

Development of Control Technology for Hospital Bed Transportation Assist Device

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In order to decrease the physical strain placed on medical workers in hospitals, we have developed a new mechanism that can assist in the difficult and unstable process of bed transportation. This development focused on mecanum wheels which can move in any direction and devised a method to control these wheels. Typical systems use four mecanum wheels, but this novel structure only requires two mecanum wheels. In addition, this assist system can detect the direction of movement and the force of a push on the bed by the transporter without using force sensors. This report introduces the new hospital bed transportation assist device and the control technology that supports the transportation using the compliance control method.

Key Words: hospital bed transportation, assist, mecanum wheels, compliance control

1. Introduction

In Japan, the elderly population has been growing in recent years, and demand for medical care is increasing. However, as a result of the shrinking of the working population caused by the declining birthrate, a labor shortage among medical workers has become a problem. There is therefore a need to reduce work involving large physical workloads in hospitals.

In hospitals, a bed is generally transported by multiple medical staff. This is for the following three reasons.

- (1) Observe the conditions of the patient during transport.
- (2) The hospital bed is heavy because medical equipment is loaded onto it in addition to the patient.
- (3) Because all four wheels of the hospital bed use swivel casters, it is easy to move it in any direction, however, the stability when going straight is low.

Focusing on the workload of (2) and (3), we studied the specifications of a transportation assist device. As prior technologies, assist devices have been developed for the movement of power-assisted wheelchairs¹⁾⁻³⁾. For hospital beds as well, devices which assist with transport by handle pushing and pulling operation have been developed⁴⁾. However, the aforementioned technologies only assist with forward/backward movement operations, and for left/right movement, the transporter must operate a foot pedal or button to raise the assist wheels and lift them off of the floor, creating a new burden on the transporter. In addition, because a complex structure is required, the devices are large, and their installation in the limited space of a hospital bed is an issue.

For these reasons, in cooperation with Kurume University, we developed the transportation assist device “Rakusteer” that can provide transportation assistance in all directions and can be installed onto an existing hospital bed⁵⁾ (Fig. 1). This device is installed on the side frame at the bottom center of an existing hospital bed, and adds assist wheels on the left and right in contact with the ground, with these assist wheels controlled by motors. This report explains the mecanum wheels used in the transportation assist device and the system configuration of the transportation assist device, and describes primarily the control method for reducing the burden during hospital bed transportation.

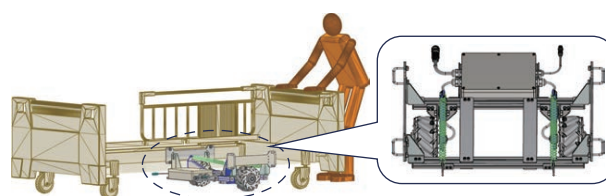


Fig. 1 Transportation assist device

2. Mecanum Wheels

During development, we studied a transportation assist device that controls wheel rotation and cornering in order to enable travel in any direction. However, the hospital beds in recent years are low floor types, and the space for installation is small. Therefore, we focused on the mecanum wheels that can travel in any direction due to simple and compact design (Fig. 2). The mecanum

wheels include multiple barreled rollers inclined at 45 degrees relative to the wheel outer axle.

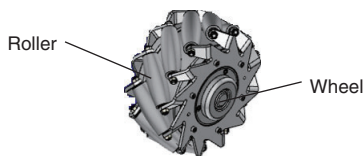


Fig. 2 Mecanum wheel

The mecanum wheels are wheels that can travel in any direction by combining forward and reverse rotation of the axle, however, existing theory says that four wheels are required for control⁶⁾. Because using four wheels increases the cost and the size of the device, in this development we considered a control method using just two mecanum wheels.

Figure 3 shows the operating principle of a transportation assist device using two mecanum wheels. The transportation assist device is installed at the bottom center of the hospital bed, and the pair of mecanum wheels is positioned so the orientation of the rollers is a mirror image on the two sides relative to the electronic control unit (ECU). As a result, when both wheels are rolling forward movement, the thrust toward the inside is canceled out and the bed moves forward. Conversely, when both wheels are rolling backward movement, the thrust toward the outside is canceled out and the bed moves backward. When one of the two wheels is rolling forward and the other is rolling backward, the thrust vector cancels the thrust in the forward or backward direction, and the bed moves to the left or right. In other words, by changing the rotating speed and direction of each wheel, it is possible to move in any direction.

Because a mecanum wheel has multiple rollers, there are concerns that factors such as roller uneven wear or partial loss may make accurate travel difficult. The mecanum wheel adopted here was subjected to a running

test, step impact test, and dropping test as durability evaluations based on the evaluation conditions of JIS standards and the hospital bed manufacturer. The results confirmed that there was no significant deformation or wear. The details are omitted here.

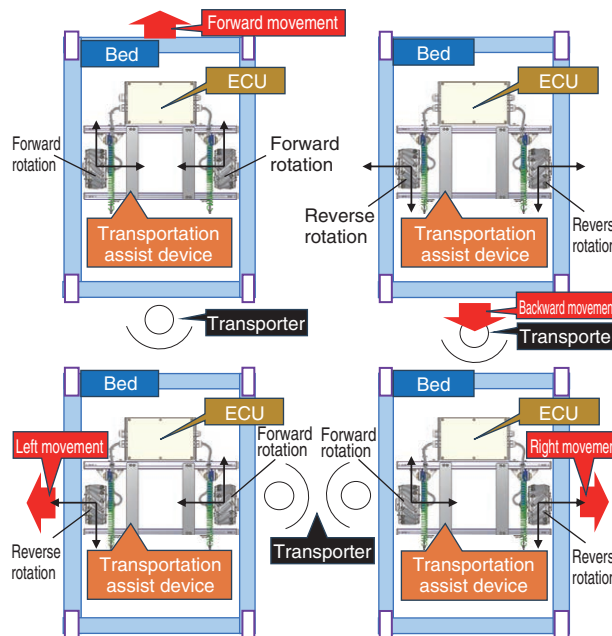


Fig. 3 Operating principle of mecanum wheels

3. System Configuration of the Transportation Assist Device

Figure 4 shows the system configuration of the transportation assist device. A DC brushless motor with encoder was used as the assist wheels drive motor in order to precisely control the rotating velocity. The ECU can control the left and right axle motors, and is composed primarily of the driver part and the controller part. The driver part reads the rotating velocity and current from the left and right motors, and information from various

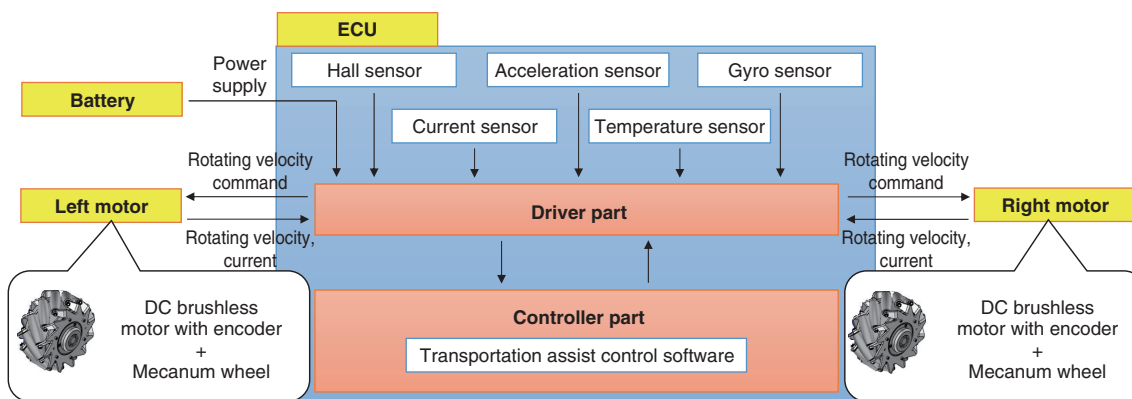


Fig. 4 System configuration of the transportation assist device

sensors in the ECU, and sends them to the controller part. Based on this information, the controller part calculates the rotating velocity command values and sends them as feedback to the driver part. Moreover, the driver part sends rotating velocity commands to drive the left and right motors.

4. Control Technology

In order to reduce the burden on medical staff in hospitals, a control system which assists with transportation without changing the conventional operating methods is needed. This section explains the detection of the bed movement direction and force of push in **Section 4. 1**, the control flow in **Section 4. 2**, the compliance control that comprises the core of the various controls in **Section 4. 3**, the forward/backward movement control and left/right movement control in **Section 4. 4**, and the cornering control in **Section 4. 5**.

4. 1 Detection of the Bed Movement Direction and the Force of Push

In order to detect the force pushing the bed (transporter operating force), although there is an example of developing a device that detects external force⁷⁾, there are problems in terms of the ease of installation onto a hospital bed and the cost.

In contrast, this system utilizes the torque current (*q*-axis current) detected by the motor to detect the bed movement direction and the pushing force. **Figure 5** shows the bed transportation assist mechanism. When the bed is pushed by hand and the velocity changes while power is supplied to the ECU, the actual measured rotating velocity value is larger than the current command value, and therefore torque is generated in the direction opposite the direction of rotation. This means that a larger difference between the rotating velocity command value and measured value (as the force pushing the bed becomes larger) results in larger torque. Therefore, providing torque feedback enables transport in the direction the bed was pushed.

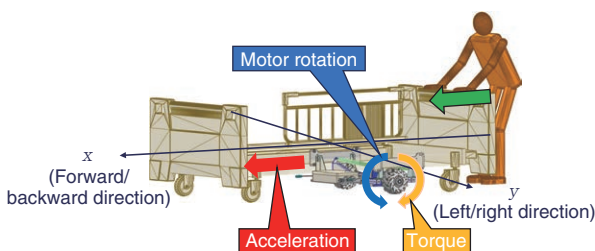


Fig. 5 Bed transportation assist mechanism

Based on the torque detected from the motor, the motor acceleration can be found from Formula (1). Because torque is generated in the direction opposite the direction of rotation, when calculating acceleration, it is multiplied by -1 so that the sign matches the direction of rotation.

$$a = -1 \times \frac{T}{rW} \tag{1}$$

Here,

a: motor acceleration, *T*: motor torque,

r: motor radius, *W*: bed mass

With the bed forward/backward direction as the *x*-axis (forward side positive) and the bed left/right direction as the *y*-axis (left side positive), the acceleration from the left and right motors can be resolved into *x*-axis and *y*-axis acceleration. As shown in **Fig. 3**, when moving in the forward/backward direction, the left and right motors are rotating in the same direction, and when moving in the left/right direction, the left and right motors are rotating in opposite directions. Therefore, the *x*-axis and *y*-axis acceleration can be found from Formulas (2) and (3).

$$a_x = a_R + a_L \tag{2}$$

$$a_y = a_R - a_L \tag{3}$$

Here,

a_x: *x*-axis acceleration, *a_y*: *y*-axis acceleration,

a_L: left motor acceleration, *a_R*: right motor acceleration

Based on the above, it is possible to judge that when $a_x > a_y$, the bed is moving in the forward/backward direction, and when $a_x < a_y$, the bed is moving in the left/right direction.

4. 2 Control Flow

Figure 6 shows the control flow in this system. First, as described in **Section 4. 1**, the *x*-axis and *y*-axis acceleration are calculated when the bed is transported. Then the direction of movement is identified. In hospitals, the bed is typically moved in the forward/backward directions during transportation, while the left/right directions are utilized when placing the bed against a wall. Because the frequency of diagonal movement is low, it is excluded from this control. Based on the above, identification of the movement direction ordinarily identifies forward/backward movement, and identifies left/right movement only when the absolute value of *y*-axis acceleration reaches the threshold. When identifying forward/backward movement, slope and cornering are also judged. Based on these judgment results, forward/backward movement control, left/right movement control, cornering control, or slope control is performed. In case the transporter lets go of the bed during transport, a safety

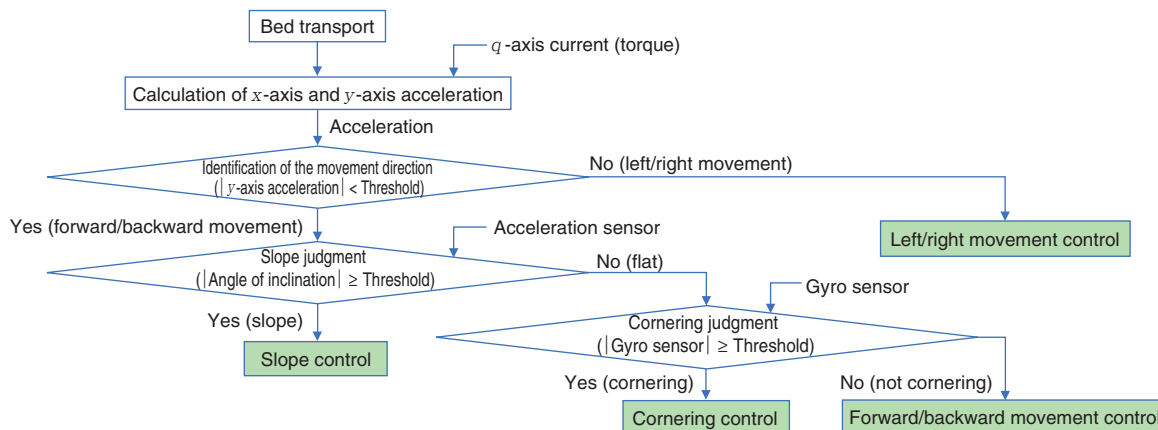


Fig. 6 Bed transportation assist control flow

stop function is provided in each control. This report explains only compliance control, forward/backward movement control, left/right movement control, and cornering control, and does not describe slope control or the safety stop function.

4. 3 Compliance Control

Section 4. 1 described the method of detecting the force pushing the bed from the motor torque. This section explains the compliance control which sends feedback of the acceleration calculated with Formulas (1), (2), and (3) from the motor torque current, and provides transportation assist in the same direction that the bed is pushed. Figure 7 shows an overview of compliance control. When the bed is transported at constant velocity (the rotating velocity measured value and command value are equal) as in Fig. 7 (a), the acceleration is zero. When the bed is pushed to accelerate it in the x-axis positive direction (the rotating velocity measured value is larger than the command value) as in Fig. 7 (b), because torque is generated in the negative direction, the acceleration is generated in the positive direction according to Formula (1). Conversely, when the bed pushing is discontinued and the transporter wants to decelerate (the rotating velocity measured value is smaller than the command value) as in Fig. 7 (c), because torque is generated in the positive direction, the acceleration is generated in the negative direction according to Formula (1). The same applies to the y-axis.

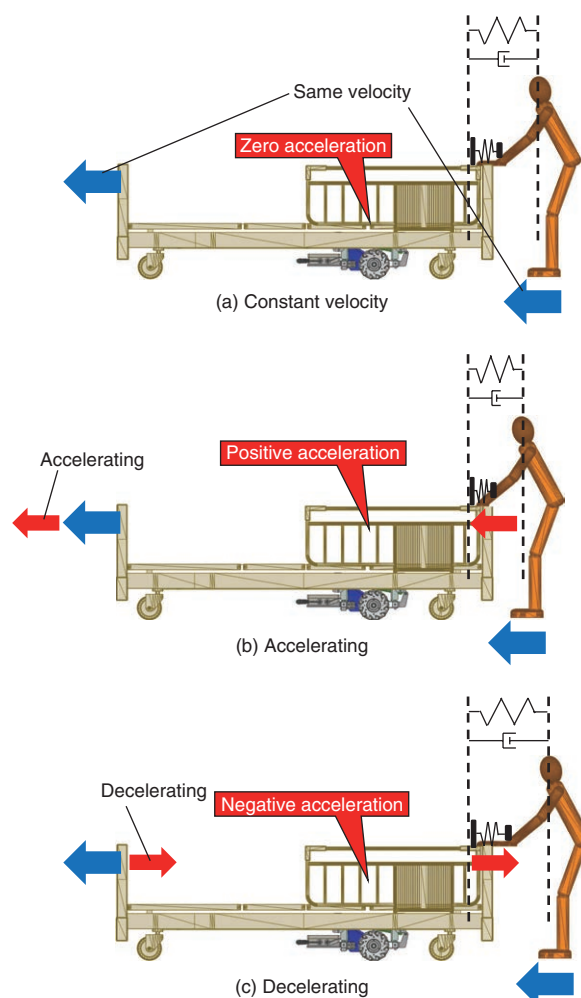


Fig. 7 Compliance control

Figure 8 shows a block diagram of compliance control. In this report, acceleration is defined as the “force” pushing the bed, and what corrects the amount of increase (decrease) in the rotating velocity command value according to the amount of push is defined as a “spring” and “damper”. They are used to decide the rotating velocity command value. The equation of motion for this control is expressed by Formula (4).

$$\frac{F}{M} = a + \frac{K}{M} \cdot \frac{1}{s^2} a + \frac{D}{M} \cdot \frac{1}{s} a \quad (4)$$

Here,

$\frac{F}{M}$: acceleration before correction (“force” pushing the bed),

a : acceleration after correction, M : factor of inertia,

K : Spring constant, D : Damping coefficient,

$\frac{1}{s}$: integral

Because velocity is the integral of acceleration, the rotating velocity command value is calculated by integration of a in Formula (4).

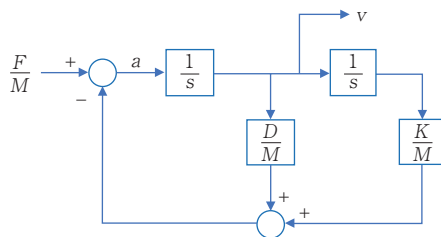


Fig. 8 Compliance control block diagram

4. 4 Forward/Backward Movement Control and Left/Right Movement Control

With forward/backward movement control, the compliance control is applied in the x -axis (forward/backward) direction, and the velocity command value for the x -axis direction is calculated from the x -axis acceleration. With left/right movement control, the compliance control is applied in the y -axis (left/right) direction, and the velocity command value for the y -axis direction is calculated from the y -axis acceleration. In order to control the mecanum wheels and motors on two axes, the velocity command values for the x -axis and y -axis directions are converted to left/right motor rotating velocity command values using the mecanum wheel kinematics shown in **Fig. 9**.

Figure 9 shows the mecanum wheel rotating velocity command values during bed transport when they are resolved into the x -axis and y -axis ($v_{Lx}, v_{Rx}, v_{Ly}, v_{Ry}$), and the resultant velocity is used as the rotating velocity command values (v_L, v_R) for the left/right motors. Based on the above, the velocity command values in the x -axis and y -axis directions v_L and v_R are found using Formula (5).

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} v_{Lx} + v_{Rx} \\ v_{Ly} + v_{Ry} \end{bmatrix} = \begin{bmatrix} +1/2 & +1/2 \\ -1/2 & +1/2 \end{bmatrix} \begin{bmatrix} v_L \\ v_R \end{bmatrix} \quad (5)$$

From Formula (5), the relationship between v_L, v_R and v_x, v_y is shown in Formula (6), and the left/right motor rotating velocity command values v_L and v_R can be derived.

$$\begin{bmatrix} v_L \\ v_R \end{bmatrix} = \begin{bmatrix} +1 & -1 \\ +1 & +1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix} \quad (6)$$

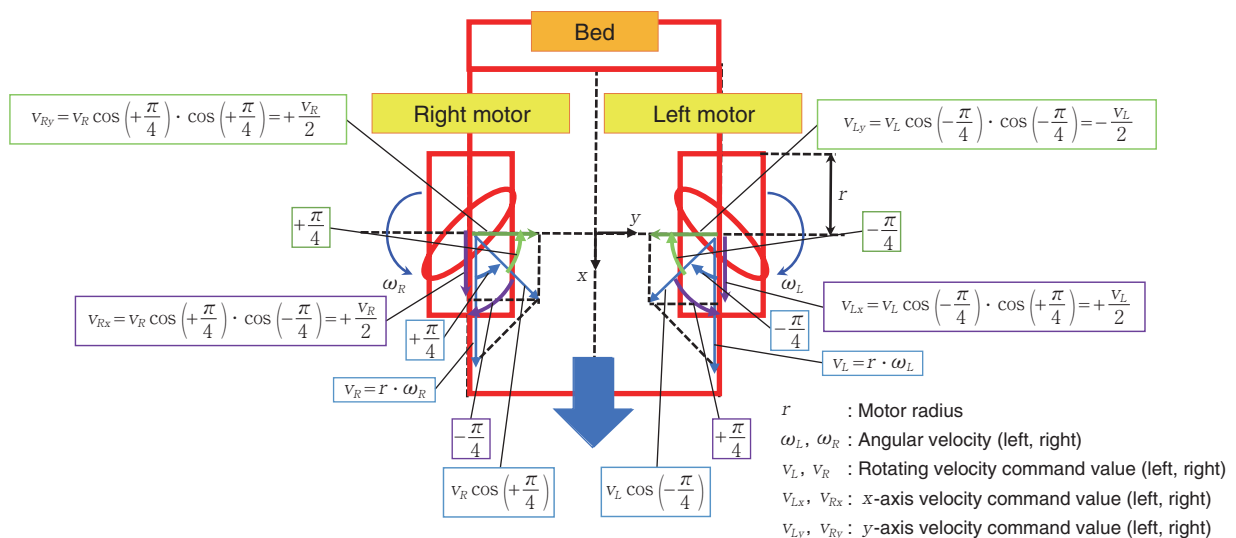


Fig. 9 Mecanum wheel kinematics

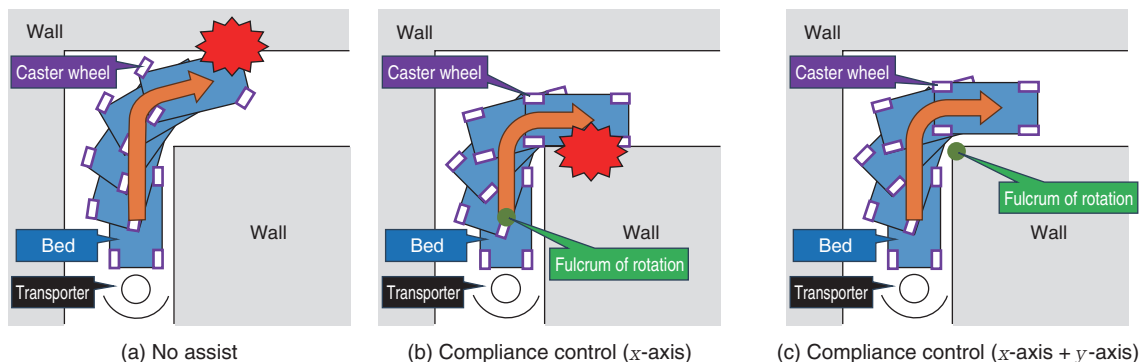


Fig. 10 Cornering

Here because $v_y = 0$ during forward/backward movement control, and $v_x = 0$ during left/right movement control, Formula (6) can be replaced by Formulas (7) and (8) during forward/backward movement control and left/right movement control, respectively.

$$v_L = v_R = v_x \tag{7}$$

$$-v_L = v_R = v_y \tag{8}$$

Because the absolute values of v_L and v_R are the same for both forward/backward movement control and left/right movement control, it is possible to achieve stable forward/backward movement and left/right movement.

4.5 Cornering Control

Figure 10 (a) shows cornering when the transportation assist is not provided. Because the four caster wheels on the hospital bed are all swivel casters, when cornering is performed during transport without assist, the caster wheels turn towards the outside of the corner due to inertia, and the bed can slide to the outside and strike the wall.

In order to perform cornering without striking the wall, it is necessary to generate a force acting to move the caster wheels toward the inside of the corner. For cornering as well, the compliance control in the x-axis (forward/backward) direction is applied to rotate the assist wheels in the intended direction, enabling cornering. However, because the left/right rotating velocity command values are the same as described in Section 4.4, the fulcrum of rotation becomes the center of the transportation assist device, and the bed may strike the wall on the inside as shown in Fig. 10 (b). Therefore, by giving different rotating velocity command values to the left and right assist wheels and changing the fulcrum of rotation, it becomes possible to corner without striking the walls, as shown in Fig. 10 (c).

Figure 11 shows the cornering control flow. Judgment of cornering is performed using a gyro sensor installed in the ECU. While only the compliance control of the

x-axis is applied when forward/backward direction is judged, when cornering is judged, the compliance control is applied to the y-axis direction as well as the x-axis direction. With the compliance control of the y-axis, in order to adjust the amount in the left/right direction, a value which multiplies the y-axis acceleration by c ($0 < c < 1$) is input. After v_x and v_y are output, because v_L and v_R are found using Formula (6) in Section 4.4, it is possible to apply different rotating velocity commands to the left and right sides.

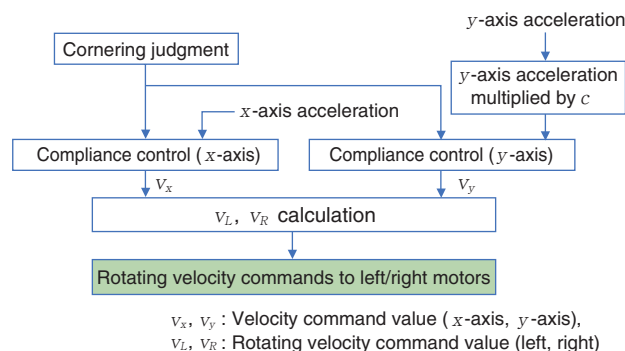


Fig. 11 Cornering control flow

5. Conclusion

This report introduced the control technology of a hospital bed transportation assist device using mecanum wheels. It uses only two mecanum wheels, and we propose compliance control that detects the bed movement direction and force of push based on the motor torque current, and tracks the operation of the transporter. The use of this control is expected to reduce the hospital bed transport workload on medical workers in hospitals for low cost. In the future, we will intend to verify the effects from the use of this product in hospitals.

References

- 1) H. SEKI, T. KURAMOTO: Proposal of Target Position Estimation Type Driving Control and Operation Training System for Power-Assisted Wheelchairs, Transactions of the Institute of Systems, Control and Information Engineers, Vol. 32, No. 10 (2019) 378-387 (in Japanese).
- 2) H. SEKI, N. HATA, Y. KOYASU, Y. HORI: Novel Control Scheme of Power Assisted Wheelchair for Preventing Overturn (Part 1) —Adjustment of Assisted Torque and Performance Evaluation from Field Test—, IEEJ Transactions on Industry Applications, Vol. 124, No. 3 (2004) 318-323 (in Japanese).
- 3) R. A. COOPER, T. A. CORFMAN, S. G. FITZGERALD, M. L. BONINGER, D. M. SPAETH, W. AMMER, J. ARVA: Performance Assessment of a Pushrim-Activated Power-Assisted Wheelchair Control System, IEEE Transactions on Control Systems Technology, Vol. 10, 1 (2022) 121-126.
- 4) KAPPERLLER, RONALD PEA., SAAFSEN, ROBERTMARC, MCCAIG, STEPHEN VI., REINKE, CHRISTIAN H.: User Interface and Control System for Powered Transport Device of a Patient Support Apparatus, JP 2008-119452 (2008).
- 5) JTEKT MACHINE SYSTEMS CORPORATION: Rakusteer, 2023-07, [https://www.machine.jtekt.co.jp/product/new_biz/rakusteer/\(reference 2024. 06\)](https://www.machine.jtekt.co.jp/product/new_biz/rakusteer/(reference%2024.06)).
- 6) M. HOSOYA, Development of Training Equipment: Omni-Directional Vehicle with Mecanum Wheels: Journal of Yamagata College of Industry and Technology, No. 11 (2005) 81-84 (in Japanese).
- 7) T. KAMIMURA, Y. ARIGA, K. WATANABE, E. MURAMATSU, S. ENDO: Study on Control System of Power Assist Device with Operation Torque Sensing Device, 51st Japan Joint Automatic Control Conference, No. 413 (2008) 198-203 (in Japanese).



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