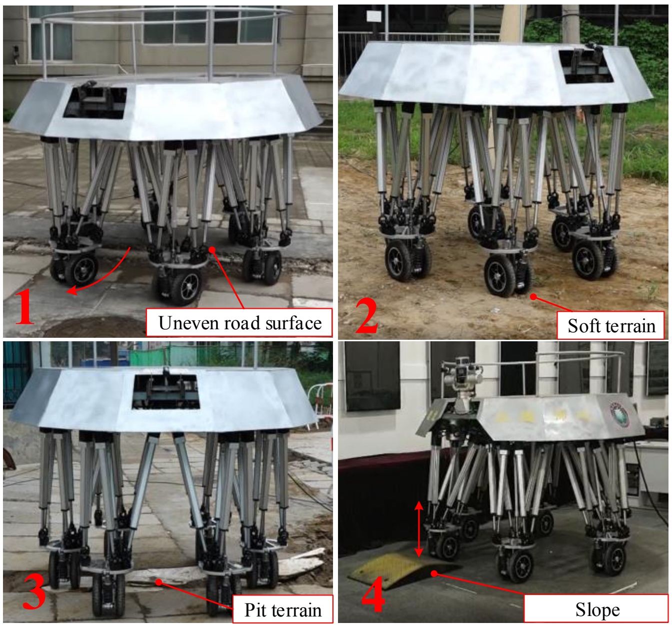

Fig. 6. Schematic diagram of attitude adjustment in different terrain.

4.2 Stability control experiment of slope terrain

As shown in Fig.7, it shows the overall attitude stability control experiment of the robot in the slope terrain. The whole experiment was completed in the indoor environment. Two slope obstacles were randomly placed on the ground, with the length, width and height of 85 cm × 50 cm × 10 cm, 83 cm × 47 cm × 8 cm, respectively. In addition, the inner wheel drive control loop is torque mode, and the outer wheel drive control loop is speed mode. Then the robot is given to move forward at a speed of 0.5 m/s.

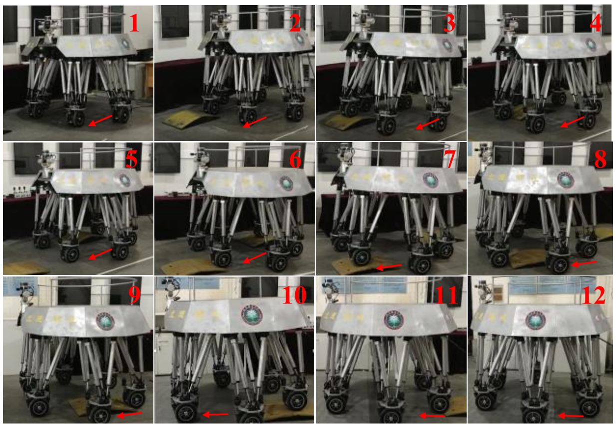

Fig. 7. Experimental scene on the slope terrain.

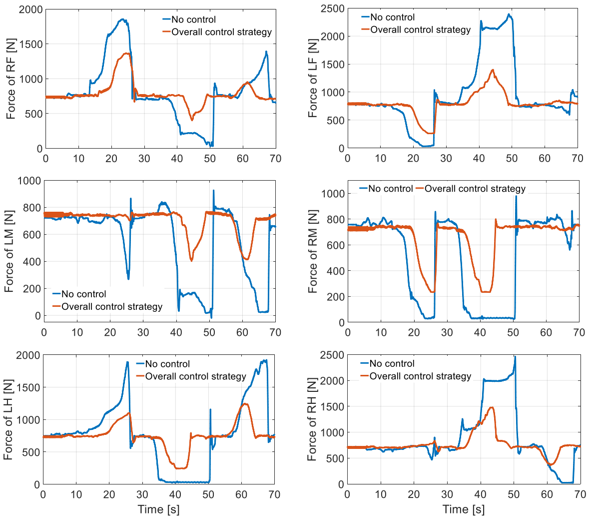

Fig. 8. Forces acting in vertical direction of each leg.

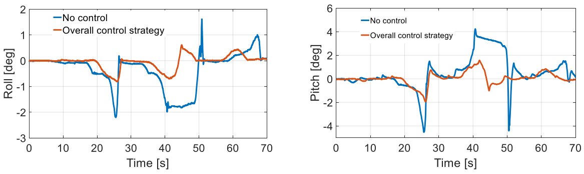

Fig. 9. Overall attitude angle of body.

The experimental results of vertical impact force between the six wheels and the ground and body postural angles on the slope terrain based on no control and overall control strategy are shown in Fig. 8 and Fig. 9. The blue line represents the curve without control, and the red line represents the curve with overall control strategy.

In the process of wheel driving, the attitude of the fuselage can be kept stable under the overall attitude control strategy, and there is no leg suspension state. From the blue curve in Fig. 8 and Fig. 9, it can be seen that at 18s, the RF leg of the robot begins to contact the slope, the posture of the robot body changes, and the foot end force of the RF leg increases. If there is no control, the force on the RF leg of the robot will increase to about 1800 N, and the attitude angle of the robot body will increase to $-2^{\circ} \sim 4^{\circ}$ in the process of $18s \sim 23s$, at this time, the fuselage begins to tilt, and the foot end force of the LF leg and the RM leg decreases to about 0 *N*, indicating that the phenomenon of leg suspension occurs due to the tilt of the fuselage. In the same way, this phenomenon also appears in other parts of the curve, which will not be explained here one by one.

However, after adding the overall attitude control strategy proposed in this paper, it can be seen from the red curve in Fig. 8 and Fig. 9 that at $18s \sim 23s$, the RF leg of the robot starts to contact the slope to the top, and the body attitude of the robot only changes slightly, basically maintaining within $-1^{\circ} \sim 1^{\circ}$, while the foot end force of the RF leg is 1400 *N*, reducing by 22 %. Because the impedance control can adjust the height of the leg through the change of the force, it can reduce the foot force and eliminate the suspension of the leg. Therefore, the experimental results show that the proposed control strategy can effectively achieve the attitude stability control of the fuselage.

5. CONCLUSIONS

In this work, a multi-sensor information fusion based wheeled-legged cooperative control strategy is proposed to solve the problem of attitude stability control for the six wheeled-legged robot. Multi-agent cooperative control can be used in complex robot system, which can be composed of multiple CPUs, actuators and network communication. The cooperative control includes attitude controller, central height controller, impedance controller and force position controller. The attitude controller can complete the closed-loop control of fuselage attitude. The central height controller keeps the foot within the range of the maximum active space. The impedance controller ensures that the foot is always in contact with the ground to prevent the leg from hanging in the air. At last, the experiment shows that the multi controller cooperative control can ensure the level stability of the fuselage and adapt to different terrain.

In the future, we will combine the collaborative control method with the environmental awareness system, and apply it to the experiment of BIT-NAZA-II robot foot stable walking. At present, this work has been carried out.

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