Load distribution and skid compensation control of omni-directional vehicle with independent driving modules

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Abstract

The demand for robots in various application fields has been increasing in recent years. Robots are becoming active in a greater variety of environments, so there is a growing need for higher robot mobility that ensures safe and smooth movement. That need has drawn attention to the omnidirectional vehicle (ODV). ODV's can move forward and backward and turn to the left and right, but they can also move directly sideways and diagonally, and rotate in a fixed position. This high mobility enables an ODV to change direction in a small space, to parallel park easily, and perform other adaptive movements that are suitable to the vehicle environment. Omni-directional mobility has previously required special mechanisms that have been associated with problems of durability and stability. To address those problems, we have developed a nonholonomic ODV that uses two-wheel modules equipped with ordinary tires. However, the stability and smooth motion of the vehicle is usually affected by the load from the road surface, so a control system that distributes that load appropriately over all the motors is needed. Another problem is that there may be a loss of total driving force and vehicle speed under conditions in which the tires spin freely without traction. To maintain total driving force, a torque compensation system for each of the wheels is important. Here, we propose a method for load distribution control and a method for skid compensation control and present test results that show the effectiveness of the proposed methods.

Key words : Omni-directional vehicle, Multiple mobile robots, Distributed coordination, Environmental load distribution, Skid detection

1. Introduction

The demand for robots in society has been increasing in recent years. Because of the diversification of the environments in which robots are being used according to the needs of people, there has been much research on high robot mobility that enables robots to move safely and smoothly, even in unknown environments. Omnidirectional vehicles (ODV) have been attracting attention for that purpose. An ODV can move in any direction and turn while maintaining the same attitude, so application in many fields is expected. For example, an electrical wheelchair that has omnidirectional mobility has been proposed by Kitagawa et al (2004), and Okumura et al (2007) have proposed a passenger vehicle that is capable of omnidirectional motion as a concept for the development of next-generation vehicles. Other examples include an autonomous mobile robot (Tang et al, 1999) and a planetary exploration robot (Otsuki et al., 2011).

Omnidirectional motion requires special mechanisms, and most previous research has resulted in proposals and development of special wheels and mechanisms that are suited to the use environment (Tadakuma, 2011). However, ODVs that use special wheels have posed problems of durability and drivability because of structural complexity. The active caster mechanism developed by Wada (2007) uses pneumatic tires, so drivability is better, but it is necessary to successively update the vehicle kinematics according to the operating situation. Also, different motors are needed for running and steering, so the efficiency of motor use is low.

Considering problems such as those described above, our research group has developed an ODV that uses modular

driving units. That ODV has a structure that offers higher drivability than previous special mechanisms and is not affected by road surface conditions. It also has higher efficiency of motor usage than the active castor mechanism that uses pneumatic tires. However, with conventional running control, the effects of the environmental load on the ODV and skid of the tires are not taken into account, so it may be difficult to achieve stable operation on uneven ground outdoors. Ishigami et al.,(2011) developed a vehicle assuming use on uneven outdoors terrain, but they used a mechanical approach to ensure stability by adding a suspension mechanism, etc. rather than taking a control approach. The generally-known control approaches to stability include use of a disturbance observer (DOB) or a reaction torque observer (RTOB). Usuki et al., (2014) have proposed a load distribution method that uses cooperative control and an RTOB for ODVs. That method, however, cannot distribute load over the entire vehicle according to the direction of motion and does not take ODV kinematics during turns into account. For tire slippage, traction control (Yoshimura et al, 2011) and other methods have been effective, but conventional traction control mostly controls tire slippage by actively decreasing torque, and so does not effectively solve the problem of reduction in overall vehicle driving force (Maeda et al., 2012).

To address the problems described above, we propose a method for distributing motor load under excessive load on the ODV without impeding driving control and a method for maintaining constant total driving force when wheel skid occurs.

In section 2, we present a control method for omnidirectional motion. In section 3, we describe the proposed methods, and in section 4 we describe tests in which actual machines were used. Section 5 concludes this paper.

2. Control for Omnidirectional Motion

2.1 Vehicle model

The proposed ODV has four wheel modules. A wheel module has two ordinary pneumatic tires that are driven independently. A translational motion is obtained by driving the two wheels (left and right) equally in the same direction and turning is obtained by driving the wheels at different speeds. The ODV has a total of eight wheel mechanisms for the four two-wheel modules, with redundant degrees of freedom in planar motion. Thus, movement in any direction on a plane can be achieved by cooperative control of the attitude angle and speed of each wheel module (Fig. 1).

Fig. 1. Movement models. (a) and (b) are translations, and (c) and (d) are turns.

2.2 Command values

Because ODV operation in planar motion requires input for three degrees of freedom, we assume a controller that has a three-axis joystick. For intuitive operation by the operator, we set the x-axis input as the speed in the x axis direction of the vehicle coordinate system, the y-axis input as the speed in the y-axis direction, and the z-axis input as the amount of vehicle turning. The ODV command values are speed v^{cmd} , translation direction ϕ^{cmd} , and turn radius r^{cmd} . The values are calculated using the following equations.

$$v^{cmd} = C_1 \sqrt{X_{in}^2 + Y_{in}^2} \quad (1)$$

In a relative coordinate system whose origin is the center of the vehicle, let x_n be the x direction distance and let y_n be the y direction distance from the vehicle center to the turning axis of a wheel module. Because the geometrical relationship of the inner and outer wheels changes in a turn to the left and a turn to the right, the sign in the equation changes according to the z-axis input. The speed of each wheel module is calculated with Eq. (9) according to the turn radius. The speeds of the left and right wheels, v_{nL}^{ref} and v_{nR}^{ref} , are calculated with Eq. (10), with L denoting half of distance between the wheels. For rotating in place, left and right wheel speeds are obtained by making the turn radius the distance D_n from the vehicle center to the turning axis of each wheel module.

$$v_n^{ref} = \frac{r_n}{r^{cmd}} v^{cmd} \quad (9)$$

$$\begin{bmatrix} v_{nR}^{ref} \\ v_{nL}^{ref} \end{bmatrix} = \begin{bmatrix} \frac{r_n + L}{r_n} \\ \frac{r_n - L}{r_n} \end{bmatrix} v_n^{ref} = \begin{bmatrix} \frac{r_n + L}{r^{cmd}} \\ \frac{r_n - L}{r^{cmd}} \end{bmatrix} v^{cmd} \quad (10)$$

3. Proposed Methods

3.1 Load distribution control

Cooperative control for each wheel module alone does not take the effect of load on the vehicle into account, so tracking performance on uneven terrain is poor. For that reason, we define the load deviation for each wheel module and propose a control that distributes excessive load on a wheel module evenly over all wheel modules.

3.1.1 Definition of load deviation

We define two indices of load deviation for each wheel module. First, we consider the ratio of the maximum continuous torque of the motor to the external torque estimated by the RTOB and define a value that indicates the balance of load on the wheel modules as Eq. (11). We will refer to the value defined by Eq. (11) as the LB_n value.

$$LB_n = \frac{|\hat{\tau}_{m,n}^{ext}|}{\tau_{m,n}^{max}} - \frac{\sum_{k=1}^N |\hat{\tau}_{m,k}^{ext}|}{n\tau_{m,n}^{max}} \quad (11)$$

The term $\tau_{m,n}^{max}$ is the maximum continuous torque of the motor and each module has the same value. $\hat{\tau}_{m,n}^{ext}$ is the external torque on the wheel module estimated by the RTOB, n is a number that identifies the wheel module, and N is total number of modules. Equation (11) is an extension of the method proposed by Tsuji et al.,(2004); its value is positive when the load is greater than the load on the other wheel modules and negative when the load is less than the load on other modules. The value of LB_n contributes greatly to the load distribution torque, which is described later in this paper.

The second index of load deviation is an evaluation function that expresses the overall load balance of the ODV as defined by Eq. (12).

$$ELB = \sum_{k=1}^N \left(\frac{|\hat{\tau}_{m,k}^{ext}|}{\tau_{m,k}^{max}} - \frac{\sum_{l=1}^N |\hat{\tau}_{m,l}^{ext}|}{n\tau_{m,k}^{max}} \right)^2 = \sum_{k=1}^N LB_k^2 \quad (12)$$

Equation (12) is an extension of the method proposed by Sasaki et al.,(1996) to this ODV. The value of ELB is zero

when the load is completely distributed evenly over all of the wheel modules. That is to say, the objective of the work reported here is keeping the value of ELB close to zero.

3.1.2 Load distribution torque

The input torque to a wheel module that is experiencing excessive load must be increased so as to offset the load. However, simply increasing the input torque will create a partial vehicle acceleration that can have a bad effect on the overall movement of the ODV. Accordingly, appropriate distribution of the environmental load requires that the torque be redistributed by decreasing the input torque to motors that have less load and increasing the torque to the motors that are under heavier load by that same amount. To satisfy those requirements, a torque that corresponds to the value of LB_n is applied at each wheel module to eliminate the load deviation. The load distribution torque τ_n^{dist} that is generated at each wheel module is defined by Eq. (13), in which C^{dist} is the gain. By adding the load distribution torque τ_n^{dist} to the input of each motor, the load deviation for the ODV as a whole can be eliminated and the ELB value can be lowered. A block diagram of this load distribution control is shown in Fig. 3.

$$\tau_n^{dist} = C^{dist} \left(\left| \hat{\tau}_{m,n}^{ext} \right| - \frac{\sum_{k=1}^N \left| \hat{\tau}_{m,k}^{ext} \right|}{N} \right) \quad (13)$$

Fig. 3. Block diagram of the load distribution control system; RTOB (ω) is a reactive torque observer that uses angular velocity and τ_n^{dist} is the load distribution torque that is calculated when an excessive load is applied to a wheel module.

3.2 Skid compensation control

This ODV is designed for eight driving wheels and has eight points of contact with the ground surface. During operation, however, if there is wheel skid, the total ODV driving force decreases and the operator unintentionally decreases the speed. We therefore propose here a method for detecting wheel skid and a method for maintaining total driving force when skid occurs.

3.2.1 Skid detection

Kadowaki et al., (2005) use the DOB to estimate a tangential force coefficient $\hat{\mu}$ and use that value to identify wheel skid. It is known that $\hat{\mu}$ decreases suddenly when a wheel skid during operation (Ohishi, 1999). For a more robust indicator, we add an RTOB to the DOB and propose a skid detection method that uses a disturbance torque $\hat{\tau}_{m,nk}^{dis}$ and an external torque $\hat{\tau}_{m,nk}^{ext}$ which are linear with respect to $\hat{\mu}$.

In the detection method that uses the DOB (Fig. 4), a skid region is set for the estimated disturbance torque $\hat{\tau}_{m,nk}^{dis}$ and skid is judged to be occurring when the value remains within that region for a certain time. The skid function

ε_{nk}^{DOB} defined by Eq. (14) takes the value of 1 when skid is judged to occur or the value of 0 when the wheel is in contact with the ground.

$$\varepsilon_{nk}^{DOB} = \begin{cases} 1 & (\tau_{Low}^{dis} \leq \hat{\tau}_{m,nk}^{dis} < \tau_{High}^{dis}) \\ 0 & otherwise \end{cases} \quad (14)$$

Next, we consider a method that introduces an RTOB (Fig. 5). The RTOB provides a purer estimate of the environmental reactive force by subtracting the viscous friction term from the external disturbance estimated by the DOB. A region for detecting the skid state is also set for the external torque $\hat{\tau}_{m,nk}^{ext}$ estimated by the RTOB. The skid function used by the RTOB ε_{nk}^{RTOB} is defined by Eq. (15), and the final skid function ε_n is defined by Eq. (16).

$$\varepsilon_{nk}^{RTOB} = \begin{cases} 1 & (\tau_{Low}^{ext} \leq \hat{\tau}_{m,nk}^{ext} < \tau_{High}^{ext}) \\ 0 & otherwise \end{cases} \quad (15)$$

$$\varepsilon_n = \begin{cases} 1 & (\varepsilon_{nk}^{DOB} = \varepsilon_{nk}^{RTOB} = 0) \\ 0 & otherwise \end{cases} \quad (16)$$

We know from experiments that the skid functions in the above equations transition more easily to 0 than to 1. Therefore, when the skid functions of Eq. (14) and Eq. (15) have different values, we can expect a reduction in detection error by using the function whose value is 1.

Fig. 4. Skid detection using DOB

Fig. 5. Skid detection using RTOB

3.2.2 Calculation of compensation torque and speed for wheel skid

Maintaining a constant total ODV driving torque requires compensation of insufficient driving torque to wheel modules that are touching the ground when skid of any of the wheels is detected. We therefore define the compensation torque for wheels that are in contact with the ground $\tau_{m,n}^{com}$ with the following equation. We will refer to this value as the skid compensation torque.

$$\tau_{m,n}^* = \varepsilon_n (\tau_{m,nL}^{res} + \tau_{m,nR}^{res}) \quad (17)$$

$$\tau_{m,n}^{com} = \frac{\sum_{k=1}^N \tau_{m,k}^*}{N_p} \quad (18)$$

In the above equations, when an n-th module skids, ε_n becomes 1, and therefore $\tau_{m,n}^*$ becomes the driving torque to decrease. And N_p is the number of wheel modules that are touching the ground. However, this ODV has a speed control, so a fast torque response cannot be achieved if we simply add the skid compensation torque $\tau_{m,n}^{com}$ to the

$$\tau^{total} = \sum_{k=1}^n (1 - \varepsilon_k) (\tau_{kL}^{res} + \tau_{kR}^{res}) \quad (21)$$

Fig. 7. Block diagram for one-wheel attitude angle control

4. Experiments

4.1 ODV structure

The ODV developed by our research group comprises a control device and four wheel modules. The control device has a three-axis joystick, a CPU board (SH7216, 200 MHz), and an OLED that displays the data that is processed internally. Each wheel module is also equipped with a same CPU board, and so is itself a robot that can move autonomously. The attitude angle and speed of each wheel module are controlled appropriately by command values issued by the control device. The box unit of the wheel module contains a battery and motor. The CPU board, power supply board and motor driver are mounted on the front and back walls of the unit. The wheel modules are connected to the chassis with free joints, so each wheel module can rotate around a vertical axis without constraint. An optical rotary encoder used to measure the attitude angle is attached here. The appearance of the ODV is shown in Fig. 8 and the specifications are listed in Table 1.

Fig. 8. Appearance of the proposed ODV

Table 1. Specifications of the proposed ODV

Overall length	610 mm
Overall width	640 mm
Overall height	325 mm
Wheelbase	500 mm
Tread	500 mm
Diameter of tire	220 mm
Width of rim	60 mm
Gross weight	44.5 kg
Weight of wheel module	9.8kg

4.2 Experimental results of Omnidirectional motion tests

We performed running experiments to test the omnidirectional movement performance of the developed ODV. The

Fig. 9. Results of running tests using actual device

trajectories of the wheel modules for translation motion, turning, and rotation in place are shown in Fig. 9. The sampling time used in these tests was 10 ms. These results confirm the omnidirectional motion performance of the developed ODV.

4.3 Load distribution tests

To test the effectiveness of the load distribution control, we performed step-passing tests and slope-climbing tests. The test conditions were to send speed command values of 0.1 m/s to the ODV from 5 s to 25 s with a sampling time of 10 ms. The values of these limits in eq.(14) and eq.(15) are selected by experiments beforehand.

4.3.1 Step-passing tests

To test the effect of an instantaneous excessive load on the ODV, we performed three step-passing tests (Fig. 10). The initial arrangement of the ODV and the step was such that at 10 s after the ODV began to move forward, the front wheels began to climb the step and at 15 s the rear wheels began the climb. At 17 s, the front wheels began to descend the step, followed by the rear wheels at 22 s. The change in *ELB* value for when the ODV passes over the 17.5-mm step is shown in Fig. 11. With the previous method, the *ELB* value rises sharply when the wheels ascend and descend the step; with the proposed method, the sharp rises in *ELB* value are suppressed and the overall *ELB* values are also lower. This result confirms the overall load distribution effect of the proposed method.

Fig. 10. Step-passing tests

Fig. 11. Results of step-climbing test A; the lower maximum *ELB* of the proposed method indicates an improvement over the previous method.

The maximum *ELB* values for each test are compared in Fig. 12. The step heights were 17.5 mm in Experiment A, 35.0 mm in Experiment B, and 52.5 mm in Experiment C. The ratios of the results for the proposed method to the results for the previous method are 29.1% for Experiment A, 14.5% for Experiment B, and 5.20% for Experiment C, showing that the maximum *ELB* was lower for the proposed method in all tests. These results confirm the effectiveness of the load distribution control when an instantaneous excessive load is applied.

Fig. 12. Results for all step-passing tests, showing the maximum *ELB* values for the previous and proposed methods

4.3.2 Slope climbing tests

We performed slope climbing tests with a 5-degree inclined plane to verify ODV operation under a continuous load (Fig. 13). The change in *ELB* values for operation on an outdoors slope is shown in Fig. 14. In the same way as for the step-passing test, the proposed method resulted is lower *ELB*.

Fig. 13. Slope climbing tests

Fig. 14. Results for slope-climbing test D; the lower maximum *ELB* of the proposed method indicate an improvement over the previous method.

Next, we consider the average *ELB* values for each of the tests (Fig. 15). Experiment D and E are respectively for outdoor and indoor slopes. Experiment F is for motion at a 45° angle relative to an indoor slope. The ratios of the results for the proposed method to the results for the previous method are 18.0% for Experiment D, 38.0% for Experiment E, and 34.1% for Experiment F. The average *ELB* was lower for the proposed method in all tests. These results confirm the effectiveness of the load distribution control under continuous load.

Fig. 15. Results for all slope climbing tests; average *ELB* values are shown for the previous and proposed methods.

4.4 Skid compensation tests

To test the effectiveness of the skid compensation control, we performed experiments in which there was wheel skid during operation of the ODV. We placed mats that have short bristles on the floor to induce wheel skid and performed four types of tests that involved translation motion and turning. The sampling time was 10 ms and speed commands were sent to the ODV at intervals of from 2 s to 8 s.

The situation of the skid compensation test for translation motion is shown in Fig. 16. The total driving torque for the case of one wheel skid in translational motion is shown in Fig. 17. In this test, the total driving torque for operation under the same conditions with all of the tires touching the ground was taken to be the theoretical value. With the previous method, the total driving torque was below the theoretical value while skid of wheel module 1 was detected, but the value remained about the same as the theoretical value when the proposed method was applied.

Fig. 16. Free-spinning compensation experiments

Fig. 17. Results for wheel skid Experiment G; (a) shows the total drive torque without the proposed method (yellow), the theoretical torque (green), and the skid function (blue). (b) additionally shows the total driving torque for the proposed method (red). The total driving torque decreases when skid occurs with the previous method, but remains about the same with the proposed method.

Next, we consider the reduction rates for the total driving torque in each test (Fig. 18). Test G is for one wheel skid during translational motion, test H is for two wheels skid during translational motion, test I is for one wheel skid during turning motion, and test J is for two wheels skid during turning motion. The torque reduction values for the previous control are 20.3% for test G, 42.6% for test H, 40.1% for test I, and 49.9% for test J. For the proposed method, on the other hand, the values were 0.998% for test G, 17.4%, 4.12% for test I, and 25.7% for test J. We can see that the proposed method resulted in lower torque reduction rates during wheel skid in all of the tests.

Fig. 18 Comparison of torque decreasing rate by previous control and by skid compensation control

5. Conclusion

We have proposed control methods for free and efficient omnidirectional motion, focusing on an ODV that has independently driven wheel modules. The control system is a distributed system that consists of a control device that serves as the master controller and wheel modules that serve as subordinate controllers. The master controller calculates command values for the ODV as a whole and sends them to the subordinate controllers. When the command values are received, the subordinate controllers control the wheel module speed and attitude angle accordingly. The subordinate controllers implement special controls such as for sharp turn control, permitted movement region, and cooperative changing of attitude to achieve smooth and stable ODV movement.

In this paper, we have proposed two control systems for improving the stability of operation on uneven ground

without improving the ODV mechanism itself. One is a method for evenly distributing load over all of the ODV wheel modules when environmental loading occurs during operation. The other is a method for maintaining the total driving torque of the ODV when wheel skid occurs.

The effectiveness of the methods we have proposed here was verified by developed ODV. Load distribution tests that included step-passing tests and slope climbing tests with large instantaneous loads and continuous loads verified that the proposed methods are effective under all test conditions. The skid compensation tests for single-wheel skid and two-wheel skid all confirmed that the proposed method resulted in less torque reduction for both translational movement and turning than did the previous method.

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