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Camera-based Indoor Navigation for Service Robots

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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 novel vehicle navigation system which realizes multiple vehicles navigation using high accuracy localization scheme by ceiling TV cameras with infrared filters and LED markers on target vehicles. Our key ideas are two topics. One topic is system integration which consists of vehicle localization system and CORBA network. Using our ideas, our system can extend navigation areas and target vehicles with low cost. The other topic is novel navigation scheme under occlusion condition. For practical use, mobile vehicles are required to continue its tasks with safety on temporary occlusion condition. Our developed system can adjust navigation path and velocity of target vehicle based on estimation odometry error. The performance of our proposed control scheme is experimented by experiments in general environment.**

Keywords; AGV Navigation, Distributed Controller, Service robots

I. INTRODUCTION

Automated Guided Vehicle (AGV), mobile vehicle have been successfully employed 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 general 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 range sensors to detect landmarks and match them to pre-provided map information for self-localization [4,5]. They implement 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.

A robot's components, however, are not restricted to a predefined location. For example, all of a robot's functions are not necessary restricted to its body. Instead, a robot's eye could be mounted on the ceiling, in order for it to better observe what is happening in a room. Based upon this idea, several new robot navigation architectures 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]. Hada developed a navigation system that can accurately control a small robot in a dynamically changing tabletop environment [8]. This system consisted of an overhead TV camera which is used to measure the positions of the robot and the obstacles, and a real-time path planner. Ishiguro proposed a distributed vision system to guide a mobile robot [9,10]. 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 [11,12]. A mobile robot navigation system, which integrates ceiling-mounted cameras and a path planner, is proposed to guide a robot in a real environment [13,14]. Asama proposes a method for putting information in the environment using the Intelligent Data Carrier (IDC) [15].

IDC is a small device which can store and process information. In their study, many IDCs are strategically distributed throughout the environment so that multiple robots can share information and use it for self-localization.

As describe above, an autonomous mobile robot 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 [11]. Generally, a practically AGV system in general environment requires the service of multiple mobile vehicles, therefore, an intelligent infrastructure costs less than employing 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.

In this paper, we proposes an advanced AGV system which can work in general populated environment, and describes the design policy, methodology, implementation and experimental results. Based on these previous ideas, our proposed system consists of two sections. One section is AGV in which a simple motion controller is implemented. The other section is an infrastructure AGV controller which consists of a distributed vision system for measuring the position of AGV, a global path planner and man-machine interface. Both sections are connected by CORBA network [16] which can adapt different platforms easily. Furthermore, our system can navigate them under occlusion condition.

This paper describes design policy of the AGV system and its implementation. It is organized as follows: Section 2 describes our indoor positioning system. Our advanced AGV system 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. Indoor Positioning System

A. System Configuration

In our previous works, we proposed positioning system using Mark-based vision [17]. 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. In this study, we extend our Mark-based vision for AGV navigation.

Fig.1 shows the overview of our positioning system. A CCD camera is mounted on the ceiling for overlook the moving area of the AGVs. For detecting AGVs accurately, by this CCD camera, 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. In order to expand the radiation range, the condensing lens are removed from every IR LED. Moreover, the IR ray pass filter (AJ43949:Edmund), which removes the spectrum of visible rays, is attached to the overhead CCD camera in order to increase detecting performance of IR LED units. Using our system, the position of AGV moving on the floor can be detecting. In next paragraph, we explain the detecting scheme closely.

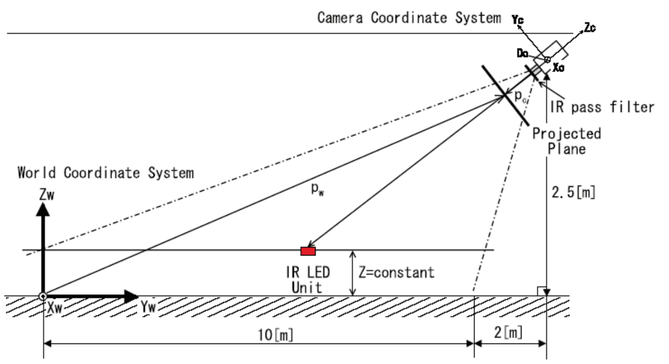


Fig. 1. Overview of our positioning system based on mark-based vision. This figure shows the pattern of single CCD camera. Of course, our system can use multiple CCD cameras for extending positioning area.

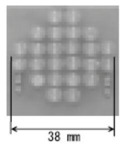


Fig. 2. IR LED unit equipped on AGV.

B. Position Measurement

The first, we calibrate overhead CCD camera to derive the following camera parameters.

- Coordinates of the origin $O_c = (x_{oc}, y_{oc}, z_{oc})^t$ of the camera coordinate frame with respect to the world coordinate system.
- An affine transformation matrix $\mathbf{A}$, which transforms an optical image on a projected plane into an electro-optimal image, namely, the image memory coordinate system.
- A rotating matrix $\mathbf{R}$, which transforms the world coordinate system into the camera coordinate system.

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

The procedure to measure the position of the LED unit with respect to the world coordinate is as follows. The image of IR LED units is projected onto CCD as ellipse, as shown in Fig.3.

By marking a binary image and labeling it, we can obtain

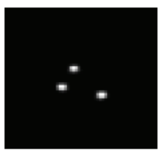


Fig. 3. Projected image.

the coordinates $\mathbf{p_f} = (x_f, y_f)^t$ of the centroid of the projected LED unit area with respect to the image memory coordinate system.

We can express a submatrix in the affine transformation matrix of (1) as $\mathbf{A}'$.

$$\mathbf{A}' = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \tag{2}$$

Coordinates $\mathbf{b}$ of a focalpoint on the image coordinate system are denoted as follows.

$$\mathbf{b} = \begin{pmatrix} a_{13} \\ a_{23} \end{pmatrix} \tag{3}$$

Then, coordinates $\mathbf{p_c}$ of the centroid of the projected LED unit with respect to the camera coordinate system become as follows.

$$\mathbf{p_c} = \begin{pmatrix} -x_c & -y_c & -1 \end{pmatrix}^T \tag{4}$$

where

$$\begin{pmatrix} x_c \\ y_c \end{pmatrix} = \mathbf{A}'^{-1}(\mathbf{p_f} - \mathbf{b}) \tag{5}$$

Coordinates $p_w = (x_w, y_w, z_w)^t$ of the projected LED unit with respect to the world coordinate system become as follows.

$$\mathbf{p_w} = \mathbf{R^t p_c} + \mathbf{O_c} \tag{6}$$

The equation of the line on which the IR LED unit and the focal point of the camera line is derived as follows:

$$\frac{x - x_w}{d_x} = \frac{y - y_w}{d_y} = \frac{z - z_w}{d_z} \tag{7}$$

where

$$\begin{pmatrix} d_x & d_y & d_z \end{pmatrix}^T = \mathbf{O_c} - \mathbf{p_w} \tag{8}$$

As the IR LED unit on the horizontal plane ($z = c$: constant), the intersection of this plane and the line expressed by (7) derive the coordinate $(X_w.Y_w)$ of the IR LED unit in the world coordinate system as:

$$X_w = \frac{(c - z_w)d_x}{d_z} + x_w \tag{9}$$

$$Y_w = \frac{(c - z_w)d_y}{d_z} + y_w \tag{10}$$

C. Derivation of Position and Orientation of AGV

A procedure to determine the position and orientation of the robot with respect to the world coordinate system is as follows:

- We arranged the IR LED units on top of the AGV as shown in Fig.4, where x-axis of the AGV internal frame coincided with the line segment on which the LED Unit 1 and Unit 2, and the y-axis is perpendicular to the x-axis and goes through LED Unit 3.
- The coordinates of the IR LED units on AGV in the world coordinate system are obtained by the above method.
- The position of AGV is represented by coordinates of the origin of the AGV internal frame in the world frame, the orientation by the angle between the X-axis of world coordinate system and the x-axis of the AGV internal frame.

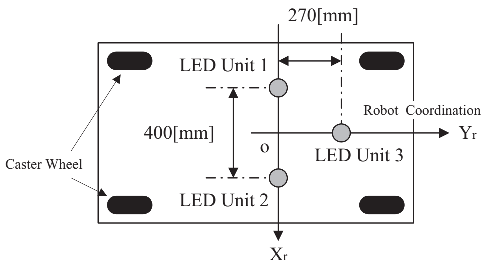


Fig. 4. The arrangement of IR LED units on AGV. The position of the joint, which connects a truck and a tractor unit, is starting position of the robot coordination. (We explain our AGV closely in next section.) This means AGV moves based on this coordination.

D. Positioning Accuracy

We evaluated the accuracy of our proposed positioning system by experiment. Fig.5 shows the result. The x and y axis of the figure corresponded to the X and Y axis of the world coordinate system, respectively. 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 38[mm], and accuracy of positioning system is sufficient to navigate AGV [18].

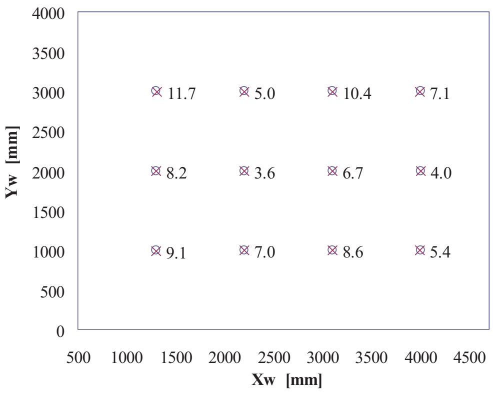


Fig. 5. Measurement error. The units of values are [mm].

III. NAVIGATION SYSTEM

A. 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.6) : the indoor positioning server, the user interface and the AGV system. The indoor positioning server [17] 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.7) 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.7(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.

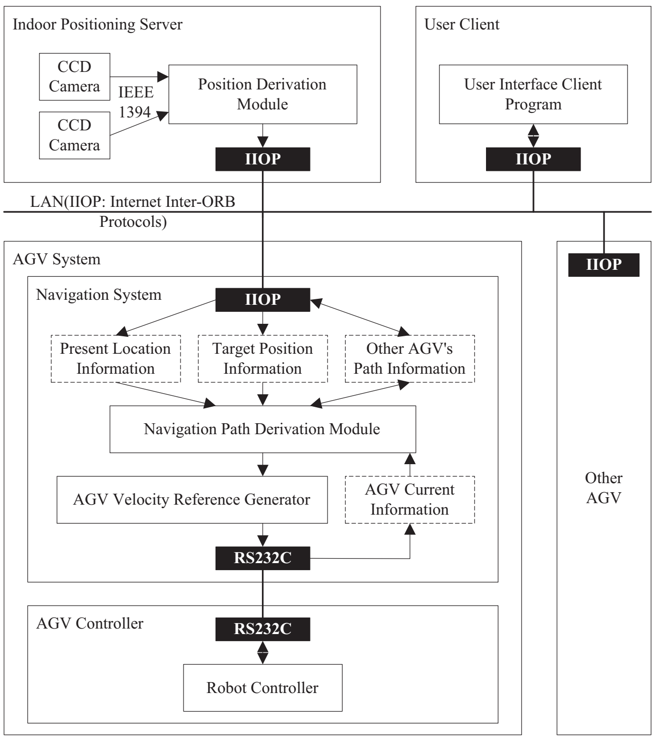
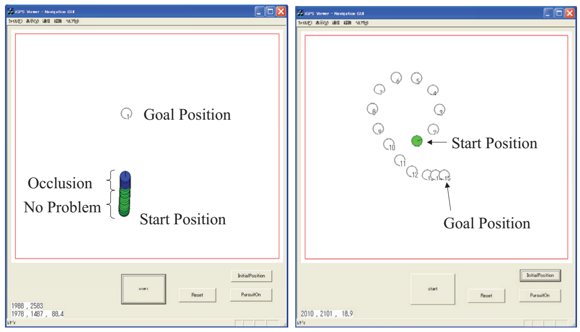


Fig. 6. AGV navigation system consisting of distributed function modules.



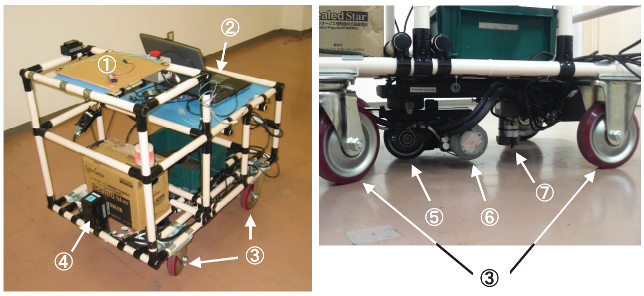
(a) (b)

Fig. 7. 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.

B. AGV

Our prototype vehicle is shown in Fig.8. 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.8 (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 indoor positioning system.



(a) (b)

Fig. 8. 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.

C. Control Scheme under 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. By ASME standard, AGV must not exceed 0.15[m] position error [18]. On the other hand, occlusion condition is 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:

- When the positioning server cannot detect the LED marker suddenly, it send occlusion signal to the target AGV system.
- If AGV receive this signal, AGV continues to run with odometry.
- 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 (11) and (12).

$$v_{ref} = \begin{cases} v_{ref}^{org} & \left(if \quad v_{ref}^{org} < v_{ref}^{od} \right) \\ v_{ref}^{org} & \left(if \quad v_{ref}^{org} > v_{ref}^{od} \right) \end{cases} \tag{11}$$

$$v_{ref}^{od} = \sqrt{2a_{b\max}\left(e - s \cdot e^{od} \cdot t^{od}\right)} \tag{12}$$

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.8. Between straight path and curve path, the odometry error is different. Therefore, the system should select appropriate coefficient by navigation path.

Fig.9 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 under occlusion condition.

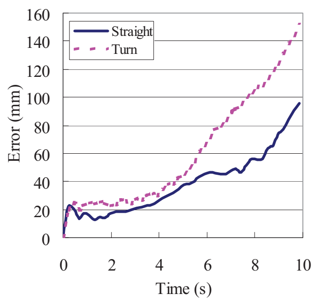


Fig. 9. Odmetry error. The Vehicle runs at 40[m/min].

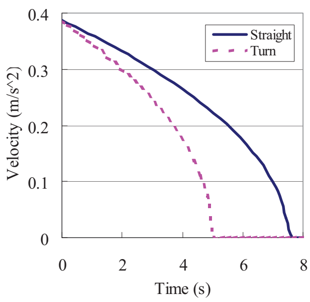


Fig. 10. Reference Velocity.

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. Using two cameras, AGV can receive its positioning information all over this room.

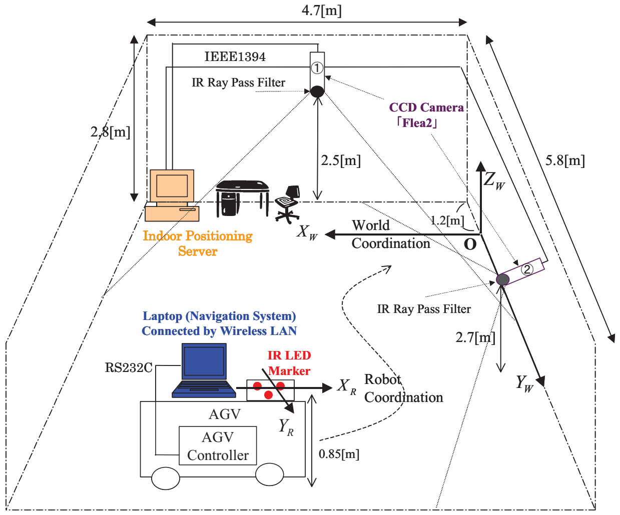


Fig. 11. Experimental Setup. There are two overhead cameras in this room to navigate AGV all over this room.

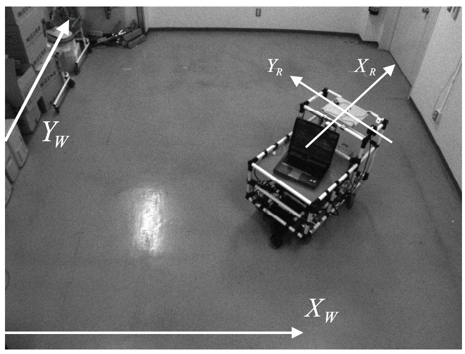


Fig. 12. Pictures of the camera (1) without IR Ray Pass Filter. During experiments, IR ray pass filter is attached to the camera, of course.

B. Occlusion Test

In this experiment, AGV moves along a path as shown in Fig.13. During experiment, we hide LED marker of AGV twice and verify our control system.

The experimental result is Fig.14. 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, ocdometry scheme under collusion condition is effective.

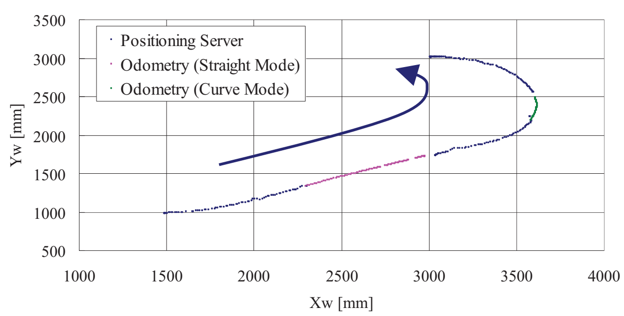


Fig. 13. Tracks of AGV. Pink and green lines show the occlusion condition.

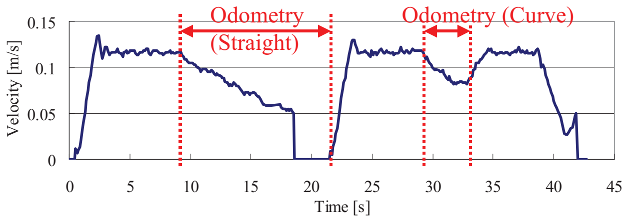


Fig. 14. The velocity of AGV. Our AGV stops using electro-magnetic brakes, thus, its velocity becomes zero suddenly before it stops.

C. *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.15. 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.

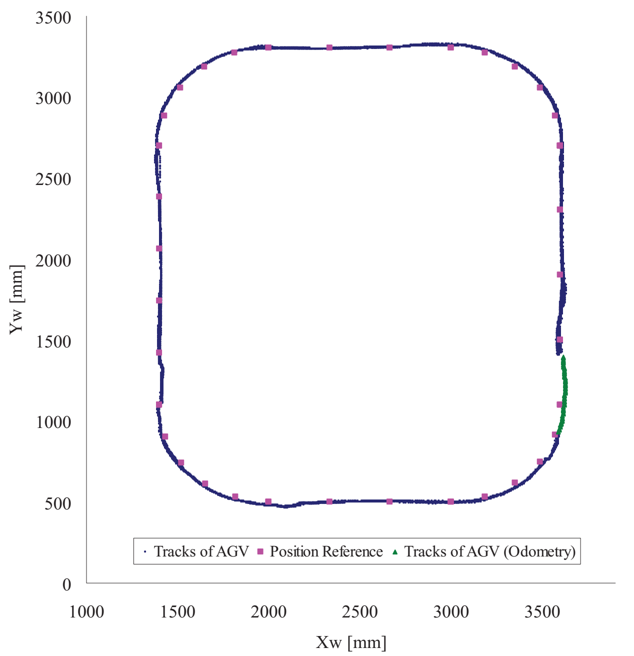


Fig. 15. 60 trajectories of AGV. Green line shows that our AGV moves using occlusion mode. These trajectories are calculated using information of positioning server and odometry information of AGV.

V. Conclusion

This paper introduces the AGV navigation system which realizes multiple vehicles navigation using high accuracy localization scheme with overhead cameras with IR pass filters and LED markers on target vehicle. The advantageous of an intelligent infrastructure over a self-contained vehicle is discussed. Based on these discussions, we describe the design policy of our AGV system and its implementation. In the duration test, our AGV successfully travels test path 60 times during more than 1 hour even if there is occlusion situation.

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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