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Camera-based AGV Navigation System for Indoor Environment with Occlusion Condition

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***Abstract* - In our current research, we are developing a practical mobile vehicle navigation system which is capable of controlling multiple vehicles on the general environment. In order to realize the practical use, navigation system should have high accuracy and be low cost. Therefore, in this paper, we propose the vehicle navigation system which realizes vehicles navigation using high accuracy localization scheme by ceiling cameras with infrared filters and LED markers. Our key ideas are two topics. One topic is system integration which consists of high accuracy recognition system for LED marker and AGV controller with low cost. The other topic is novel AGV navigation scheme with high accuracy under occlusion condition. For practical use, mobile vehicles are required to continue its tasks with safety and high accuracy on temporary occlusion condition. Our developed system can navigate target vehicle based on estimation odometry error with simple algorithm. The performance of our proposed control system is experimented with our prototype.**

Index Terms* – *iGPS, Mobile robot, Service robot.

I. INTRODUCTION

Automated Guided Vehicle (AGV) has been used in many large factories for delivery tasks. Furthermore, in recent years, there is an increasing demand for mobile vehicles which can excuse their delivery tasks in general populated environment such as offices, welfare care facilities and hospitals. Many AGV systems, which are actually used in large factories, run along the guideline (magnetic tapes etc) which is equipped on the floor [1]. Usually, AGV system with guideline is highly precise and low cost. However, in such environment, AGV is required to excuse many types of tasks and it is difficult to prepare the required guide tapes on the environment beforehand. Therefore, practical AGV system, which realizes highly precise navigation with low cost as same as AGV with guidelines, is required.

In the research field of autonomous mobile robots, technical developments related to AGV navigation method have been proposed [2,3]. Previous studies on autonomous robots concentrated on self-contained robots which integrate all of their necessary functions for their tasks. In general, these approaches utilize visual sensors such as cameras or laser range sensors to detect landmarks and match them to pre-provided map information for self-localization [4,5]. They implemented matching process using environmental objects such as walls or poles projecting from the environmental plane. However, such conditions may not be satisfied due to non-uniformity in general environment. Although many researchers have attempted to create this type of robots, it is difficult for a stand-alone robot to successfully execute task in a real-world environment.

On the other hand, several new robot navigation architectures, which are supported by the intelligent infrastructure, have been proposed. Wahl proposed an AGV navigation system concept that uses TV cameras installed in the robot's work environment to accurately measure its location [6,7]. Ishiguro proposed a distributed vision system to guide a mobile robot [8,9]. Lee proposed an intelligent space where TV cameras are strategically arranged in the environment to measure the positions of the robots and the motions of people [10,11]. A mobile robot navigation system, which integrates ceiling-mounted cameras and a path planner, is proposed to guide a robot in a real environment [12,13].

The robot navigation system supported by intelligent infrastructure has several advantages over a self-contained mobile robot. First of all, an intelligent infrastructure has the capacity to support multiple robots simultaneously. In addition, the implementation of an intelligent infrastructure allows for a very simple robot configuration, as discussed in [10]. In general, a practically AGV system in general environment requires the service of multiple mobile vehicles, therefore, an intelligent infrastructure costs less than self-contained robots because many of the components are shared. Finally, the scale of an intelligent infrastructure is flexible. Function modules can easily be added to the environment to extend the work domain of service robots.

Thus, in our previous work, we developed a navigation system that can control plural robots in a dynamically changing environment [14][15]. This system consists of an overhead CCD camera for measuring the positions of the robot and a real-time path planner. However, for practical use, the robot is required to continue its tasks with high position accuracy under temporary occlusion condition when the ceiling camera cannot detect LED marker.

In this paper, we propose a vehicle navigation scheme for occlusion condition with high accuracy. This paper is organized as follows: Section 2 describes our prototype system. Our proposed navigation scheme under occlusion condition is detailed in Section 3. Experiments are performed to validate the effectiveness of the proposed system, and the results are presented in Section 4. Finally, Section 5 summarizes our proposed AGV system.

II. PROTOTYPE AGV SYSTEM

A. *Indoor Positioning System*

In our previous works, we proposed positioning system using Mark-based vision [14][15]. This system observes robots using the overhead camera which can cover the robot's working domain, and detects artificial marks attached to the robots and obstacles to locate them globally.

Fig.1 shows the overview of our positioning system. A CCD camera is equipped on the ceiling for overlook the moving area of the AGVs. For detecting AGVs easily, all AGVs have IR LED units (Fig.2), which are invisible for human eyes. The IR LED unit consists of many IR LEDs for sufficient optical emission. The IR ray pass filter, which removes the spectrum of visible rays, is attached to the overhead camera for increasing the detecting performance.

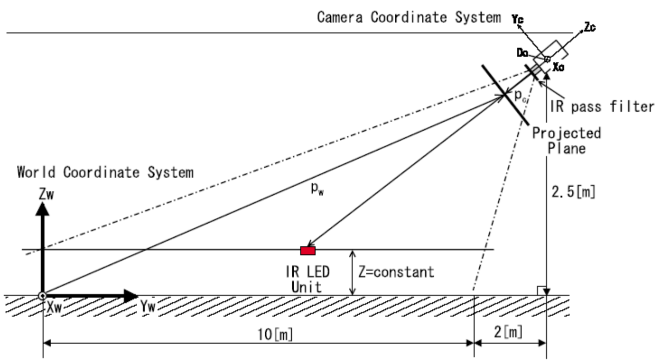


Fig. 1 Overview of our positioning system based on mark-based vision. This figure shows the pattern of single CCD camera. Of course, our system can use multiple CCD cameras for extending positioning area.

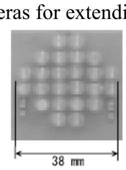


Fig. 2 IR LED unit equipped on AGV.

B. *System Configuration*

This study assumes that AGVs deriver objects between stations within their working domain and the users input start and goal station using computers attached to a network. Our proposed system consists of three subsystems (Fig.3): the indoor positioning server, the user interface and the AGV system. The indoor positioning server [15] tracks the AGVs within the area covered by the overhead CCD cameras. Our positioning server can have four CCD cameras maximally for extend its covered area. Furthermore, if the user requires larger area, our system can install more positioning server.

In our system, we design the user client system for realizing easy-to-use interface. We use Microsoft Visual C++ for developing the user interface system. (Fig.4) The users request a start and goal position, and then system accepts their requests and sends it to AGV system. The user interface system also shows the current information of AGV, for examples, its current position and navigation path generated by AGV system.

AGV system consists of navigation system and AGV controller. This system is equipped on AGV because the system has to continue to control AGV even if the network is down suddenly. Navigation system has navigation path derivation module and AGV velocity reference generator. Navigation path derivation module creates navigation path (Fig.4(b)) considering with present position information of AGV from positioning server, target position information from user client and other AGV information from other navigation system of AGV. Velocity reference generator derives velocity control of AGV based on navigation path.

These functions are independent applications connected via the network. CORBA (Common Object Request Broker Architecture) is a middleware used to connect distributed functional modules on network and we use this protocol because the system can be extended easily with CORBA [16].

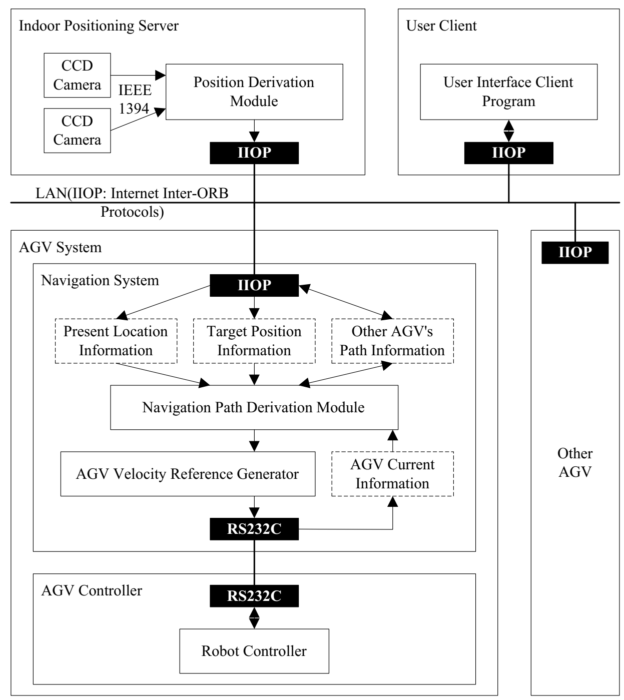
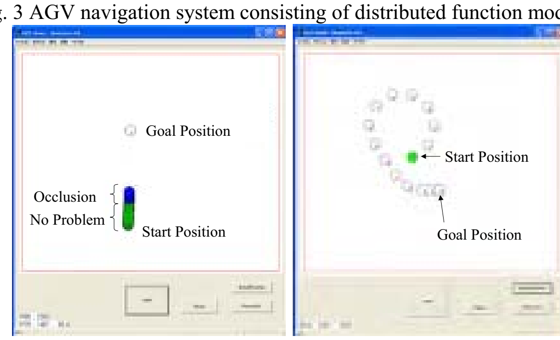


Fig. 3 AGV navigation system consisting of distributed function modules.



(a) (b)

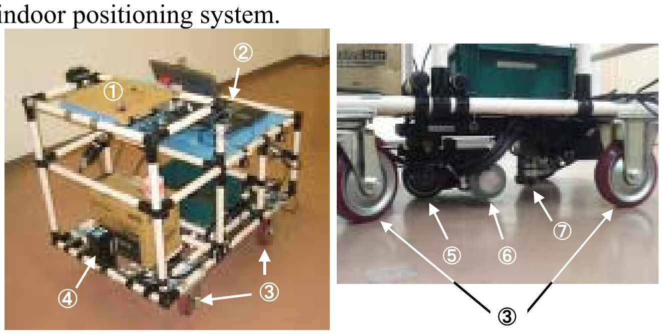
Fig. 4. The user interface system. Users can set start and goal position with easy mouse operation. This figure shows the experimental rooms with no objects, but of course, users can set the position over the room map with

object information. (a) shows the moving information of AGV. Blue point is occlusion condition. (b) shows the navigation path generated by our system automatically. In our future work, we will develop the path creating system with the blueprint of the factory.

C. AGV

Our prototype vehicle is shown in Fig.5 and layout of LED markers is shown in Fig.6. Our vehicle consists of a truck with four caster wheel and a tractor unit which has one wheel connected to a single DC motor and one steering motor as Fig.5(b). It can move at maximum speed of 50[m/min] carrying 350[kg] load. The size of prototype vehicle is 750[mm](Length) x 540[mm](Width) x 520[mm](Height) and its weight is 27[kg] include batteries.

A controller of a tractor unit and laptop with navigation system are connected by RS232C. The laptop has wireless LAN and navigation system connects network via it. This vehicle equips laser range finder for detecting human or other unfixed objects on its path for safety reason. IR LED markers are installed on the top of the vehicle for measuring with our indoor positioning system.



(a) (b)

Fig. 5. Overview of our prototype AGV. (1) is LED marker, (2) is laptop which is installed the navigation system, (3) is caster wheel, (4) is laser range finder, (5) is actuated wheel, (6) is actuator and (7) is steering actuator. (5)-(7) is equipped on a tractor unit.

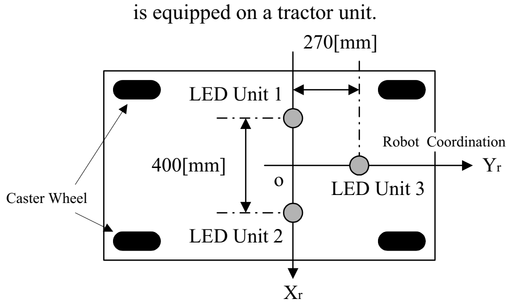


Fig. 6. The arrangement of IR LED units on AGV. The position of the joint, which connects a truck and a tractor unit, is starting position of the robot coordination. (We explain the relationship between the layout of LED markers and position estimation in next section.) This means AGV moves based on this coordination.

III. Navigation Scheme under Occlusion Condition

A. Layout of Markers

In our system, AGVs have 3 IR LED units each other. The relationship between the robot coordination and world coordination is defined as Fig.7. The kinematical relationship between markers is known. (The distance between LED Unit 1 and 2 is L_1, one between Unit 2 and 3 is L_2 and one between Unit 3 and 1 is L_3) Thus, our system can derive the position and inclination of the robot uniquely using these three markers. (Detailed are shown in next paragraph.)

The robot position in Fig.7 is defined as (1).

$$\begin{cases} x_R = (x_1 + x_2)/2 \\ y_R = (y_1 + y_2)/2 \\ \theta_R = \tan^{-1}\left((y_R + y_3) - (x_R - x_3)\right) \end{cases} \tag{1}$$

where the position of each marker is $\left(x_j, y_j\right)$, ($j = 1, \cdots, 3$).

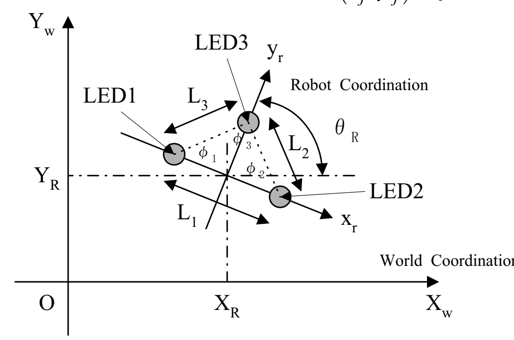


Fig. 7. The kinematics of LED markers.

B. Position Detection of AGV

If our system detects the N LED markers, the derived position of LED marker using our positioning system is defined as $\left(x_l, y_l\right)$, ($l = 1, \cdots, N$). From these LED markers, we choice the marker on the target robot as followings;

- From the kinematical relationship, the true markers will minimize J in (2). Therefore, our system tries all combinations of detecting LED markers.

$$\begin{aligned}
&for\ l_1 = 1\ to\ N \\
&\quad for\ l_2 = 1\ to\ N \\
&\quad\quad for\ l_3 = 1\ to\ N \\
&\quad\quad d_1 = \sqrt{\left(x_{l_1} - x_{l_2}\right)^2 - \left(y_{l_1} - y_{l_2}\right)^2} \\
&\quad\quad d_2 = \sqrt{\left(x_{l_2} - x_{l_3}\right)^2 - \left(y_{l_2} - y_{l_3}\right)^2} \\
&\quad\quad d_3 = \sqrt{\left(x_{l_3} - x_{l_1}\right)^2 - \left(y_{l_3} - y_{l_1}\right)^2} \\
&\quad\quad \mathbf{a}_1 = \left(x_{l_2} - x_{l_1}, y_{l_2} - y_{l_1}\right) \\
&\quad\quad \mathbf{b}_1 = \left(x_{l_3} - x_{l_1}, y_{l_3} - y_{l_1}\right) \\
&\quad\quad \mathbf{a}_2 = \left(x_{l_1} - x_{l_2}, y_{l_1} - y_{l_2}\right) \\
&\quad\quad \mathbf{b}_2 = \left(x_{l_3} - x_{l_2}, y_{l_3} - y_{l_2}\right) \\
&\quad\quad \mathbf{a}_3 = \left(x_{l_1} - x_{l_3}, y_{l_1} - y_{l_3}\right) \\
&\quad\quad \mathbf{b}_3 = \left(x_{l_2} - x_{l_3}, y_{l_2} - y_{l_3}\right) \\
&J = \sum_{n=1}^{3}\left[\left(d_n - L_n\right)^2 + \left\{\cos^{-1}\left(\left(a_n \cdot b_n\right)/\left(\left|a_n\right| \cdot \left|b_n\right|\right) - \phi_n\right\}^2\right]
\end{aligned} \tag{2}$$

where L_n and ϕ_n are defined in Fig.7.

- If the combination of markers, which minimize J, exists and derived J is smaller than threshold, which is derived experimentally, our system recognizes that this combination of LED markers is true. Then, the indoor positioning server calculates the position of the robot using (1) and sends these data to the navigation system on AGV.
- If there are no combinations, which fulfill the above

condition, our system retries to detect LED markers.

C. Position Estimation using Information of Positioning System

Our positioning server sends the following data to the navigation system.

- The positioning data. (x_R, y_R, θ_R)
- The ID of Robot in case that there are plural AGVs.
- The position detecting time.

If the navigation system of AGV receives these data of t_1 at t_2, system estimates its position $(x_R^{est}, y_R^{est}, \theta_R^{est})$ at t_2 as follows:

$$\begin{cases} x_R^{est}(t_2) = x_R(t_i) + \int_{t_1}^{t_2} v(t)\cos\theta(t)dt \\ y_R^{est}(t_2) = y_R(t_i) + \int_{t_1}^{t_2} v(t)\sin\theta(t)dt \\ \theta_R^{est}(t_2) = \theta_R(t_i) + \int_{t_1}^{t_2} \dot{\phi}(t)dt \end{cases} \quad (3)$$

where v is velocity and ϕ is steering angle of AGV. These values are defined as Fig.8 because the tractor unit pulls the vehicle body.

Our navigation system creates the vehicle velocity reference and steering angle reference $(v_{ref}^{org}, \phi_{ref}^{org})$ from the goal position and present position. (The velocity reference derivation scheme is discussed in our previous work [17].)

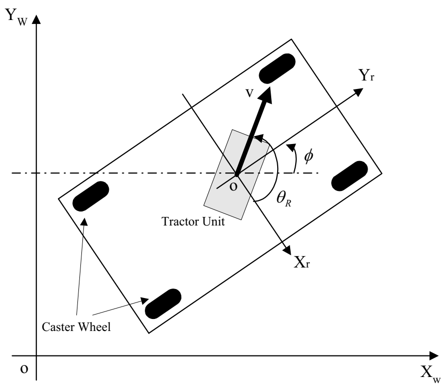


Fig. 8. The kinematics of our AGV.

D. Vehicle Navigation with Occlusion Condition

Our AGV system uses position information by overhead camera. However, in general environment, there are many obstacles and these will cause the occlusion condition. In occlusion condition, the navigation system cannot obtain its present position data. Furthermore, time delay of network causes a difficulty to obtain the present position data. In these cases, our system estimates its position using odometry using (3). However, using the odometry long time, estimation error will increase. By ASME standard, AGV must not exceed 0.15[m] position error [18]. On the other hand, these occlusion conditions are temporary in many cases and AGV should continue to execute its task. Thus, we propose navigation scheme under temporary occlusion condition. Our proposed scheme is as follows:

- The navigation system estimates its position using (3). Therefore, when the navigation system on the AGV cannot receive its position data from the indoor positioning server suddenly, it can estimate its position continuously.
- However, odometry tends to have estimation error. In our vehicle, odometry errors are shown as Fig.9. Capable error is 0.15[m] and the odometry error should less than this value. Therefore, we coordinate velocity control reference v_{ref} which enables AGV to stop within capable error as (4) and (5).
- The advantage of this algorithm is simple and generality. The system estimates its position using only (3) all times, thus, its implementation is easy. Furthermore, this algorithm can navigate under not only occlusion condition but also all fault of receiving its positing data, for example, network delay.

$$v_{ref} = \begin{cases} v_{ref}^{org} & \left(if \quad v_{ref}^{org} < v_{ref}^{od}\right) \\ v_{ref}^{org} & \left(if \quad v_{ref}^{org} > v_{ref}^{od}\right) \end{cases} \quad (4)$$

$$v_{ref}^{od} = \sqrt{2a_{b\max}\left(e - s \cdot e^{od} \cdot t^{od}\right)} \quad (5)$$

where v_{ref}^{org} is velocity reference in case of connecting positioning server normally. $a_{b\max}$ is a maximum breaking acceleration and e is capable error. s is safety rate, e^{od} is estimating odometry error and t^{od} is moving time with odometry. e^{od} is derived from preliminary experiment as Fig.9. Between straight path and curve path, the odometry error is different. Therefore, the system should select appropriate coefficient by navigation path.

Fig.10 is example of v_{ref}. In our prototype, a maximum breaking acceleration is $a_{b\max} = 0.5[m/s^2]$, estimating odometry error is $e^{od} = 0.01[m/s]$ (straight) or $0.015[m/s]$ (curve). We set safety rate as $s = 2$ and capable error is $e = 0.15[m]$. From Fig.10, AGV can move about 8 seconds on straight path without receiving its position data.

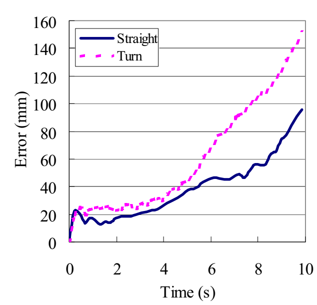


Fig. 9. Odmetry error. The Vehicle runs at 40[m/min].

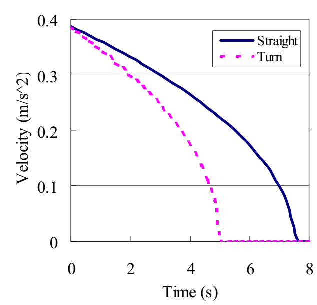


Fig. 10. Reference Velocity.

IV. Experiment

A. Experimental Setup

Here, we verify the performance of our navigation system by the experiment using our prototype. Experimental setup is shown as Fig.11. Two overhead cameras with IR pass filter covers 4.7[m] width and 5.8[m] length room. The camera (1) is used for AGV navigation. In this room, there is the obstacle which hides LED marker from the camera (1) for occlusion experiment (in paragraph C, D and E). The camera (2) is used for the position evaluation in the experiment. The obstacle does not hide the maker from the camera (2).

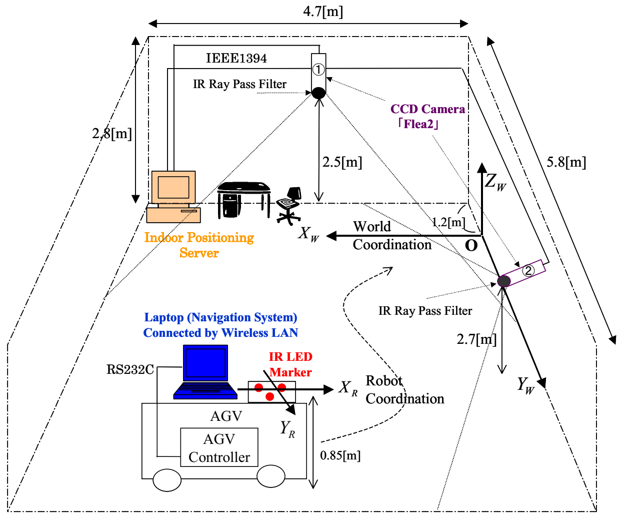


Fig. 11. Experimental Setup. There are two overhead cameras in this room to navigate AGV all over this room.

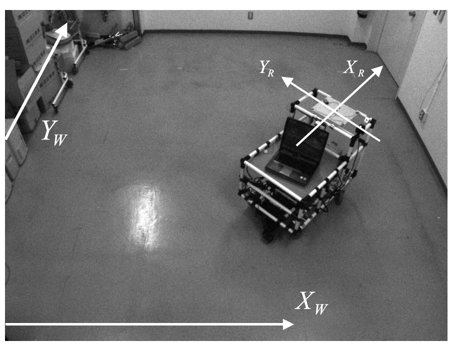


Fig. 12. Pictures of the camera (1) without IR Ray Pass Filter. During experiments, IR ray pass filter is attached to the camera, of course.

B. *Positioning Accuracy*

The first, we evaluated the accuracy of our proposed positioning system by experiment. Fig.13 shows the result. The x and y axis of the figure corresponded to the X and Y axis of the world coordinate system. O and × denote the true values and measurement values. The number beside × indicates the error norm at the point of measurement. The maximum value error is 11.7[mm], and accuracy of positioning system is sufficient to navigate AGV [18].

C. *Occlusion Test*

In this experiment, AGV moves along a path as shown in Fig.14. During experiment, we hide LED marker of AGV twice and verify our control system.

The experimental result is Fig.15. During occlusion condition, the velocity of vehicle is down and at last, it stops. Furthermore, the deceleration in case of curve path is larger the one in case of straight path as Fig.10. From these results, odometry scheme under collusion condition is effective.

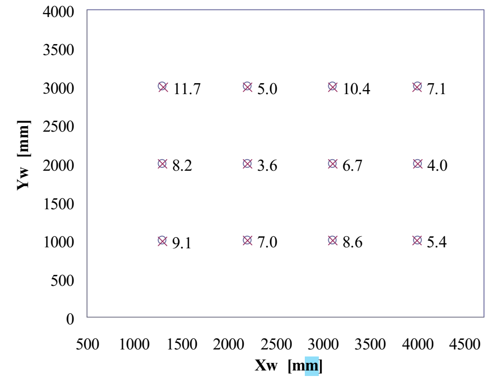


Fig. 13. Measurement error. The units of values are [mm].

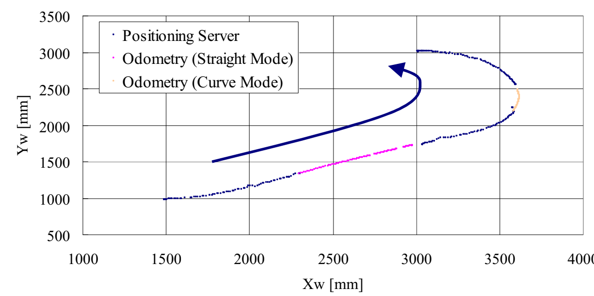


Fig. 14. Tracks of AGV. Pink and orange lines show the occlusion condition.

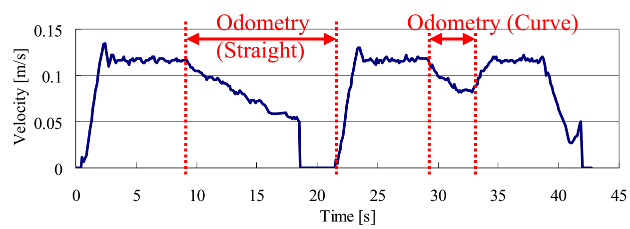


Fig. 15. The velocity of AGV. Our AGV stops using electro-magnetic brakes, thus, its velocity becomes zero suddenly before it stops.

D. *Duration Test*

For verifying accuracy and reliability of our navigation system, we experiment a duration test. In this experiment, AGV travels along a circular trajectories 60 times, during more than one hour. The maximum velocity is 50[m/min]. In this trajectory, there are obstacles which cause an occlusion.

The experimental result is as shown in Fig.16. AGV can finish its required path. During experiments, maximum position error is 27.9[mm] and average error is 12.2[mm]. These results are enough for ASME standard [18] and it means our system is effective for practical use.

E. *Multiple AGV Navigation Test*

For verifying the multiple AGV navigation, we experiment the follower test. In this experiment, we operate one AGV and the other AGV (Follower) follows on the AGV which proceeds after 2[m] with same velocity. During experiments, we hide LED marker temporary which assumes occlusion condition. The follower receives the position of AGV which it runs after and its own position from the positioning server. The positioning server broadcasts all position data, thus, it is easy to receive all data without special technique. The follower uses the position of AGV which proceeds as reference and derived its the vehicle velocity reference and steering angle reference. Please note this algorithm is temporary used for evaluation our system. In our future work, we will develop multiple AGV path creation scheme.

The experimental result is as shown in Fig.17. The follower can run after the AGV which proceeds. During experiments, maximum position error is 22.4[mm] and its accuracy fulfills ASME standard. Thus, our system can navigate plural AGVs with enough accuracy.

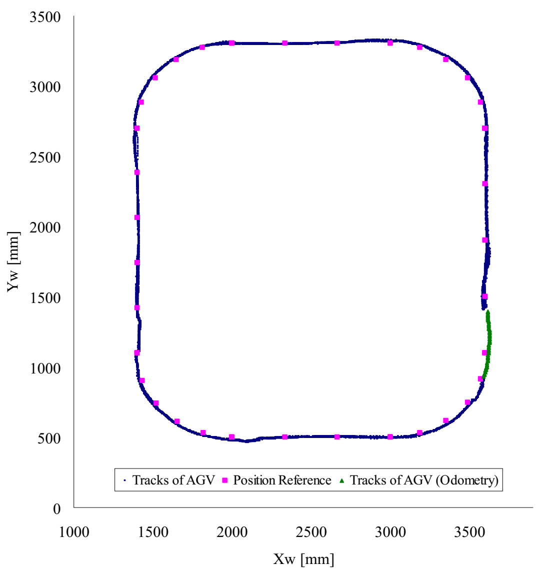


Fig. 16. 60 trajectories of AGV. Green line shows that our AGV moves using occlusion mode. These trajectories are calculated using information of positioning server using the camera (2).

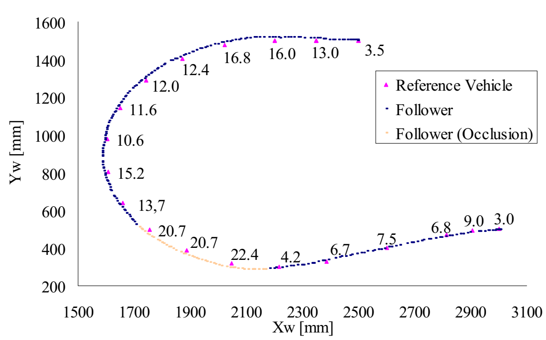


Fig. 17. The trajectories of two AGV. The follower moves 2[m] after the reference vehicle with same speed. Orange line shows the occlusion condition and the follower uses occlusion mode. The number beside Δ indicates the position error [mm].

V. Conclusion

This paper introduces the AGV navigation system which realizes multiple vehicles navigation using high accuracy localization scheme with overhead cameras. Advantages of our system are low cost, high accuracy and high reliability. Furthermore, our navigation system guarantees the position error within ASME standard with simple algorithm under occlusion condition. Effectiveness of our system is verified in the experiment using our prototype based on AGV which is actually used in the factory generally.

In our future work, we will develop a switching system between our camera-based navigation and guideline system which is already used in general factories.

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