Development of Cart with Providing Constant Steerability Regardless of Loading Weight or Position: 3rd Report on Evaluation of a Steering Assist System on Translational Movement

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Abstract: The steering of the shopping cart is affected by its load, leading to the need for the user to make corrective adjustments and apply excessive force. In this study, the system assists the steering of a shopping cart by actively steering casters based on the user's operational intention estimated from the user's force. This paper provides a brief introduction to the operational interface and the active steering caster. Subsequently, it elaborates on the steering assist system designed for translational movement. Furthermore, we conduct experiments to evaluate the steerability through subjective and objective assessments. These results confirmed that the system can support the operating force and corrective steering. In addition, subjects feel less weight than the conventional carts and have more intuitive sense than the conventional cart.

1 INTRODUCTION

The shopping cart is designed to carry heavy or many items while providing intuitive omnidirectional movement. These advantages enhance the overall comfort of shopping experiences for customers (hereafter referred as "users"). However, the steerability of a shopping cart is influenced by several factors such as the weight and position of loads or items. Consequently, users are often compelled to make corrective steering or exert excessive force when operating the cart. As a result, this situation can lead to discomfort and decreased safety. Addressing these issues can be achieved by ensuring constant steerability of the shopping cart, irrespective of the weight or position of the load. Therefore, the primary objective of this study is to develop a shopping cart that provides constant steerability regardless of the loading weight and position.

Several studies have been conducted on assisting cart operation, but there are some particular challenges and limitations. For instance, in the case of the 'A Person-Following Shopping Supported Robot (Islam, 2019)', the robot tracks the user's position using omnidirectional camera and ultrasonic sensor. However, it has been observed that the absence of physical contact between the user and the cart results in decreased sense of agency (Yun, 2017), potentially increasing the risk of accidents such as collisions in a store. In case of the 'Omnidirectional Power-assisted Cart (Maeda, 2003)', the cart achieves omnidirectional movement using omni-wheels to align with the user's intention. However, due to the motor-generated driving force, the system poses an increased risk of the shopping cart losing control. Another problem arises when the cart remains immobile when assistance is not needed. Such problems also occur in another study, 'Add-on Type

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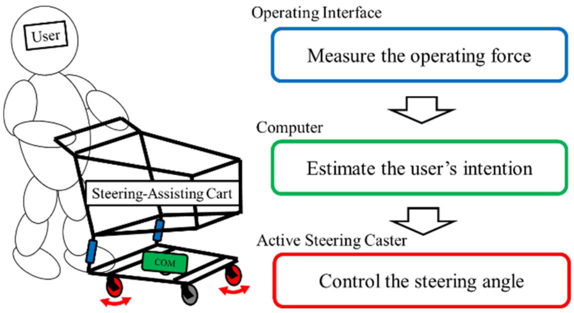


Figure 1: Conceptual illustration of the steering-assisting cart.

Electric Wheelchair Using Active Caster (Nakayama, 2023)’. Another limitation observed in studies such as Passive Intelligent Walker (Hirata, 2007) is an inability to achieve omnidirectional movement due to the fixed casters.

To address these challenges, we propose steering-assisting carts that incorporate passive robotics, as illustrated in Figure 1. This system utilizes the operational interface (Aoki, 2023), where strain gauges are directly bonded to the handle posts, to estimate the user's operational intention. The active steering casters (Aoki, 2022) generate the necessary steering force to assist in the cart's operation. Essentially the moving direction of a cart with all casters hypothetically fixed is restricted to one direction. Thus the steering angle of the casters determines the moving direction of the cart. In the proposed system, the actuator actively steers the caster in intended direction by user, allowing the user to advance the cart in the intended direction simply by applying a pushing force. This constant steerability makes shopping more comfortable and safer. In addition to improving the shopping experience, this system can ease the work in a warehouse or any loading station. Figure 2 illustrates the prototype assembled to validate the function of the individual components. Chapter 2 provides a concise overview of these components.

In this paper, we develop a steering-assisting system designed explicitly for translatory movement. Specifically, we discuss how the system estimates a user’s intended translatory moving direction and accordingly controls the active steering casters to follow this user intention. Furthermore, we comprehensively evaluate the steerability using both subjective and objective assessments. To be more specific, we compare the active steering cart with passive steering cart in terms of the steering and corrective force required by the user and their subjective experience of operability.

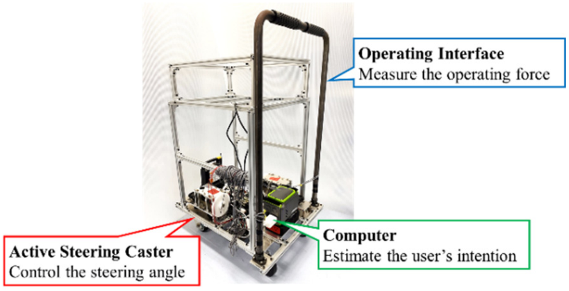


Figure 2: Prototype of the steering-assisting cart.

2 SYSTEM CONFIGURATIONS

This chapter briefly overviews the operational interface (Aoki, 2023), the active steering caster (Aoki, 2022), and its wheel arrangement in order to enhance the paper's readability.

2.1 Operational Interface

The operational interface serves as a sensing system to estimate the user's operational intention. In this study, we propose an operational interface that measures the user's operating force (F_x, F_y) [N] and moment of force M_z [Nm]. The intention is estimated using a method based on the omnidirectional power-assisted cart (Maeda, 2003) as a reference. While various methods have been proposed for such operational interfaces, it is essential to note that they also come with their challenges. For example, some operational interfaces face challenges such as complex mechanisms by using a 6 DOF force-torque sensor (Ueno, 2014), the need for mounting movable parts by using a potentiometer (Seino, 2017), and the requirement to measure objects other than the cart's frame by using an indirect displacement sensor (Maeda, 2003). To address these challenges, we propose an operational interface in which strain gauges are directly bonded to the handle posts. This interface utilizes the structure's strain as the operational interface's input. Consequently, the system eliminates the need for additional parts, allowing for the direct measurement of the operating force. Figure 3 showcases the prototype of the operational interface described above. The strains on the handle posts $(\varepsilon_{xr}, \varepsilon_{xl}, \varepsilon_{yl})^T$ are converted into the applied forces on the handle posts using equation (1). Furthermore, these forces are then transformed into the operating force (F_x, F_y)[N] and moment of force M_z[Nm] on the cart using equation (2).

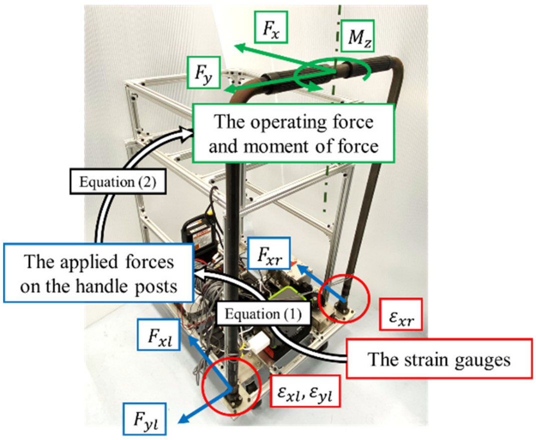


Figure 3: Prototype of the operational interface and operating force conversion flow.

$$\begin{pmatrix} F_{xr} \\ F_{xl} \\ F_{yl} \end{pmatrix} = \boldsymbol{A} \begin{pmatrix} \varepsilon_{xr} \\ \varepsilon_{xl} \\ \varepsilon_{yl} \end{pmatrix} + \boldsymbol{B} \tag{1}$$

$$\text{here } \boldsymbol{A} = \begin{pmatrix} \alpha_{xr} & 0 & 0 \\ 0 & \alpha_{xl} & 0 \\ 0 & 0 & \alpha_{yl} \end{pmatrix}, \boldsymbol{B} = \begin{pmatrix} e_{xr} \\ e_{xl} \\ e_{yl} \end{pmatrix}.$$

$$\begin{pmatrix} F_x \\ F_y \\ M_z \end{pmatrix} = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 1 \\ \frac{d}{2} & -\frac{d}{2} & 0 \end{pmatrix} \begin{pmatrix} F_{xr} \\ F_{xl} \\ F_{yl} \end{pmatrix} \tag{2}$$

In this context, the matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ represent the coefficient matrix and the offset matrix, respectively, which facilitate the conversion of the strains $(\varepsilon_{xr}, \varepsilon_{xl}, \varepsilon_{yl})^T$ into the corresponding force on the handle posts F_{xr}, F_{xl}, F_{yl} [N]. The parameter d [m] denotes the distance between the handle posts.

2.2 Active Steering Caster

The active steering caster plays a crucial role as a fundamental component of the steering-assisting cart. It generates the steering force and determines the arbitrary moving direction of the cart. Figure 4 shows the prototype of the active steering caster. It incorporates a stepping motor to drive the steering axis and an electromagnetic clutch for switching between active and passive steering modes. This design serves as a backup system, allowing the caster to function as a conventional cart that passively steers when assistance is unnecessary or when the battery is depleted. The problems with related research are resolved by the driven steering axis (not driven wheel axis) and the switching mechanism.

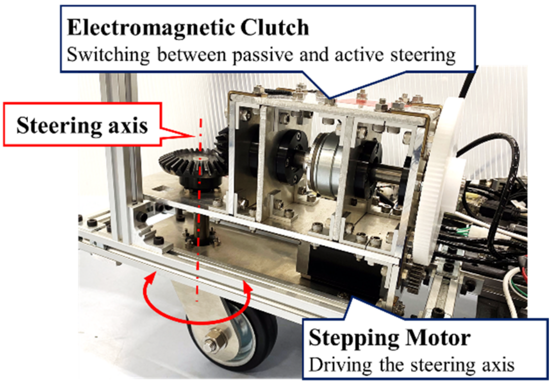


Figure 4: Prototype of the active steering caster.

The steering angle of the active steering caster determines the traveling direction of the cart. To achieve determine the arbitrary moving directions for the cart, it is necessary to arrange two active steering casters among the four casters and control their respective steering angles. This configuration allows for control over the cart's movement in various directions. However, when the wheel axes of the active steering casters are aligned in a straight line, as depicted in Figure 5, the center of rotation can be any point along this line. In other words, when the wheel axes of the active steering casters are aligned on the same straight line, the traveling direction is not uniquely determined. We proposed that two active steering casters and two conventional casters are arranged diagonally to reduce this problem (Aoki, 2022).

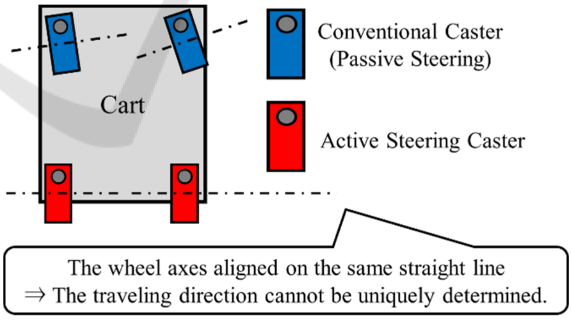


Figure 5: Indeterminate traveling direction with two active steering caster axes on the same straight line.

3 STEERING-ASSISTING SYSTEM

The proposed system is implemented by estimating the operational intention and commanding the steering angle for the active steering casters, as well as other functions. The communication between processes in the system is facilitated by the Robot Operating System (ROS). The ROS network, which visualizes the interconnectedness of these processes, is depicted in Figure 6. The steering-assisting system is implemented by establishing a unidirectional data flow of operating force information among the ROS nodes. In this chapter, we provide detailed explanations regarding the role, algorithm, and specifications of the involved hardware in the system. Additionally, Table 1 presents a comprehensive overview of the hardware components and their corresponding elements utilized in this system.

The "/interface_node" measures the strains on the handle posts. The strains on the handle posts, induced by the operating force, change the resistance of the strain gauges. The strain amplifiers are utilized to convert the resistance variation into a corresponding voltage variation. However, it is essential to note that the strain amplifiers' output may contain some noise. To mitigate the effects of noise, a low-pass filter with a cut-off frequency of $f_c = 1.59$[Hz] is employed to smooth the output of the strain amplifiers. Subsequently, an Arduino is utilized to measure the voltage after the smoothing process.

The "/force_calculate_node" converts the measured strains into the corresponding operating force. Upon invocation, this node conducts calibration to determine the parameters in the offsets matrix $\boldsymbol{B}$. Following calibration, it performs the conversion based on Equation (1) and Equation (2) as explained in Section 2.1. This conversion process enables the calculation of the operating force from the measured strains. The calculated operating force is subjected to software smoothing using the moving-average method with a window size of $\boldsymbol{n} = 13$. This smoothing technique helps to reduce noise and fluctuations in the operating force data. The delay of these procedures is designed to be less than 100 [ms], considering the subjective evaluation of the perception of delay time, as discussed in the study by (Miyasato, 1995).

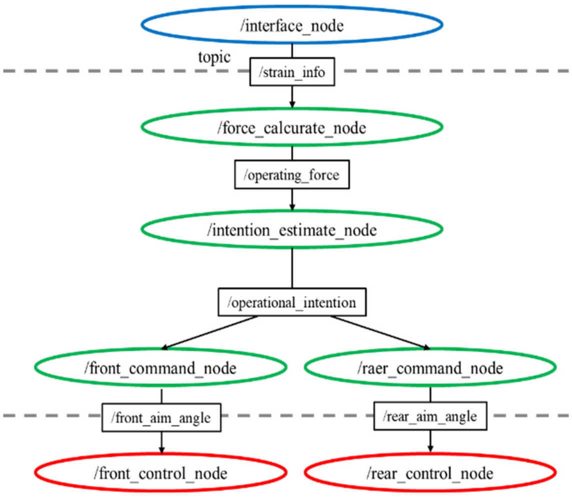


Figure 6: ROS network in the steering-assist cart on translational movement.

Table 1: Hardware components.

Function	Hardware	Parts / Model No.	Total
Operational Interface	Strain Gauge	FLA-5-11-3LJC	6
	Strain Amp	STA-12L	3
Compute	Input Controller	Arduino Uno	1
	Computer	Raspberry Pi 4	1
	Output Controller	Arduino Leonardo	2
Active Steering Caster	Motor Driver	CMD2120P	2
	Stepping Motor	PKP258U20AA2	2
	Electromagnetic Clutch	102-05-11	2

The "/intention_estimate_node" estimates the user's operational intention based on the measured operating force. In estimating the traveling direction of translatory movement, the system calculates the resultant force vector between the x-component and y-component of the operating force. The system assumes that the direction of the resultant force vector represents the traveling direction of the cart. This assumption allows for determining the intended direction of movement based on the calculated force vector. However, it is worth noting that the resistance of the strain gauge may also change undesirably in the direction where no force is applied due to the structural stretching. For instance, during straight translatory movement in the positive x-direction, it is observed that the resistance of the strain gauge on the y-axis also changes, leading to variations in the y-component of the operating force. Consequently, these changes in the y-component of the operating force can create a discrepancy between the resultant force vector and the user's intended traveling direction. The system incorporates a process to determine whether the deformation is significant or insignificant to address this issue. This judgment is carried out by comparing the difference from a predetermined threshold, as specified in Equation (3). The method of determining the threshold is described in the previous paper (Aoki, 2023).

$$\begin{cases} F_x = F_x \ (F_x \geq F_{threshold}) \\ F_x = 0 \ (F_x < F_{threshold}) \end{cases} \tag{3}$$

The "/front_command_node" and "/rear_command_node" calculate the target steering angle to control the active steering caster. In the case of translatory movement, the target angle for the active steering caster is set to be the same as the estimated traveling direction. Therefore, the system determines the estimated traveling direction and translates it into the target steering angle, which is then used to command the respective front or rear active steering caster. If the target angle is too fine, it can lead to unstable vibrations in the steering axis caused by noise. To ensure system stability, our approach involves determining the target steering angle at regular intervals of $\pi/12$. We derived this interval through a trial and error, considering the system's response and stability. By discretizing the target steering angle in this manner, we mitigate the noise impact and minimize the occurrence of unstable vibrations in the steering axis.

The "/front_control_node" and "/rear_control_node" control the active steering caster to align with the commanded target steering angles. These nodes are implemented on an Arduino microcontroller, utilizing a timer interrupt with a cycle duration of 800 microseconds. During each interruption, the system compares the current steering angle with the target steering angle and determines the appropriate rotation direction to minimize the difference between the two angles. Subsequently, suppose a rotation is necessary to align the current steering angle with the target steering angle. In that case, the system issues a command to the motor driver to initiate a one-step rotation. The stepping motor used in the system has a stepping angle of $\frac{\pi}{100\times 2^7}$ [rad], and the gearing ratio between the motor and the steering axis is 8. As a result, the rotation speed of the steering axis is calculated to be 23.4 rpm. This rotation speed was determined based on experimental measurements of the steering speed during passive steering.

4 PERFORMANCE EVALUATION

This chapter assesses the effectiveness of the steering assist system for translational movement discussed in the previous chapter. The steering assist system on translational movement requires two functions. One function generates the steering force to change the direction of movement, while the other supports corrective steering. We evaluate these functions using subjective and objective evaluation indicators.

For the performance evaluation, we utilize a prototype cart loaded with a 30 kg experimental eccentric weight. The weight is intentionally designed to create eccentricity in the load. This cart can switch between passive and active steering modes. In this experiment, the passive steering is also evaluated as a control for the proposed system. We compare the active and passive steering methods' operating force and subjective evaluation scores to assess their performance. The subjects first operated the cart with one of the two steering methods. Then, after a one-week interval, they operated the cart with the remaining other steering method. We divided the 16 subjects (14 men and 2 women, aged 23±1) into two groups, ensuring no significant differences in body height, dominant hand, or sex. One group of subjects started the experiments with passive steering, while the other started with active steering. The questionnaire items for subjective evaluation are as follows: (A) How would you rate the operation in terms of heaviness? (B) How would you rate the operation in terms of intuitiveness? (C) How would you rate the operation in terms of the cart's non-swaying motion? (D) How would you rate the steerability? Subjects answer each questionnaire item using a five-score scale ranging from -2 to 2 $(+2, +1, 0, -1, -2)$.

4.1 Evaluation of Steering Force

In this section, we assess the operability of changing the moving direction of the cart. Figure 7 illustrates the experimental setup and method used in this evaluation. At the start of the experiment, all caster wheels are initially aligned in a same straight direction (x-direction). After that, subjects move the cart in a cross direction for one meter. The evaluation indicators include the maximum operating force in the y-direction $|F_y|_{max}$ and the questionnaire items (A) ~ (D). We evaluated the differences in each evaluation indicator using a two-way analysis of variance (ANOVA), considering the factors of

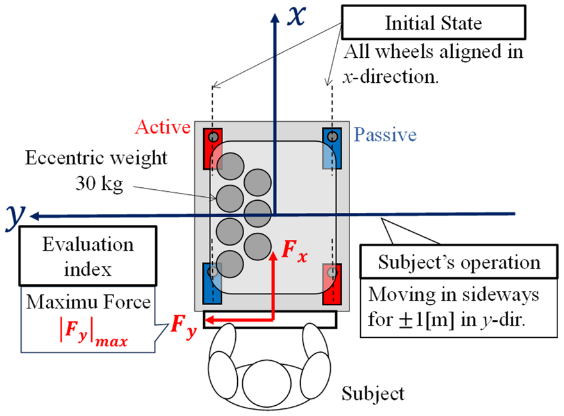
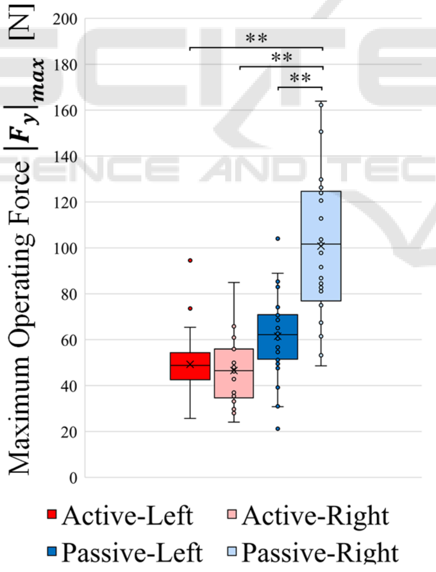


Figure 7: Experimental setup and method employed for evaluating steering force.

steering method (active or passive steering) and moving direction (left and right) in a total of four groups. Each subject performs this experiment twice, using each steering method and moving direction (±y) combination.

4.1.1 Objective Evaluation

Figure 8 displays a box plot illustrating the maximum operating force required when changing the direction of movement. That data is measured 32 times (each subject experimented twice) for each steering method. The two-way ANOVA indicates that active steering requires less operating force than passive steering when changing the direction of movement. The result of multiple comparisons using the Tukey method reveal significant difference in the maximum operating force for passive steering across different directions. However, for active steering, there was no significant difference between them. It is suggested that active steering can achieve consistent steerability regardless of the moving direction, even when being affected by the loading weight and position. This suggests that our system is superior to a conventional cart system.

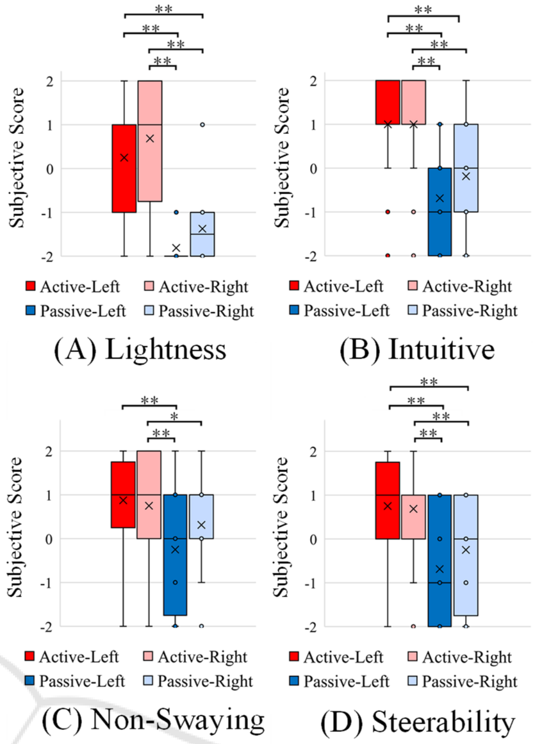


** : p < 0.01

Figure 8: The Maximum operating force $|F_y|_{max}$ during directional movement of the cart (shown in Fig. 7).

4.1.2 Subjective Evaluation

Figure 9 presents a box plot illustrating the subjective evaluation scores for each questionnaire item. The two-way ANOVA reveals that active steering outperforms passive steering, as there are significant differences in all questionnaire items. The multiple comparisons using the Tukey method indicate that there is no significant difference between left and right-moving when using the same steering method. However, in the case of different steering methods, most questionnaire items show significant differences at a 1% significance level. Therefore, it is suggested that the proposed system is superior in terms of subjective evaluation during directional movement of the cart.



(A) Lightness

(B) Intuitive

(C) Non-Swaying

(D) Steerability

* : p < 0.05   ** : p < 0.01

Figure 9: The subjective evaluation scores during directional movement of the cart.

4.2 Evaluation of Corrective Steering

In this section, we assess the operability of translational movement when the cart is affected by eccentricity resulting from the loading position. Figure 10 illustrates the experimental setup used to evaluate the operability of translational movement. In this experiment, the weight is positioned eccentrically in the y-direction. At the experiment's beginning, all casters' wheel orientations are aligned in a same straight direction (x). After that, subjects move the cart in a straight direction (+x) for a distance of four meters. The evaluation indicators include the maximum operating (pushing) force in the x-direction, the standard deviation of the operating force in the y-direction, and the questionnaire items (A) ~ (D). The reason for incorporating the standard deviation of the operating force in the y-direction is that the corrective steering effect causes the operating force to fluctuate in the y-direction in case there is an effect of the eccentricity weight. Therefore, the standard deviation is used as an indicator to assess this variability. Each subject performs this experiment twice, using each steering method.

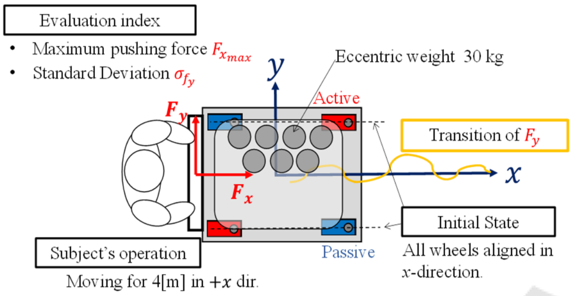


Figure 10: Experimental setup and method employed for evaluating corrective steering

4.2.1 Objective Evaluation

Figure 11 is a box plot showing the maximum operating force in the x-direction and the standard deviation in the y-direction during the straight movement. That data is measured 32 times (each subject experimented twice) for each steering method. The data indicate that active steering requires less operating force than passive steering. Furthermore, the standard deviation of the operating force in the y-direction is lower for active steering compared to passive steering. It suggests the steering assist cart requires less corrective steering than a conventional cart.

4.2.2 Subjective Evaluation

Figure 12 shows the results of the subjective evaluation scores for each questionnaire item. Our analysis reveals that, except for stability, there are significant differences between active and passive steering in terms of subjective evaluation scores, with a significance level of 5%. Based on these findings, we can confirm that active steering is superior to passive steering.

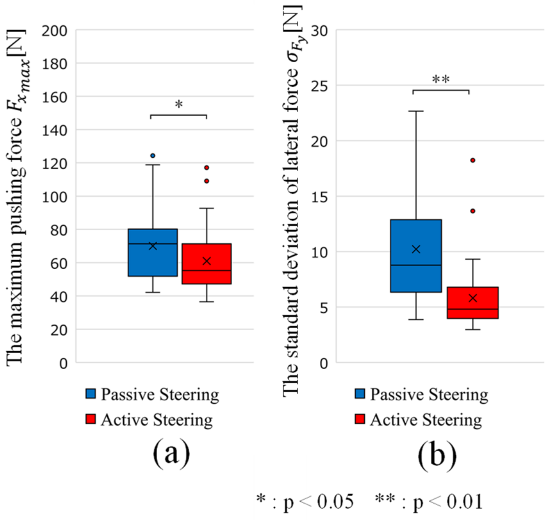


Figure 11: In case of pushing the cart in x direction with eccentric weight (a) The maximum pushing force $F_{x_{max}}$ (b) The standard deviation of lateral force σ_{F_y}.

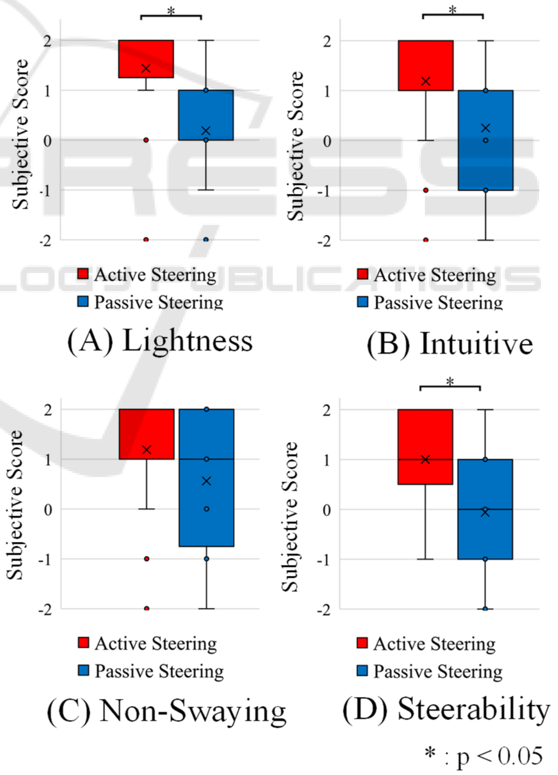


Figure 12: The subjective evaluation scores of translational movements during pushing the cart in x-direction with eccentric weight.

5 CONCLUSION

In this paper, we have implemented a steering assist system for translational movement to achieve consistent steerability regardless of the loading weight and position. Objective and subjective evaluations of this system were then conducted.

Initially, we briefly introduced the proposed active steering caster and operating interface. We then explained the ROS nodes and network used to realize the steering assist system, including detailed information about each function's algorithm and hardware specifications.

Subsequently, we evaluated the implemented steering assist system objectively and subjectively. In the objective evaluation, we confirmed that the system effectively supports the operating force and corrective steering. In the subjective evaluation, we verified that the proposed system reduces the perception of weightiness and enhances the intuitiveness of the operation for users. In other words, the provided constant steerability makes shopping more comfortable and safer.

A limitation of this paper is that the effectiveness was confirmed only for assisting the parallel motion of the carts. Therefore, our future work is to implement the steering assist system for rotational movement. To achieve this, we will model the relationship between the angles for diagonally arranged active steering casters and the center of rotation in the cart. Additionally, we will devise a method to estimate the center of rotation based on the measured operating force from the operational interface. Furthermore, we will develop a control system to ensure that the steering angles of the active steering casters align with the desired center of rotation and moving direction. These will enable a steering assist system capable of omnidirectional translations and rotation.

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