Development of robotic transportation system -Shopping support system collaborating with environmental cameras and mobile robots -

Nobuto MATSUHIRA, Fumio OZAKI, Seiji TOKURA, Takafumi SONOURA, Tsuyoshi TASAKI, Hideki OGAWA, Toshiba Corporation, Kawasaki, Japan
Masahito SANO, Akiko NUMATA, Toshiba TEC Corporation, Mishima, Japan
Naohisa HASHIMOTO, Advanced Industrial Science and Technology, Tsukuba, Japan
Kiyoshi KOMORIYA, Tokyo Metropolitan Industrial Technology Research Institute, Tokyo, Japan

Summary

A robotic transportation system for shopping assistance has been developed. The system consists of a guidance robot, a cart robot, and environmental cameras. The guidance robot is an autonomous mobile robot with a position localization function, the cart robot with a shopping basket can follow the guidance robot, and environmental cameras can detect the robot and humans. A verification test has been performed in the test environment assumed for a food store. The guidance robot was able to guide the person to his/her desired place and to follow the person, and the cart robot was able to carry the articles while a shopping demonstration. Furthermore, safety technologies in the environment where robots and humans co-exist have been developed.

1 Introduction

Recently service robots have been developed for the daily life environment [1]-[6]. Here, a robotic transportation system has been developed that guides or follows a person and moves autonomously, in order to realize a robot system that helps a person in his/her daily life environment as distinct from industrial environments where robots are already working [7]. We focus on the development of a mobile robot platform applicable for multi-purpose tasks and the development of a robotic transportation system that works safely in an environment where robots and humans co-exist. We have developed a prototype robot system that supports the elderly and those with disabilities in retail environments such as shopping malls, supermarkets and home centres. Recently, such big facilities have become prevalent in Japan. It is difficult for customers, especially the elderly, to know where the articles are placed and to walk widely with a shopping cart. Furthermore, we have developed the basic technologies applicable to the various tasks such as an information service for shopping, patrolling, replenishing products, and cleaning the mall or other large retail facility. The system consists of an autonomous mobile robot and a cart robot, and environmental cameras in the store. The aim of the robotic system is also to increase versatility as a transportation system. This paper describes the concept, the whole system, and the results of the verification tests in the experimental setup simulating a retail store.

2 System configuration

The robotic transportation system consists of an autonomous guidance mobile robot that can go to the destination autonomously and a cart robot that carries a shopping basket containing purchases, and a camera system mounted in the store that measures the robots and customers positions in the store. The cart robot follows the guidance robot. During shopping, the guidance robot follows the customer, and the cart robot follows the guidance robot. In future, the guidance robot and the cart robot may be combined in a single robot. An application image for a retail store is

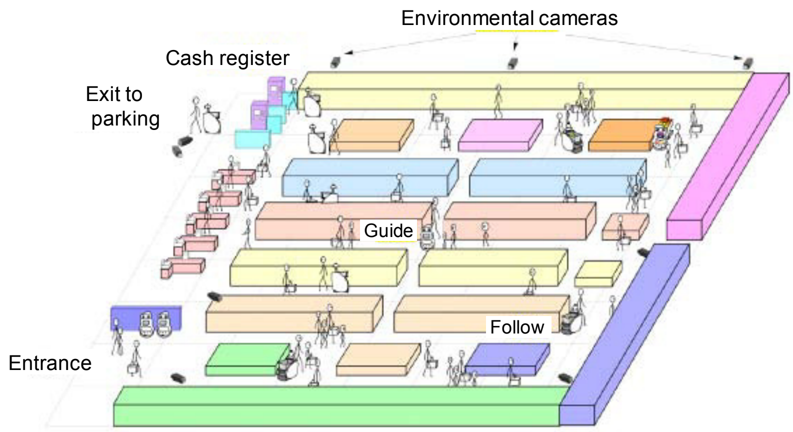


Figure 1 Application image of the robotic transportation system

ISBN 978-3-8007-3273-9

shown in Fig.1. At the entrance, a customer picks a shopping support robot using a membership card. During shopping, the robot guides him/her to the desired place, carries articles and follows him/her, and the positions of the robot, the customer, and other customers are managed by the environmental cameras in the store to ensure safety. At the checkout, the robot automatically calculates the charge and carries the purchases to the parking lot.

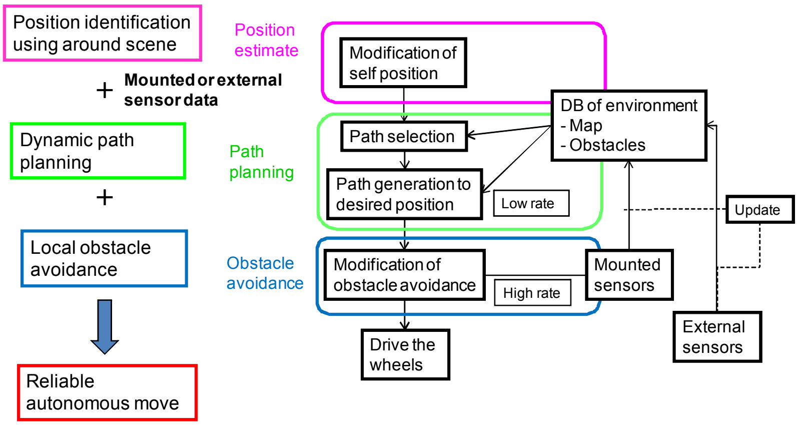


Figure 2 Control architecture of the guidance robot system

2.1 Guidance robot system

The guidance robot requires functions to guide a customer to his/her desired place and follow the customer. The following technologies have been developed. Multi-control layer architecture with global and local viewpoints for a mobile robot is effective to realize the safe and stable motion in the environment where the situations are changing frequently such as a shopping mall.

(1) A three-layer-architecture — consisting of a self-localization layer, a dynamic path planning layer, and a motion control layer — for the autonomous mobile robot has been developed. The architecture is robust with respect to change of environmental conditions as shown in Fig.2. Owing to the architecture, it is possible not only to execute local object avoidance in the motion control layer, but also to make a global behaviour plan using information of the whole environment in the upper control layer.

(2) Self-localization layer

A fast estimation method of self-position localization that uses trackable invariants for rotation and scale size by an omnidirectional camera has been developed. Furthermore, the estimated self-localization accuracy was improved by the environmental map matching method using a laser range finder (LRF) and a position compensation method using the cameras mounted in the environment.

(3) Dynamic path planning layer

A dynamic path planning method has been developed using a map management module updatable by information both from sensors mounted on the robot and in the environment. As a result, the calculation cost was reduced and real-time path planning was realized.

(4) Motion control layer

An unknown object avoidance method employing LRFs and ultrasonic sensors has been developed based on an anisotropic pseudo-distance reflection model which changes the distance sensibility according to the distance to objects. Thus, the sensibility is raised when the robot moves close to the object. Smooth

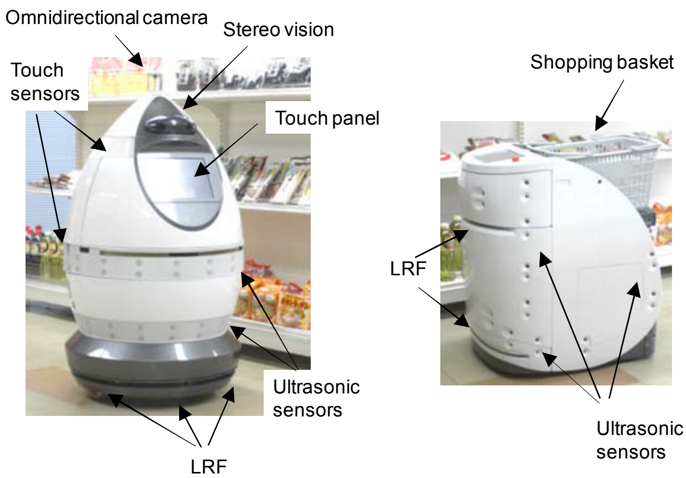
Table 1 Specifications of guidance robot

Size	1200 mm(H), 650 mm(Diameter)
Weight	75 kg
Operating time	1.0 hr. by battery
Mobile velocity	1.0 m/s (Max.)
Step height	Up to 10 mm
Vision sensor	Stereo camera Omnidirectional camera
Distance sensor	LRF(4 sets) Ultrasonic sensor(32 sets)
Contact sensor	Touch sensor, Force sensor

Functions

- Menu selection for motion modes via a touch panel
- Person following mode and autonomous navigation mode to go to the desired place in the store
- Dynamic path planning in cooperation with a map management module
- Self-localization by an omnidirectional camera and LRFs
- Dynamic and static obstacle recognition by an omnidirectional camera during travelling*
- Collision prevention and object avoidance using LRFs and ultrasonic sensors
- Collision absorbing control using a force detection ring*
- RTC modules for communication with the inner system and the outer system including the cart robot and the environmental camera system. RTC modules are shown in Fig.8.(see 4.1)

* The function has been verified by a functional model of the guidance robot.



(a) Guidance robot (b) Cart robot

Figure 3 Developed guidance robot and cart robot

ISBN 978-3-8007-3273-9

object avoidance motion during high-speed motion was realized within the high-speed process at 1 ms sampling rate. A person following method has also been developed combining LRFs and image processing by a stereo camera [8]. Person following motion was realized with a function that detects a person, who the robot follows in a test environment. An overview of the guidance robot is shown in Fig.3 (a) and its specifications are shown in Table 1.

2.2 Cart robot system

The cart robot equipped with a shopping basket should avoid moving obstacles such as wagons and shelves when it follows the guidance robot in a store. In addition, to facilitate practical use, the cart robot is designed to be as simple as possible, thus it has been developed as follows. To realize the main function, namely, following the guidance robot with a shopping basket in stores, the mobile base mechanism of the cart robot designed in common specifications of the guidance robot and the centre of the rotation is designed at the front in its stretched body shape to be long backward for loading baskets at the rear. As primary sensor system to detect obstacles, there is an array of ultrasonic sensors: 32 sets of ultrasonic sensors connected by a serial bus are used. In addition, 3 sets of LRFs are collaboratively used as secondly sensor system. The desired position of the cart robot is generated by the measurement of the relative position of the guidance robot by the LRFs.
The ultrasonic sensors comprise a subsystem connected to a control PC via USB 2.0. The characteristics of the detection distance are changed by setting positions and fast measurement was realized while restraining self-interference by optimizing the transmission sequence. A path generation algorithm has been developed to ensure that the cart robot smoothly avoids obstacles difficult to be detected by LRFs, such as shopping carts and wagons with thin legs, while following the guidance robot. The direction in which the cart robot travels is decided by the evaluation of the polar histogram generated from combining the ultrasonic sensor data and LRF data based on VFH algorithm [9]. An overview of the cart robot is shown in Fig.3 (b) and its specifications are shown in Table 2.

Table 2 Specifications of cart robot

Size	850 mm(H)-550 mm(W)-785 mm(L)
Weight	45 kg without payload
Operating time	1.5 hr. by battery
Radius of pivot turn	525 mm
Mobile velocity	1.2 m/s (Max.)
Step height	Up to 20 mm
Load capacity	10 kg
Distance sensor	Ultrasonic sensor (32 sets), LRF (3 sets)
Contact sensor	Bumper sensor (5 sets)
Functions - Following the guidance robot with a 10 kg load and collaboration with the guidance robot during a shopping sequence - Automatic return to the home position - Consisting of RTC modules as shown in Fig.8.	

2.3 Environmental camera system

An environmental camera system has been designed to develop a redundant system to monitor the positions of the guidance robot, the cart robot, and people in the store. These positions are detected not only by the sensors mounted on the mobile robot but also by cameras attached to the ceiling, which work as an environment camera system. Using images captured by environmental cameras, the recognition module obtains position information of people by image processing based on background subtraction. A person tracking algorithm is applied to images captured by an environmental camera, it continues tracking to the views of the adjacent cameras. The recognition module

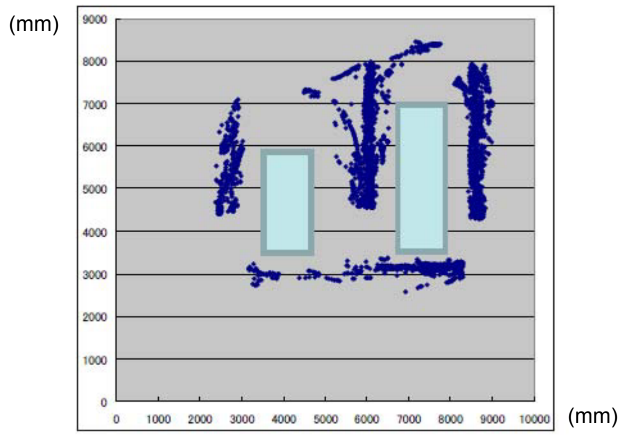


Figure 4 Result of robot position from environmental cameras

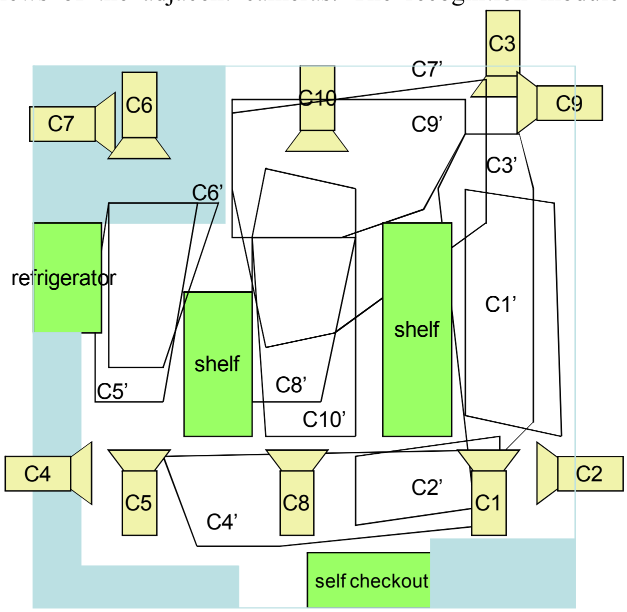


Figure 5 Camera layout and visible area(C1'-C10') in the experimental room

ISBN 978-3-8007-3273-9

obtains the position of the guidance robot by image processing that combines background subtraction and detection of LED markers from the camera image. This system has the data about height of the mobile robot. By utilizing the data, it estimates their positions with high-precision. The image processing computers send the time and the position data of the robot to the server. The result is shown in Fig.4. Here, boxes indicate the shelves and dots indicate the position trajectories. Fig. 5 shows the layout of the environmental cameras, the visible areas from the cameras are shown as polygons (C1'-C10'). Ten cameras were installed in the test environment.

The developed system collects the positions of people and the guidance robot detected by the cameras in the environment and sends the information to the robot server PC through the RT middleware. The database constructed on the PC functions as a robot server of the robotic transportation system.

3 Safety in environments where humans and robots co-exist

This chapter discusses safety in environments where humans and robots co-exist. A multilayer control system of the safety for the guidance robot has been developed that monitors the overview by environmental cameras, obstacle detection and avoidance control using cameras and LRFs installed on the robot, and contact force control in the case of contact with the person by touch sensors and a force sensor installed on the guidance robot.

- A dynamic path generation method using environmental cameras has been developed.
- A dynamic and static object detection method during travelling has been developed by employing an omnidirectional camera.
- A motion control method in 1 kHz has been developed; when an obstacle is detected, the robot is prompted by information captured by ultrasonic sensors and LRFs to avoid it or to stop.
- A force control method has been developed that controls the contact force to the desired force to absorb the acting force by the detection mechanism using a force sensor when the force acts on the robot. Here, a force detection ring was newly developed. It was attached around the body of the robot like a bumper sensor in the function model of the guidance robot previously developed. The desired force was 10 N and human density was four people in 3 m^2. This method was useful in the crowded conditions.
- Furthermore, in the cart robot, for which an inherently safe design (light weight / a low centre of gravity, outer shape without projections) is applied, a speed control system using the sensor system consisting of ultrasonic sensors, LRFs, and bumper sensors according to the situation, has been developed. A mechanism that can move the load of a loaded cart to stabilize the cart posture in the case of an emergency stop has been developed.

4 Experiments

4.1 Experimental environment

The experiments have been done using an experimental room at Toshiba Tec Corp. simulating a store in which ten cameras were installed. The cameras measure the positions of people and robots. These position data together with the data detected by the guidance robot and the cart robot are accumulated in the server PC that managed the environmental data. In the experimental environment, the guidance robot and the cart robot moved and avoided obstacles in the room to ensure the safety of people. The developed system is shown in Fig.6. The environmental map and verification scenario are shown in Fig.7. The following technologies have been developed for the system integration.

(1) System integration by the RT middleware (RTM)

Software for the control of the environmental cameras, the database on the environment, GUI, the guidance robot and the cart robot has been developed as RTC modules to realize reuse of the software. The whole system consisting of many RTC modules integrated by RTM [10] is shown in Fig.8. 22 RTC modules, shown as green blocks, are connected through the RTM. Here, the RT (Robot Technology) middleware was developed in a national project of Japan.

(2) Synchronization of ultrasonic sensors

To avoid interference of the ultrasonic sensors between the guidance robot and the cart robot, these sensors are synchronized by infrared communication for time sharing. Since the ultrasonic sensor array has been developed as a subsystem with a universal interface (USB2.0), it is easily

Figure 6 Overview of the developed robotic transportation system

ISBN 978-3-8007-3273-9

applied to other systems. The ultrasonic sensor device is of the 40 kHz resonance type for low cost.

4.2 Experiments in a simulated environment

A demonstration of the shopping support was carried out according to the scenario depicted in Fig.7: from (A) register phase where a person is recognised to the guidance robot, (B) following phase and (C) selecting phase where the person selects the articles, to (D) leading phase. The guidance robot has a person following mode and a guidance mode. In the person following mode, the robot, using the stereo camera and the LRFs, follows a person. During shopping, the guidance robot, communicating with the cart robot, autonomously moves to the position where the person can easily put articles in the basket. In the guidance mode, the robot guides the person to the article selected via the touch panel on the robot. The cart robot measures the position of the guidance robot by the LRF, and follows the guidance robot, and supports shopping in collaboration with the guidance robot. The cart robot also has a function for autonomously returning to the home position from the register. The experimental scene is shown in Fig. 9. Fig.9 (a) shows the person following scene, and Fig.9 (b) shows the article input to the basket scene. The robots' arrangement with respect to the person is changed through cooperative control between the guidance robot and the cart robot as shown in Fig.9 (b). The conditions in the experiment were as follows:

- Experimental area: 10 m x 10 m
- Human density: five or six people within 5 m radius are assumed in the store
- Distance between the guidance robot and the cart robot: 0.5 m
- Distance to the people: 1.2 m from the guidance robot during a person following mode
- Step height: 10 mm
- Payload: 10 kg for the cart robot

Furthermore, the dynamic path planning using environmental cameras was carried out. Here, the

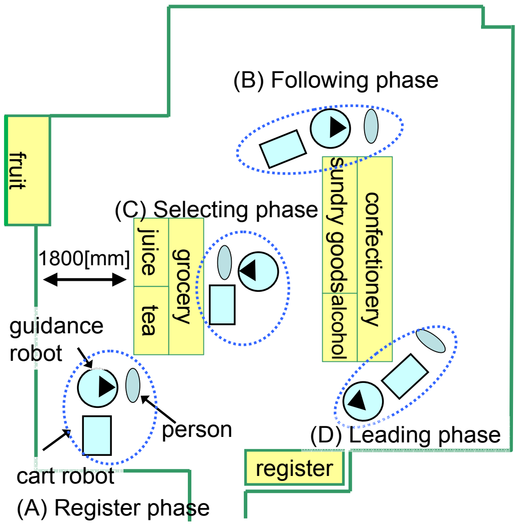


Figure 7 Experimental environment and verification scenario

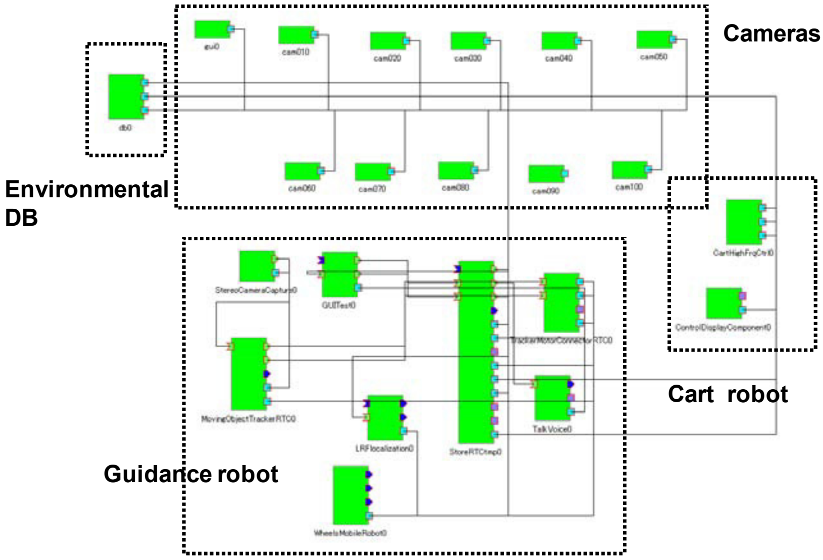


Figure 8 RTC control system of the robotic transportation system

(a)Person following scene (b) Shopping scene

Figure 9 Experimental scene in the simulated store

ISBN 978-3-8007-3273-9

planned path in the motion control layer was modified by the dynamic path planning layer according to the human density. The validity of the dynamic path modification with global information was verified [11].

5 Conclusions

A robotic transportation system that works in environments where people and robots co-exist, such as retail stores, has been developed and the components and functions of the system were introduced. According to the assumed scenario in the shopping, the validity of the robotic transportation system was verified. Furthermore, the important technologies for service robots, including autonomous navigation to destinations, obstacle avoidance, path planning, and safety, that are applicable to other fields have been developed.

Acknowledgement

This research was supported by the New Energy and Industrial Technology Development Organization (NEDO) project for strategic development of advanced robotics elemental technologies.

Literature

[1] W. Burgard, A.B. Cremers, D. Fox, D. H hnel, G. Lakemeyer, D. Schulz, W. Steiner, and S. Thrun: "Experiences with an interactive museum tour-guide robot," Artificial Intelligence, vol. 114, pp. 3-55, 1999.

[2] G. Baltus, D. Fox, F. Gemperle, J. Goetz, T. Hirsch, D. Magaritis, M. Montemerlo, J. Pineau, N. Roy, J. Schulte, and S. Thrun: "Towards personal service robots for the elderly," Proc. of the Workshop on Interactive Robotics and Entertainment (WIRE-2000), Citeseer, 2000.

[3] Hans, M., Graf, B., and Shraft, R.D.: " Robotic Home Assistant Care-O-bot: Past-Present-Future, " Proc. 11th Int. Workshop on Robot and Human Interactive Communication, ROMAN2002, pp.399-404, Berlin, 2002.

[4] R. Philippsen and R. Siegwart: "Smooth and efficient obstacle avoidance for a tour guide robot," IEEE International Conference on Robotics and Automation (ICRA2003), pp.446-451, Taipei, 2003.

[5] Nobuto Matsuhira, Hideki Ogawa Takashi Yoshimi, Fumio Ozaki and Hideaki Hashimoto, Hiroshi Mizoguchi: "Research and Development for Life Support Robots that Coexist in Harmony with People," Mobile Robots: Towards New Applications, intechweb.org, pp.287-308, December, 2006.

[6] Takashi Yoshimi, Manabu Nishiyama, Takafumi Sonoura, Hideichi Nakamoto, Hirokazu Sato, Fumio Ozaki, Nobuto Matsuhira, Hiroshi Mizoguchi: "Development of a Person Following Robot with Vision Based Target Detection," The 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2006), pp.5286-5291, Beijing, 2006.

[7] S. Tokura, T. Tasaki, T. Sonoura, M. Sano, N. Matsuhira and K. Komoriya: "Robotic Transportation System for Shopping Support Services," 18th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN2009), TuBH.3, Toyama, 2009.

[8] T. Tasaki and F. Ozaki: "Obstacle Classification and Location by Using a Mobile Omni-directional Camera Based on Tracked Floor Boundary Points," The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2009), pp.5222-5227, St. Louis, 2009.

[9] J. Borenstein and Y. Koren: "The vector field histogram – fast obstacle avoidance for mobile robots," IEEE Journal of Robotics and Automation, Vol. 7, No. 3, pp.278-288, June 1991.

[10] Noriaki Ando, Takashi Suehiro, Kosei Kitagaki, Tetsuo Kotoku, Woo-Keun Yoon: "RT-Middleware: Distributed Component Middleware for RT (Robot Technology)," Proc. of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2005), pp.3555-3560, Edmonton, 2005.

[11] Seiji Tokura, Takafumi Sonoura, Tsuyoshi Tasaki, Junji Oaki, and Nobuto Matsuhira: "Development of robotic transportation system -Dynamic path modification with global information-,"Proc. of the 2009 JSME Conference on Robotics and Mechatronics (ROBOMEC2009), 1P1-D05, Fukuoka, 2009 in Japanese.

ISBN 978-3-8007-3273-9