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Study on Omnidirectional Cooperative Trasnport System Using Multiple Dual-wheeled Mobile Robots with Active-Caster Control

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Abstract— **In this paper, we propose a omnidirectional transport system with multiple dual-wheeled mobile robots and a LiDAR-based robot self-orientation estimation method. The proposed transport system applies active caster control to the dual-wheeled mobile robots, enabling them to move the transport object in all directions. The orientation of the robot with respect to the object is very important in control of the robot used in this system. To estimate the orientation of the robot immediately, we propose a method to measure inner substructure of the object using LiDAR and estimate the orientation from a point cloud. In proposed method, the orientation is estimated from vertex location information obtained from the point cloud, and most of the points in the point cloud are not directly used for orientation estimation. Although this method cannot perform localization and mapping like SLAM, it is effective than SLAM in terms of computation time in estimating an orientation of an object in an invariant environment and position in the environment, as in our transport system. Through experiments, we confirmed that this estimation method works effectively in the proposed conveyance system.**

I. INTRODUCTION

In recent years, research and productization of automatic transport technologies using robots, such as automatic guided vehicle (AGV), have been promoted, and these technologies are contributing to automation in various fields, including industrial fields. Conventional automatic transport technologies use a variety of robots, towing dolly [1], carrying bascket or shelf on top of the robot themselvse [2], and using other methods [3]-[5]. Most of these robots are of the type that move on two wheels, called dual-wheeled mobile robot.

The dual-wheel mobile robot generates forward, backward, and rotating motion by rotating left and right wheels with independent angular velocity, but it cannot move immediately in the left and right direction, so, when move sideways, it must change direction by turning and then move forward or backward. This limitation of the robot's motion makes it less convenient for the robot to pass through narrow aisles, such as between shelves in a logistics warehouse, so it is necessary to replan the environment to make the aisles wider for the robot, or to set movement path of the robot so that it does not pass through narrow path. Various studies have been conducted to solve this problem [6],[7].

In order to solve this problem, we propose an omnidirectional transport system with dual-wheeled mobile robots that applied active caster control (Fig.1). In the proposed system, it is poosible to move the object to be carried in all direction by appling active caster control to the robots and cooperative control of the robots.

This paper describes a method for estimating the orientation of a robot with respect to an object to be carried using a point cloud acquired by LiDAR which is used in the proposed transport system. Measuring the orientation to the object to be carried is an important issue in active caster control theory. Conventional estimation methods using point clouds, such as SLAM, can accurately estimate the position and orientation of the robot, but they need long computation time [8]-[10]. Since such methods are not suitable for proposed transport system which uses small robots that can only be equipped with low processing power processor, we reduced computation time of estimation by using a self-orientation estimation method for estimate only orientation of the robot from a few feature points extracted from point cloud of inner substructure of the object.

The structure of this paper is described below, with a particular focus on the localization methods for the robots required for the proposed transport system. In Section II, we describe theories of active casters and the omnidirectional mobile robot with active casters that form the basis of the proposed method and the application of these theories to actual systems. Section III describes self-orientation estimation methods used for robots performing automatic transport using 2D-LiDAR and skirt structure. In Section IV, we present the results of experiments we conducted to validate the effectiveness of our proposed method.

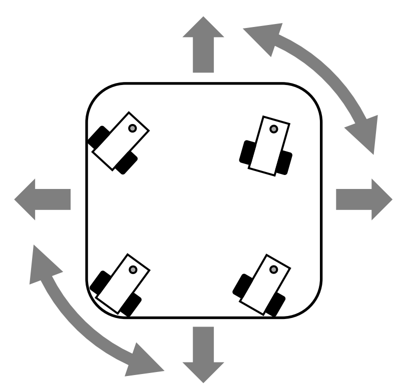

Fig. 1: Conceptual diagram of proposed system

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II. METHODS FOR REALIZING PROPOSED AUTOMATIC TRANSPORT SYSTEM

A. Active Caster

The active caster is an omnidirectional moving mechanism whose structure is same as passive caster shown in Fig.2, has two shafts: a wheel shaft to rotate a wheels and a steering shaft to change an orientation of the caster [11]. There is an offset s between the wheel grounding point and the steering shaft, which generates velocity in an orthogonal direction to the wheel when the casters are oriented.

This mechanism generates the velocity $(\dot{x}, \dot{y})$, in a spatial rectangular coordinate system, according to forward kinematics shown in Equation (1),(2); where ω_w is wheel shaft angular velocity and ω_s is steering shaft angular velocity ω_s [12]. In Equation (1) and (2), the orientation ϕ is angle formed by the x-axis of spatial coordinate system and w-axis of caster coordinate system.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \mathbf{A}_{(\phi)} \begin{bmatrix} \dot{\theta}_w \\ \dot{\theta}_s \end{bmatrix} \tag{1}$$

where,

$$\mathbf{A}_{(\phi)} = \begin{bmatrix} r\cos\phi & -s\sin\phi \\ r\sin\phi & s\cos\phi \end{bmatrix} \tag{2}$$

Fig.3 shows a dual-wheeled active caster that is another type of active caster and consists of a mechanism with twin caster configulation in which two parallel wheels located of off-centered position from steering shaft [13]. The rotation of the left and right wheels indirectly generates the wheel shaft angular velocity and steering shaft angular velocity according to Equation (3).

$$\begin{bmatrix} \dot{\theta}_w \\ \dot{\theta}_s \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ r/w & -r/w \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \tag{3}$$

Then, velocity in spatial rectangular coordinate system is according to Equation (4).

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \mathbf{A}_{(\phi)} \mathbf{B} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \tag{4}$$

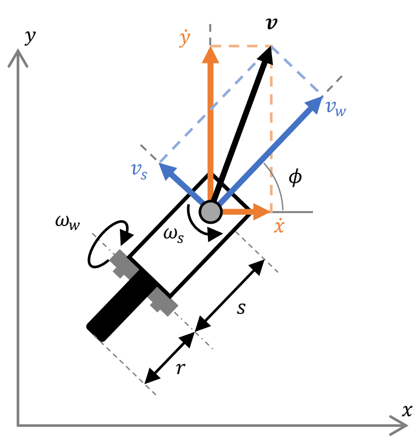

Fig. 2: Kinematics of active caster

where,

$$\mathbf{B} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ r/w & -r/w \end{bmatrix} \tag{5}$$

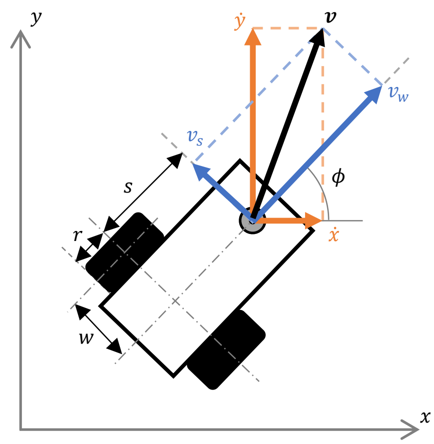

Fig. 3: Kinematics of dual-wheeled active caster

B. Omniderectioanl Mobile Robot with Active Casters

A schematic of an omnidirectional mobile robot with active casters of $n(=3)$ units as drive units is shown in Fig.4 [14]. Equation (6) is the inverse kinematics of this robot. Where u and v are the axes of omnidirectional mobile robot rectangular coordinate system, $(\dot{u}_i, \dot{v}_i)$ is the velocity generated by i-th caster, and (u_i, v_i) is the cordinate of i-th caster, which is fixed to the robot.

$$\begin{bmatrix} \dot{u}_i \\ \dot{v}_i \end{bmatrix} = \begin{bmatrix} 1 & 0 & -v_i \\ 0 & 1 & u_i \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{\theta} \end{bmatrix} \tag{6}$$

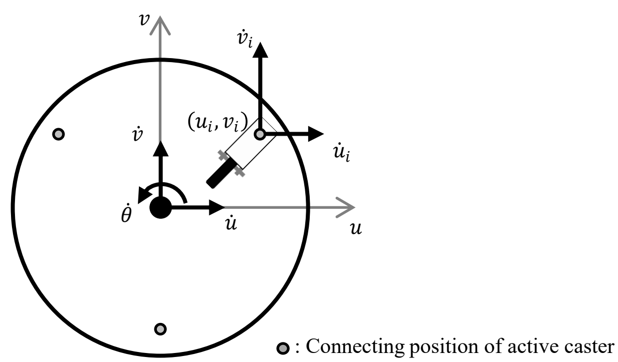

Fig. 4: Schematic of omnidirectional transport system

C. Omnidirectional Cooperative Trasnfer System

The proposed omnidirectional cooperative transport system consists of an object to be transported replacing an omni-directional robot body and independent multiple dual-wheeled robots replacing active casters, in the omni-directional mobile robot configuration. Since dual-wheeled mobile robots have a structure similar to that of dual-wheeled active casters, it is possible to perform omnidirectional movement by treating group of robots used for the omnidirectional transport system as active casters and controling them with active caster control. If the object is moved at $(\dot{u}, \dot{v}, \dot{\theta})$, the left and right wheel speeds of i-th robot $(\dot{\theta}_{Ri}, \dot{\theta}_{Li})$ must satisfy inverse kinematics shown in Equation (7). Where orientation of i-th robot ϕ_i is angle formed by the w-axis of the robot coordinate system and the x-axis coordinate system ofthe object to be carried.

$$\begin{bmatrix} \dot{\theta}_{Ri} \\ \dot{\theta}_{Li} \end{bmatrix} = \mathbf{B}^{-1}\mathbf{A}^{-1}_{(\phi_i)} \begin{bmatrix} 1 & 0 & -v_{mi} \\ 0 & 1 & u_{mi} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{\theta} \end{bmatrix} \tag{7}$$

For cooperative transportation, a TCP server is prepared outside the robot, and each robot is operated as a client of this server. The server transmits the object's transport motion via wireless LAN upon user designation. When receiving this information, each client calculates the required left and right wheel speeds using the calculation in Equation (7), and drives the wheel to perform the transport. After execution of each motion command, the client sends its own displacement, wheel rotation amount, etc. to the server side as a result of the execution.

The proposed transport system has the following advantages.

- Flexible route selection is possible due to the omnidirectional movement.
- The power unit is a small dual-wheeled mobile robot, making it easy to apply to various object transports, such as human-powered transport dolly or bed.
- The number of robots used can be changed according to the weight of the object to be carried, enabling efficient operation.

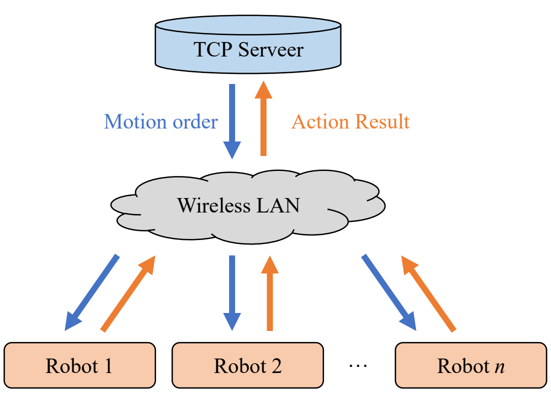

Fig. 5: Trasnfer system communication overview

III. SELF-ORIENTATION ESTIMATION METHOD

A. Estimation Method Overview

The kinematics calculation of omnidirectional transport system depends on the orientation of the i-th robot ϕ_i as shown in Equation (7). While an omnidirectional mobile robot with active casters can measure orientation of active caster by measuring the rotation of the steering shaft using a rotary encoder, it is difficult to measure the orientation by such a method in proposed transport system. Odometry is a common method of estimating the orientation of a robot, but this method causes errors between the estimated result and the actual value when the wheel slips [15]. In the proposed system, the probability of slipping is high when the robot exerts the steering shaft angular velocity more strongly than the wheel shaft angular velocity, and this effect prevents correct control for transport.

Therefore, in this study, a point cloud of the object substructure is acquired using 2D-LiDAR, and the orientation ϕ_i is estimated using this point cloud information. In general, LiDAR-based localization method, including SLAM, estimates the position by matching a point cloud map of the environment with the most recently scanned point cloud [16],[17]. In this system, however, the robot is small, and it is difficult to install a processor with sufficient processing power, so we proposed an self-orientation estimation method, which is lighter-loaded than point cloud matching, without localization and mapping.

B. Actual Processing

A 2D-LiDAR(HOKUYO URG-04LX) is mounted on each dual-wheeled mobile robot, and a skirt structure is installed on the lower part of the object to be carried. The skirt structure should not be point symmetrical around the connection point between the dual-wheeled robot and the object to be carried, for exmaple shown in Fig.6. This structure allows the orientation of the robot to be uniquely determined from the point cloud information acquired by LiDAR. In order for the orientation estimation method described below to work effectively, the skirt structure should be a polygon with multiple vertices.

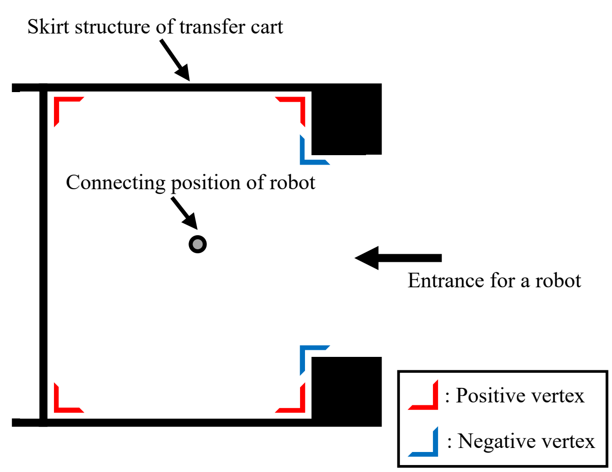

Fig. 6: Skirt structure

LiDAR measured point cloud can be treated as discrete angle-distance data. When the vertices of the polygon are included in the point cloud, a sharp variation in numerical derivative dr/dt appears, similar to the numerical derivative of a continuous and non-differentiable function such as $y = |x|$, as shown in Fig.7. The central difference method is used for numerical differentiation; if the angular resolution of 2D-LiDAR is always constant, the calculation can be simplified to the following Equation (8). The proposed method uses the variation of this numerical derivative as a flag to detect vertices and extracts vertex information from the point cloud.

$$dr_i = (r_{i+1} - r_{i-1}) \tag{8}$$

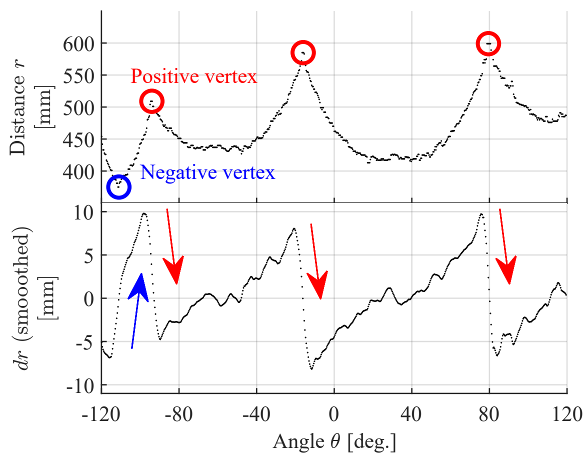

Fig. 7: Angle-distance and differentiated graph

When extracting a vertex, it is discriminated between negative vertices whose vertices are convex toward the inside of the polygon and positive vertices whose vertices are convex toward the outside of the polygon. At the negative vertex, the derivative value dr is large on the small side of θ and small on the large side of θ, and large small relationship of dr is reversed at positive vertex, as shown in Fig.7. This feature is used to discriminate vertices and add polarity information to the measured vertex information. Finally, the proposed method performs attitude estimation by comparing the measured data with a map to which polarity information has been added.

In the actual processing, the central difference for vertex detection and the simple moving average for smoothing LiDAR measurement data are performed, both of which take n^1 order computation time for n data points in the point cloud. In the comparison of map and measurement data, the process takes m^1 order computation times for m number of vertices ($m \ll n$). A comparison of several types of 2D-SLAM and the proposed method is shown in Table I [8]-[10].

TABLE I: Comparison of Proposed Method and SLAM

	2D-SLAM	Proposed Method
to estimate	orientation & positon	orientation only
mapping	can	can't
Available environment	unknown & known	known only
Computation time	n^2 or more than	n^1

IV. EXPERIMENT AND RESULT

A. Prototype Robot and Transport Dolly

The prototype dual-wheeled mobile robot and transport dolly for testing the proposed system are as follows.

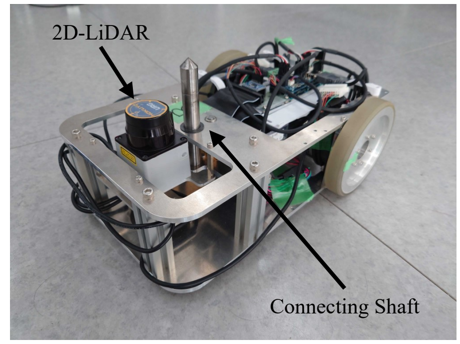

Fig. 8: Experimental Dual-wheel robot

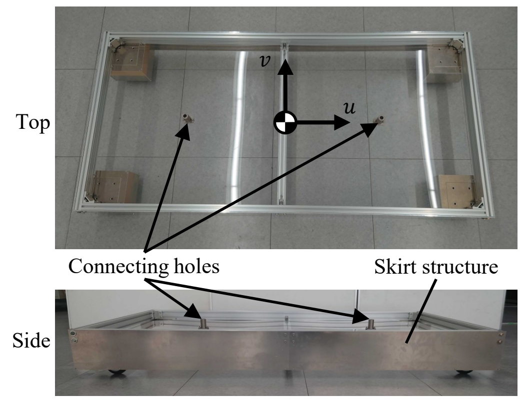

Fig. 9: Experimental Transport Dolly

Table II shows the specifications of the dual-wheeled robot and Fig.8 shows overview of the robot. The wheel motors are rotated by speed control with the control software written in Python. The robot is equipped with a connecting shaft, which rises when the robot connects with transport dolly. This shaft functions as a steering shaft while the robot is connected to the dolly. The structure of transport dolly is shown in the Fig.9.

TABLE II: Dual-wheel robot specifications

Size	[mm]
Body size	L345 × W240 × H100
Wheel raduis	$r = 60$
Steering shaft offset	$s = 165$
Distance from body to wheel	$w = 110$
Equipment	
Cumputer	Raspberry Pi 4B (RAM:8GB)
2D-LiDAR	HOKUYO URG-04LX
Motor	MTL MDH-7018-648KE
Motor Driver	MTL MC-200C-6018

B. Experiment Details

To verify the effectiveness of the proposed estimation method, experiments were conducted to compare two patterns: one in which the orientation is estimated only by odometry, and the other in which the orientation is estimated by odometry every execution cycle of the robot and then corrected using the proposed LiDAR-based orientation estimation method. Each pattern was tested 10 times each.

We use a prototype dual-wheeled mobile robot and transport dolly for experiments. Only one robot was connected to the dolly at the coupling position on the positive side of the u-axis. The results were measured when the robot was commanded to tow the dolly 0.4π m along the u-axis. This distance is equal to the distance traveled for 10 seconds at 10% of the robot's maximum speed. The initial orientation of the robot to the dolly was 135 degrees. In this experiment casters at the corner merked red were replaced with fixed pararel wheels to prevent dolly rotation. The spatial coordinate system is initially set so that the origin coincides with the dolly coordinate system and the orientation of the x axis coincides with the orientation of the u axis.

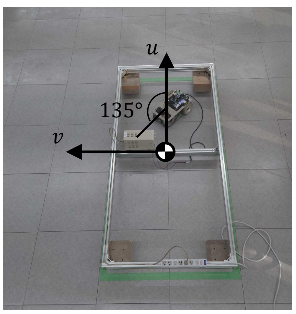

Fig. 10: Condition at the start of experiments

C. Results of Experimanet

The experimental results are shown in the Fig.11-13.

Fig.11 and Fig.13 show that the pattern that used only odometry without self-orientation estimation using LiDAR, transport dolly traveled in a direction tilted an avarage of 21.6 degrees to the commanded path. This is because the dual-wheeled robot's orientation change relative to the dolly was overestimated due to errors caused by left and right wheels slippage when the robot exerted its steering shaft angular velocity, and the forward motion was performed with an insufficient amount of turning for the required.

On the other hand, for the pattern using proposed method shown in Fig.12 and Fig.13, the dolly traveled in a direction tilted an avarage of -6.8 degrees to the commanded direction. The magnitude of error in the direction of travel was reduced compared to the pattern without proposed method. This confirms that the estimation error in odometry caused by left and right wheel slip can be corrected by proposed method, thereby reducing the error in the direction of travel.

Comparing the distances traveled in both patterns, the average traveled distance was 1.19 m for the pattern with odometry only and 1.20 m for the pattern with proposed method. Since the commanded travel distance was 0.4π (≈ 1.25) m, there was an error of about -0.05 m in the travel distance for both patterns.

The orientation of the robot to the dolly at the end of the experiment is approximately 0 degrees in both patterns,

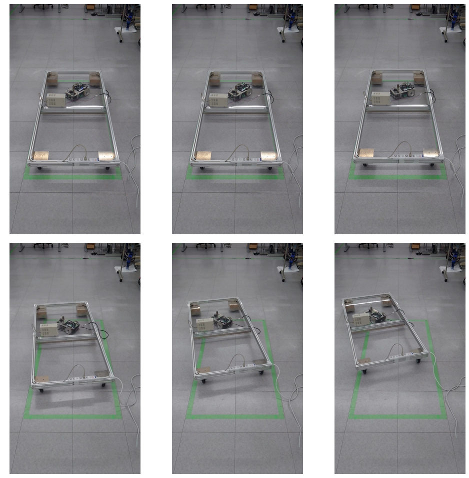

Fig. 11: Expreient progress of the pattern that using only odometry; Sequential photographs taken at 1.5 sec. intervals from the start of the experiment

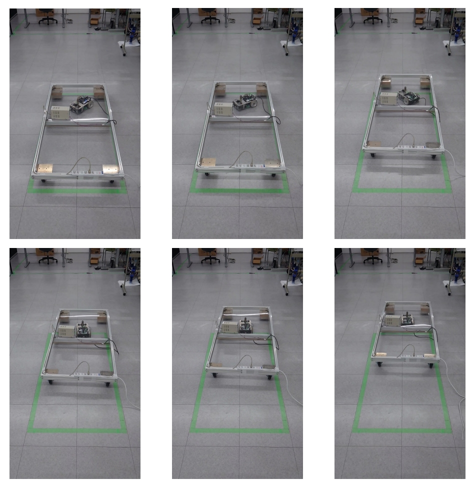

Fig. 12: Expreient progress of the pattern that using proposed estimation method; Sequential photographs taken at 1.5 sec. intervals from the start of the experiment

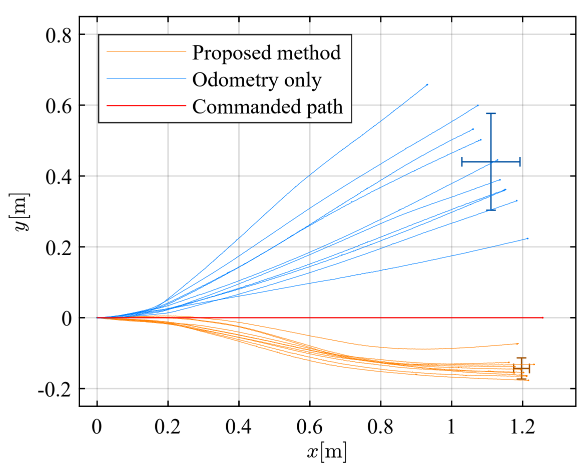

Fig. 13: Path of the cart movement in the experiment

but this is because the orientation of the dolly automatically changes to follow the direction of the dolly and the robot, and the same results are expected to be obtained with or without modification by self-orientation estimation.

In this experiment, one run of LiDAR attitude estimation took an average of 110 ms; the actual processing time was about 3 ms, since it takes about 100 ms to measure LiDAR and about 10 ms to receive point cloud information from LiDAR.

D. Discussion

Experiments confirmed that the proposed transport system can apply active caster control to a dual-wheeled robot and accurately control it by estimating the orientation using LiDAR. It was also confirmed that it is easier to move a dolly to the target direction accurately than when only odometry is used.

The issues are that the amount of movement is smaller than the commanded value and that the time required for each estimation is longer. We believe that the decrease in the amount of movement can be compensated for by estimating the amount of slip and the actual distance traveled based on the difference between the value estimated by odometry and the value estimated by the LiDAR-based orientation estimation method. As for the processing time of the estimation, we are considering modifying the algorithm for faster processing and reducing the processing time by implementing the algorithm in a language with short execution time, such as C language.

V. CONCLUSION

In this paper, we propose omnidirectional transport system with multiple dual-wheeled mobile robots. By applying the active-caster control to the dual-wheeled robots, the steering shaft of the robot can move in any direction instantaneously. To achieve accurate caster motion of the dual-wheeled robot, relative angle between an object and the robot has to be measured accurately. However, odometry of robot wheels gave in accurate self-orientation information due to wheel slips. To solve this problem, we propose self-orientation estimation method using LiDAR. To reduce the calculation cost, the corner identification algorithm was applied to match the corner locations and the internal shape of the object. These algorithms were installed on the prototype mobile robot and some experiments were conducted for verifying the proposed method. The successful caster motions were presented by the prototype dual-wheeled mobile robot. The availability and usefulness of the self-orientation estimation method were also confirmed by the comparison with the wheel odometry.

The future work will include a development of a position measurement algorithm by using LiDAR, an automatic docking, and the omnidirectional motion control of an object by the multiple dual-wheeled mobile robots.

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