Control of an Omni-directional Power-assisted Cart*

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This paper describes an easy-to-operate, omni-directional cart. This cart includes power assist technology that acts for both the longitudinal and rotational motions of the cart. Two objectives are set for this development. The first objective is to overcome the difficulty of shifting the cart laterally. Therefore, the equation for calculating the cart turning speed is modified so that the moment, which is driven by the operating force in the right/left direction, is offset. As a result, it becomes possible to stabilize the balance between the operating force in the right/left direction and the operating moment, and improve the operating performance. The second objective is to overcome the other difficulty whereby, during the one-hand pull-operation, the cart tended to run off course to the right/left. To solve this problem, we add a positional control in the right/left direction. As a result, we reduce the lateral deviation of the cart, and improve the operating performance.

Key Words: Motion Control, Mechatronics and Robotics, Power Assist System, Omni-directional Vehicle, Universal Wheel, Speed Control, Positional Control, Meal Delivery Cart in Hospital

1. Introduction

Hospitals use meal-carrying carts (meal delivery carts) with heat-retaining and cool storage capacity. The meal delivery carts weigh up to 700 [kg] and are mainly electric-powered. For example, power-assist driven meal delivery carts have been developed to run according to the operating force of the operator.

However, the meal delivery carts mentioned above are equipped with 2-drive wheels, which drive independently, and have difficulties in pulling over to the kerb in a corridor and in an elevator, as well as parking parallel in the kitchen.

Thus, the authors develop a power assisted cart that can travel in the longitudinal direction and turn,

and moreover, travel laterally and obliquely.

So far, many proposals have been made on holonomic omni-directional vehicles (ODV: Omni-directional vehicle)^{(1)–(5)}.

The holonomic ODV⁽⁵⁾ using ordinary wheels is effective for heavy vehicles because the wheel structure can be produced to have small-scale vibration when traveling and high endurance. However, this structure requires space for drive wheel turning under the vehicle body, and therefore, it is not suitable for meal delivery carts which have heat retaining and cooling equipment under the vehicle body. In this application, the most suitable is a holonomic ODV⁽⁴⁾ employing a universal wheel that requires no large arrangement space without turning the drive wheel.

The authors develop two control methods to enhance operability and safety in the development of an omni-directional power assisted cart employing universal wheels.

The first method is a control method to slide-travel smoothly in the lateral direction.

With a long cart, when slide-traveling in the

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lateral direction, it is difficult to balance the traveling operation in the lateral direction and the cart turning operation, and therefore, to travel smoothly. Thus, by making a correction to the equation for cart rotating speed to decrease the moment generated by the right/left directions' operating force, the right/left directions' operating force and operating moment are balanced, and operability in the lateral direction is considerably enhanced.

The second method is a control method to prevent shifting of the cart to the right/left.

In such a case, as the operator pull-operations by one hand, it is difficult for the operator to apply moment on the operating handle. Particularly in cornering, the cart easily shifts to the right/left directions. Thus, the right/left directions traveling amount is detected from the rotating ratio of the respective drive wheels, and position control is applied to eliminate the motion to both sides. This facilitates the cornering operation without shifting in the right/left directions.

This paper describes the control method to enhance operability and safety of an omni-directional power assisted cart employing universal wheels.

2. Overview of the Omni-directional Power Assisted Cart

2.1 System configuration

A schematic view of the omni-directional steering power assisted cart is given in Fig. 1. The control system comprises, as shown in Fig. 2, a force detecting unit, a CPU and a driving unit. First, the force-detecting unit detects the operating force. Based on the detected values, the CPU calculates the traveling speed in the longitudinal and right/left directions and the turning speed of the cart, and furthermore, it

Fig. 1 Overview

calculates the rotation speed of each driving wheel to achieve the traveling speed. Based on the calculated values, each driving wheel generates driving power, respectively.

The force-detecting unit measures the displacement of multiple flat springs with three eddy current gap sensors. The conceptual diagram is shown in Fig. 3 (a).

The operation part (handle) is connected to the body of the cart on both the left and right sides through the handle base and flat springs. The handle base is restrained by the flat springs so that it allows both sides of the handle to travel independently in a forward and lateral direction relatively to the body of the meal delivery cart. Two gap sensors detect the forward displacement d_r and d_l of the right and left flat spring, respectively. Another gap sensor detects the relative lateral displacement d_c between the handle base and the body of the cart. Controls f_{hx} (forward and backward), f_{hy} (left and right) and $f_{h\psi}$ (moment) applied to the operation part are obtained by the following expressions using the output value of each gap sensor.

$$\left. \begin{aligned} f_{hx} &= k_1 \times (d_r + d_l) \\ f_{hy} &= k_2 \times d_c \\ f_{h\psi} &= k_3 \times (d_r - d_l) + k_4 \times d_c \end{aligned} \right\} \quad (1)$$

where, k_1 , k_2 , k_3 and k_4 : Empiric constant. For the above, see Figs. 3 (b) to (d).

In this way, vector $([f_{hx}, f_{hy}, f_{h\psi}])$ is obtained from the values of the gap sensors mounted on the handle as shown in Figs. 3 (a) through (d). The relation between the displacements d_r , d_l and d_c and the force vector $([f_{hx}, f_{hy}, f_{h\psi}])$ is shown in Figs. 4 (a)

Fig. 2 Control system

(a) Handle schematic diagram

(b) When f_{hx} (positive) is applied (c) When f_{hy} (positive) is applied (d) When $f_{h\psi}$ (positive) is applied

Fig. 3 Force detecting unit

through (c). The d_c relative displacement is omitted because it is almost zero in (a) and (c). The three axis force sensor is very accurate and highly linear.

2.2 Power assist control

Figure 5 illustrates a schematic view of the power assist system.

The final goal to be achieved by the system is to obtain smooth control of the traveling speed ($[V_{ax}, V_{ay}, V_{a\psi}]$ measured with respect to the control center) of the cart according to the operating force ($[f_{hx}, f_{hy}, f_{h\psi}]$). First, the force acting on the control center ($[f_{hx}, f_{hy}, f_{h\psi} + L_h \cdot f_{hy}]$) is calculated based on the operating force ($[f_{hx}, f_{hy}, f_{h\psi}]$). The product of the force acting on the control center and "assist gain" (K_x, K_y, K_ψ) is the traveling speed of the cart ($[V_{ax}, V_{ay}, V_{a\psi}]$). The respective values are obtained from the following equation.

(a) When f_{hx} (positive) is applied (b) When f_{hy} (positive) is applied (c) When $f_{h\psi}$ (positive) is applied

Fig. 4 Relationship between control and the relative displacement

$$\left. \begin{aligned} V_{ax} &= K_x \cdot f_{hx} \\ V_{ay} &= K_y \cdot f_{hy} \\ V_{a\psi} &= K_\psi \cdot (f_{h\psi} + L_h \cdot f_{hy}) \end{aligned} \right\} \quad (2)$$

where, the subscript x denotes the longitudinal direction, y denotes the lateral direction, and ψ denotes the counterclockwise rotation. Furthermore, L_h denotes the distance between the handle and the control center.

This speed reaches the target value by PID con-

Fig. 5 Power assist system

trol. Accordingly, in Eq.(2), when the force is zero, the target speed becomes zero. By this control, if the operator releases his grip from the handle, the cart brakes and can be stopped safely.

Next, the peripheral velocity of each driving wheel is calculated based on the cart speed given by Eq.(2). Universal wheels are located at the four corners of the cart and each of them is provided with a drive motor.

The peripheral velocity $([v_1, v_2, v_3, v_4])$ is calculated based on the cart speed $([V_{ax}, V_{ay}, V_{a\psi}])$ using the following equations.

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} -\sin \theta & \cos \theta & (L_1 \cdot \cos \theta + L_v \cdot \sin \theta) \\ -\sin \theta & -\cos \theta & (L_2 \cdot \cos \theta + L_v \cdot \sin \theta) \\ \sin \theta & -\cos \theta & (L_2 \cdot \cos \theta + L_v \cdot \sin \theta) \\ \sin \theta & \cos \theta & (L_1 \cdot \cos \theta + L_v \cdot \sin \theta) \end{bmatrix} \times \begin{bmatrix} V_{ax} \\ V_{ay} \\ V_{a\psi} \end{bmatrix} \quad (3)$$

Using Eqs.(2) and (3), the omni-directional power assist control, which provides smooth operation in every direction according to the operating force given to the cart by the operator, is obtained.

2.3 Steering control

Since the cart has a height almost the same as the operator, if it is designed to operate in a manner of push-operation, the view of the operator is obstructed. Accordingly, it is basically designed to operate in the manner of pull-operation by one-hand. When the cart is operated in the manner of pull-operation in the omni-directional mode, there is the danger of the cart running off its course laterally during cornering resulting in a collision with the wall as shown in Fig. 6. Accordingly, a control, by which the cart detects the one-handed pull-operation mode and selects the traveling mode, is adopted. That is to say:

- During pull-operation: Two-dimensional steering mode (longitudinal traveling and turning)

By fixing the value of the lateral shifting speed at

Fig. 6 Pull-operation in omni-direction mode during cornering

Fig. 7 Handle-grasping modes and control axes

zero, the lateral shift amount is restricted. As a result, it is virtually realized that the rear wheels act as if fixed steering wheels; the front wheels act as if universal casters, respectively.

- Other cases (pulling the cart over to the side of the corridor): Three-dimensional steering mode (longitudinal traveling, right/left shifting, turning)

As a means of detecting operation mode, three photoelectric sensors are provided on the handle as shown in Fig. 7. When the photoelectric sensor at the center is grasped, the two-dimensional steering mode is selected; when the photoelectric sensors at both sides are grasped simultaneously, the three-dimensional steering mode is selected. Owing to this, during one-handed pull-operation, unintended changes of posture of the cart can be reduced. Also, when shifting the position of the cart in the omni-directional mode, since the operator naturally grasps the handle with both hands, it is not necessary for the operator to change the operation mode.

3. Objective 1: Problem When Shifting in the Lateral Direction

3.1 Problem

An omni-directional power assist of the cart has been achieved by the above-mentioned control. However, the operator may still experience difficulty in shifting the cart in the lateral direction when it has a relatively long body.

Assuming that the operator holds the handle with his hands spacing a distance, he operates the cart giving it a couple-of-forces (see Fig. 8).

The operating forces acting on the handle, f_{hx} and

Fig. 8 Operating force in shifting the position of the cart in lateral direction

f_{hx} , are given as follows :

$$\left. \begin{aligned} f_{hx} &= f_{lx} + f_{rx} \\ f_{h\psi} &= f_{lx} \cdot \frac{L_s}{2} - f_{rx} \cdot \frac{L_s}{2} \end{aligned} \right\} \quad (4)$$

To shift the cart in the lateral direction, it is necessary that $V_{ax}=0$ and $V_{a\psi}=0$. Therefore, from Eq.(2) :

$$\left. \begin{aligned} f_{hx} &= f_{lx} + f_{rx} = 0 \\ f_{h\psi} + L_h \cdot f_{hy} &= f_{lx} \cdot \frac{L_s}{2} - f_{rx} \cdot \frac{L_s}{2} + L_h \cdot f_{hy} = 0 \end{aligned} \right\} \quad (5)$$

Combining the above two equations,

$$f_{rx} = -f_{lx} = \frac{L_h}{L_s} \cdot f_{hy} \quad (6)$$

That is to say, to shift the cart in the lateral direction, a longitudinal operating force L_h/L_s times as large as the lateral operating force is required. This means that the operator may still experience difficulty in operating a cart which has a relatively long body.

3.2 Corrective measures

To solve the above-mentioned problem, another assist gain $K_{y\psi}$ is added to the equation for calculating $V_{a\psi}$.

$$\left. \begin{aligned} V_{ax} &= K_x \cdot f_{hx} \\ V_{ay} &= K_y \cdot f_{hy} \\ V_{a\psi} &= K_\psi \cdot f_{h\psi} + K_{y\psi} \cdot L_h \cdot f_{hy} \end{aligned} \right\} \quad (7)$$

The value of assist gain $K_{y\psi}$ may be determined considering various factors including the cart dimensions (L_h/L_s , etc.) and its center of rotation etc., so that a variation in operating feeling can be obtained.

3.3 Experimental results and discussion

Using a cart about 2.3 m long, 0.8 m wide and 600 kg in weight, a shifting operation test in the lateral direction was conducted. This experiment used two different equations for calculating the rotation speed $V_{a\psi}$. That is, one is Eq.(2) ; the other is Eq.(7) with $K_{y\psi}=2.5 K_\psi$.

Figures 9 and 10 show a comparison of the operating force between the two cases. To compare these

Fig. 9 Experimental results of control using Eq.(2)

Fig. 10 Experimental results of control using Eq.(7)

two figures, a couple-of-forces is used in place of the moment $f_{h\psi}$.

In Fig. 9 which shows the result before improvement, the force of couple is nearly 2.5 times that of the lateral operating force f_{hy} . The f_{hy} tends to fluctuate due to this unbalance, and f_{hx} , which is the longitudinal operating force, shifts largely under this influence. The reason is that the operability is bad and the cart is unnecessarily travelled in the lateral direction.

On the contrary, in Fig. 10 which shows the result after improvement, the magnitude of the lateral operating force f_{hy} becomes nearly the same as that of the force of couple f_{rx} as set. Furthermore, smooth start-up and ending of the operating force are observed. Vibration and fluctuation of f_{hx} and f_{hy} are considerably reduced.

In this way, as a result of the assumption that if lateral direction operating force nearly equals the force of couple within a range of force easily generated by a person, lateral motion can be easily made, it is confirmed that lateral motion can be made without any unnecessary force and that operability is considerably improved.

The above assumption is made in this study, however, there's still room for study on balance between the lateral direction operating force and the force of couple.

4. Objective 2: Problem in One-handed Operation

4.1 Problem

The second problem is that in the situation where it is difficult for the operator to give moment to the handle during one-handed pull-operation, especially during cornering, the cart tends to run off its course right/left (refer to Fig. 6). Accordingly, to realize the operating feeling of the conventional cart, a control technique is required that prevents the cart from running off its course in the right/left direction during one-handed pull-operation where the target speed $V_{a\phi}$ in the right/left direction is fixed at zero. The control block diagram is shown in Fig. 11.

However, with this control technique, the deviation of the right/left travel amount is accumulated, and the right/left positional displacement is not completely cleared.

4.2 Corrective measures

To solve the problem described above, the following corrective measures are added.

1) Based on the values from the encoder equipped on the motor, the right/left displacement speed V_y , right/left displacement amount L_y and accumulated value $S_y(\Sigma L_y)$ of the right/left displacement amount are calculated with respect to the control center of the cart.

2) Calculate the value w_y which results in:

$$w_y = D \cdot V_y + P \cdot L_y + I \cdot S_y \quad (8)$$

(P, I, D are control constants)

Fig. 11 Control block diagram (speed control only)

Fig. 12 Control block diagram (addition of right/left positional control)

as the correction speed of the right/left displacement based on the control speed ($V_{ax}, 0, V_{a\phi}$) at the cart control center obtained from the handle operating force.

The speed control block diagram, to which the above corrective measures are added, is shown in Fig. 12.

4.3 Experimental results and discussion

Using the same cart as that described in section 3.3, a verification test concerning the corrective measures described above was conducted; speed control only was compared with speed control added with right/left positional control. The cart was operated at the same speed (≈ 0.8 m/s) along a corridor. Speed at the control center of the cart and the right/left displacement amount when the cart made a turn (90-degree turn) was measured, respectively. Speed and the right/left displacement amount were calculated based on the value of the speed detected by each motor encoder in the manner of inverse kinematics calculation.

Figure 13 shows the experimental result of cart speed control only; Fig. 14 shows the experimental result of speed control added with right/left positional control.

In Fig. 13, during turning, the speed component in the lateral direction is always nearly negative ($-0.1 - 0$ [m/s]). This is because centrifugal force generates deviation on speed control in the lateral direction.

(a) Variation in operating force

(b) Motion of cart

Fig. 13 Experimental results (speed control only)

(a) Variation in operating force

(b) Motion of cart

Fig. 14 Experimental results (addition of right/left positional control)

Accordingly, the traveling amount in the lateral direction to be integrated simply increases, and an error of 0.1 [m] is generated after turning at the corner of 90 [deg]. The larger the cornering speed, the larger the centrifugal force and the error becomes. In Fig. 14, the speed component in the lateral direction converges in the proximity of 0 [m/s]. Even when these were integrated and were to be the traveling amount, these integrated values were nearly in a range of error (0.02 [m]).

This system speed-feedback controls each wheel. When the wheels are controlled according to the commanded values, the vehicle speed V_{ay} in the lateral direction unlimitedly closes to zero; at the same time, the positional deviation is accumulated. This time, limitation to control under consideration of only the speed is considered in order to eliminate the positional deviation. Thus, an assumption was made that the positional deviation can be decreased by feedbacking on the speed command value according to the deviated amount. As shown in the above result, the deviated amount was successfully decreased by employing this proposed control.

The proposed two-dimensional drive control is a very effective method because the cornering characteristic of the omni-directional vehicle is considerably

enhanced.

5. Conclusion

By combining the power assist control technique and the omni-directional steering technique, a new control method was developed which is capable of detecting the operating force in three directions, i.e., longitudinal, right/left and turning, and performing omni-directional assist on the operating force.

This paper described the problems caused by the addition of the lateral movement function and their corrective measures.

The operating performance has been largely improved by inventing a control technique. That is, regarding the problem that shifting in the lateral direction is difficult, a correction is made to the equation of the turning speed of the cart so that the moment generated by the right/left direction operating force is reduced.

As for the problem that the cart tends to run off its course right/left when operating it in the one-handed pull-operation mode, the right/left positional displacement has been reduced successfully by inventing a control technique in which, by utilizing the rotation speed of the driving wheel, the right/left travel amount is detected by dead reckoning, and positional control is added to eliminate the run-off of the cart.

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