Cooperation of Distributed Intelligent Sensors in Intelligent Environment

Joo-Ho Lee, *Member, IEEE*, Kazuyuki Morioka, *Student Member, IEEE*, Noriaki Ando, *Member, IEEE*, and Hideki Hashimoto, *Member, IEEE*

***Abstract*—We propose an architecture of intelligent space based on distributed intelligent sensors. Intelligent space is an environmental system able to support humans in informative and physical ways. Since an intelligent space should adapt to the various sizes and shapes of an environment, an architecture based on distributed intelligent sensors is designed. The proposed architecture satisfies not only scalability but also reconfigurability, modularity, easy maintenance, and affinity problems in building an intelligent space. Intelligent sensors are distributed among a space and they provide functions based on position information. According to the particular situation, cooperation among intelligent sensors or cooperation among function modules in the intelligent sensors are performed. Selected demonstrations are described in the paper.**

***Index Terms*—Distributed system, intelligent space, ubiquitous computing.**

I. Introduction

INTELLIGENT space was proposed by Lee [15] of the University of Tokyo, Tokyo, Japan as an environmental system able to support humans in informative and physical ways. Most intelligent systems interact with humans in a passive space; but in an intelligent space, being a space that contains human and artificial systems, the space itself is an intelligent system. Human and artificial systems become clients of the intelligent space and simultaneously the artificial systems become agents of the intelligent space. Since the whole space is an intelligent system, intelligent space, as a spatial system, is able to easily monitor and provide services to clients. Specific tasks, which cannot be achieved by just the intelligent space, are accomplished by utilizing its clients. For example, an intelligent space utilizes computer monitors to provide information to humans, and robots are utilized to provide physical services to them as physical agents. If necessary, robots as well as humans are supported by an intelligent space. When a robot lacks the sensors to navigate around an intelligent space, the robot is treated as a client of the intelligent space and the information lacked is provided to the robot by the intelligent space.

An intelligent space has two roles in respect to a robot working in it. One is the enlargement of ability, the other is resource sharing. Generally an intelligent robot has its own sensors and it is designed to move without help from outside. However, even an intelligent robot has limitation of ability; for example, when a person in different room needs the help of the robot, the robot has difficulty ascertaining that there is a request. Even though it has good sensors, this kind of problem cannot be overcome. An intelligent space has a role as an extended sensor for the robot and enhances the ability of the robot to receive the request form a distant place. Resource sharing is valid when more than one robot uses the resources of an intelligent space; and robots can decrease their common resources such as sensors to localize, sensors to detect target objects, devices to interact with humans, etc. However, an intelligent space does not aim to get rid of sensors or autonomy from robots; rather, it supports a robot by providing the resources it lacks to act as a normal robot, while helping a robot with good resources to act as an even better robot [17].

The ultimate goal of our intelligent space project is to accomplish an environment that comprehends human intentions and satisfies them. Such a system appears difficult to achieve, since a many functions must be prepared and human-like intelligence is required. Though such a complete system cannot be immediately achieved, we are convinced that a useful system can be achieved utilizing current technology assisted by proper system integration.

This paper aims to propose an architecture of intelligent space based on distributed intelligent sensors. Since an intelligent space is a spatial system, its size and shape are not predetermined or restricted, intelligent sensors are therefore proper elements with which to build such kinds of system. If sensors are directly connected to a centralized system and the system processes all data for the sensors, the sensor cannot really adapt to alternations in target environments. Intelligent sensors, however, differ from conventional ones in their ability to process large amounts of data close to the source, and in their ability to communicate bi-directionally. These features help to build intelligent spaces in various shapes and sizes.

We will describe a space that is watched by many distributed intelligent sensors and the sensors cooperate with each other in this intelligent space. By cooperation among intelligent sensors, the service of an intelligent space can be provided globally and seamlessly in a space. An intelligent sensor in an intelligent space watches a fixed local area and it provides position based data continuously for high level and complex functions.

In Section II, intelligent space and related works are introduced. An architecture for intelligent sensors for use in intelligent spaces is proposed and basic functions are described in Section III. Section IV shows how intelligent sensors cooperate

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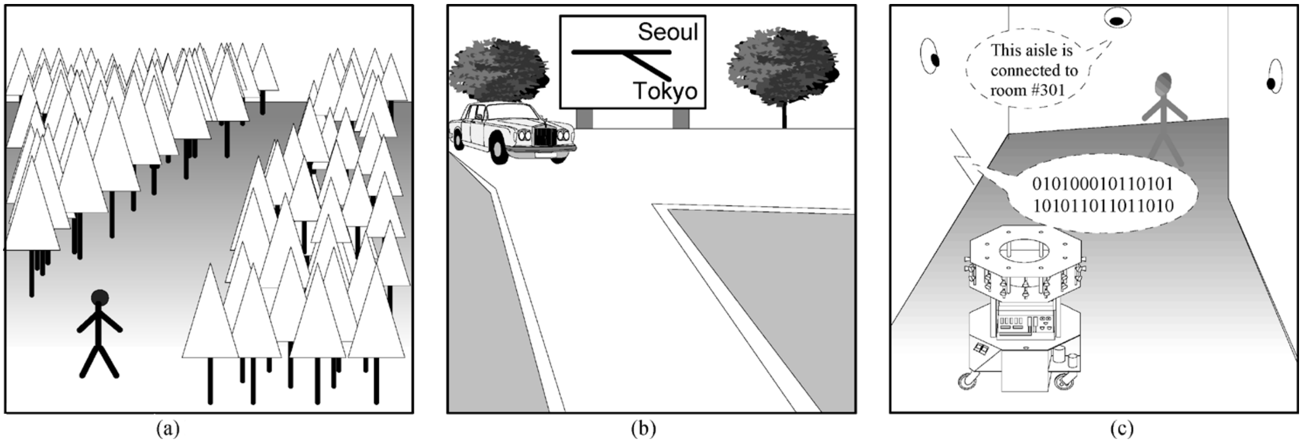


Fig. 1. Classification of spaces. (a) Potential information space. (b) Passive information space. (c) Active information space.

in intelligent space. Future works and conclusion are described in Section V and VI, respectively.

II. Intelligent Space

A. What Is Intelligent Space?

In recent years, computer and computer networks have proliferated and become an important part of most people's daily lives. Not only diverse research on computers and computer networks, but also computer aided research has been greatly advanced over the last several years. Intelligent environments are one example. Intelligent environments are able to monitor what is occurring in themselves, to build models, to communicate with their inhabitants and to act on the basis of decisions they make. Especially the capability of the environment to act as a context-sensitive user interface (e.g., to respond to gestures) and react in certain situations (e.g., accidents, intruders) promises a range of application scenarios such as intelligent hospital rooms, offices, factories, asylums for the aged, etc. We concluded that such systems are the natural product of technological progress and since 1996 have been promoting the concept of "intelligent space."

The main purpose of intelligent space is the accomplishment of human-centered systems. Many intelligent systems have already been developed. However, when a human wants to use such a system, that person must first learn how to operate the system. Moreover, since most systems have no mobility, humans should move to operate them. In our concept of intelligent space, humans can express their will in intuitive actions or unconscious usual actions so that the human does not need to learn how to use intelligent space. Since humans are in an intelligent space, humans do not have to move around to interact with it. Even other intelligent systems (e.g., computers, VCRs, air conditioners, etc.) can be operated in an intelligent space, as long as they are agents of that intelligent space. To achieve intelligent spaces, many functions have been developed: such as autonomous topological map building by watching humans [1], inference of the internal state of humans by motion tracking [2], and mobile robot control for following humans [3]. Particularly in [3], it was found that robots, the same as for humans, can be supported by intelligent space.

B. Classification of Space

According to affordance [4], we classified spaces into three classes; as shown in Fig. 1. In Fig. 1(a), there is a road in the middle of a forest and people can recognize it from their experience. Only local and simple information of the space is afforded to the client of the space. Most natural environments belong to this type of space. We name it a "potential information space." In Fig. 1(b), people can know where the roads lead to from a road sign. Whether there is a road sign or not, it does not change the fact of where the roads lead to. A space with artificial signs is named a "passive information space." Artificial signs help people to perceive affordance of the space that cannot be found in a potential information space. However, to comprehend the meaning of an artificial sign, a user needs to study it in advance of that understanding. In Fig. 1(c), active devices are distributed in the space and inform affordance of the space in a form that is relevant for clients. Therefore, the clients of the space do not need to study to perceive affordance of the space in advance. This space is named an "active information space." In this space, the clients are able to request information of the space and the space replies to the requests. The first two spaces are common in our daily life. However, the last space is rarely found in our environments. Intelligent space belongs to this active information space. Due to its feature that the space adapts itself to clients, intelligent space is a soft environment to humans but also to artificial systems including robots. It is noticeable that while the affordance of the roads in each space is the same, there is a difference in how easily that affordance is perceived by clients. From the classification, it becomes clear that intelligent space is an extension of the progression of our environment.

C. Required Architecture of Intelligent Space

The most important required property of intelligent space is scalability of the system. Since intelligent space is a spatial system, it must be adaptable to be a space of any shape or size. Coherently, intelligent space should be easily applicable to a general environment where people live. Therefore, a large change in that environment to apply the concept of intelligent space is undesirable. Incompatibility also should be considered since the environment is not for the benefit of the system, but for the people who inhabit it. Designers of intelligent spaces should make efforts to ensure people do not feel incompatible with the system.

From the standpoint of developing intelligent space, several points need to be satisfied. Since functions of intelligent space are developed continuously, new functions or revised functions should be easily applied to intelligent space. If both hardware and software are made as modules, intelligent space might be easily renewable. Additionally, intelligent space should also be easily administrable.

III. Related Works

Integrated intelligent environments have their origin in ubiquitous computing. In 1991, Weiser introduced the area of ubiquitous computing that people can use computational resources everywhere in environments [5]. Ubiquitous computing promises more than just infrastructure, suggesting new paradigms of interaction inspired by widespread access to information and computational capabilities.

From the mid 1990s, intelligent environment research began to appear. Since then, recognition and awareness of people in environments have been more focused on intelligent environment research rather than other ubiquitous computing research. Furthermore, intelligent environment is apt to free people from artificial devices around their body. Small mobile devices are often used in ubiquitous computing for accessing computers, but intelligent environments pursue human-centered system. Since the origin of intelligent environments is ubiquitous computing, its research is proliferated from computer science fields. Several famous corporation laboratories perform research on various fields related to intelligent environments [6]–[8].

Not only for interaction between human and computer resource, but also for communication between people and people, intelligent environments are considered as tools [9], [10].

At several research groups, intelligent environments are developed for specialized purpose. A group at the Georgia Institute of Technology, Atlanta, has designed and extensively used a particular instrumented environment called classroom 2000 [11]. They actually utilized the system in a real university classroom for three years. MIT Media Laboratory developed the KidsRoom, a perceptually-based, interactive, narrative play space for children [12]. They integrated high-end technology to make a space where children can have fun. Sato, from the University of Tokyo, proposed the robotic room to realize a robot system to offer services for human living inside during his or her daily activities in the form of environment [16]. The robotic room thinks much of the configuration of a room which is composed of multiple robot components surrounding the inhabitant. At Stanford University, Stanford, CA, the Interactive Workspaces Project is in progress [18]. The purpose of the project is to explore new possibilities for people to work together in technology-rich spaces with computing and interaction devices on many different scales.

A lot of works on intelligent environment have been done. However, most of works are focusing on developing functions of intelligent environment. There are only a few works that propose architecture of intelligent environment in consideration of adapting it to a real environment.

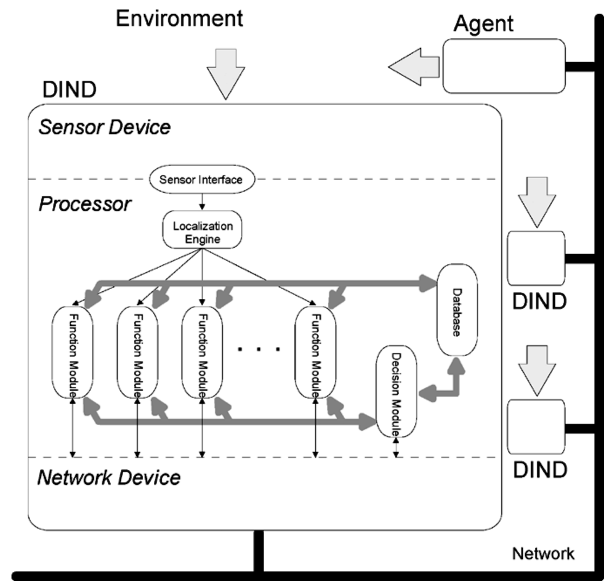


Fig. 2. Fundamental structure of DIND.

IV. Distributed Intelligent Networked Device

To satisfy the enumerated conditions of architecture required for intelligent space, a distributed intelligent networked device (DIND) is proposed. A DIND is an intelligent sensor of a novel architecture for intelligent space. Simply by installing DINDs around an existing environment turns it into an intelligent space.

A. Structure of DIND

Normal environment is changed into intelligent space by installing DINDs. DINDs, a basic element of the intelligent space, consist of three basic elements. The elements are sensor, processor, and communication parts. DINDs use these elements to achieve three functions. First, the sensor monitors the dynamic environment, which contains people and robots. Second, the processor deals with sensed data and makes decisions. Third, DINDs communicate with other DINDs or agents through networks.

Fig. 2 shows the basic structure of a DIND and the intelligent space based on it. Since DINDs are connected to networks, DINDs are able to communicate with each other through networks. A DIND monitors the local environment with its sensor which is assumed to be a vision sensor in the current architecture. Data from the sensor are processed in the processor part by a localization engine and position information of possible targets is generated. The possible targets are considered as mainly heads or hands of humans or robots. This position information itself is meaningless because the positions are based on the two-dimensional (2-D) coordinates of the sensor, but the position information is utilized by function modules after processing by the localization engine. Function modules store/refer data to/from databases in DINDs. A decision module decides which function modules to activate according to the situations occurring in the space. As shown in Fig. 2, a DIND is able to use

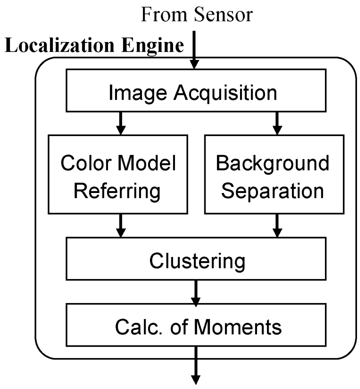


Fig. 3. Localization engine in DIND.

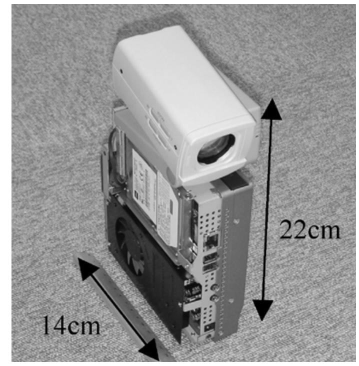


Fig. 4. Photo image of prototype DIND.

networked agents: computer screens for providing information, robots for providing physical services, etc.

In the proposed DIND architecture, all functions are operated based on position information from the localization engine. Position information is indispensable whatever the service provided by intelligent space. For example, if the function module is face recognition, face recognition is performed in the area of the neighborhood of the position of a possible target identified from the localization engine. Fig. 3 describes the current structure of the localization engine. After acquiring a vision image from the DIND sensor, color modeling referring and background separation are performed in parallel. The color model referring process searches over the image and finds target colors; skin color of a human and color barcodes of robots. The background separation process compares the current image frame and adaptive background image frame to find parts of the image that have changed. The overlapped areas of results from both color model referring and background separation are clustered, and calculating the moments of each area generates the position of each of the clusters. The results are sent to function modules to perform their functions based on the results.

B. Merits of Building Intelligent Space With DINDs

Since DIND monitors fix local areas and cope with events that happen within the area, intelligent space is easily constructed by just attaching DINDs around a space. Regardless of the size and shape of a space, intelligent space is achieved by disposing DINDs and, even if the space is altered, adding or redisposing DINDs is all that is required to keep the space as intelligent space. A DIND is a small device and does not require big changes to be made in an environment. Moreover, it does not require much effort to change a space to intelligent space with DINDs.

That a DIND is an intelligent sensor allows for the easy renewal of the functions of a DIND. In previous reports [1], [2], the functions were deeply involved with the system and so it was almost impossible to renew the system without renewing it all. However, with DINDs, since all functions are made as modules, without any influence on or from other function modules, a function can be easily renewed. DIND hardware as well as software is made modular (sensor, process, and network modules) so that it can be replaced easily.

Another important feature of DINDs are their networks. Since DINDs are connected to a network, a user can access DINDs through that network and even though there are lots of DINDs in a space it takes little time replacing a function module in all the DINDs. Networked DINDs also provide features for resource sharing. The fact that DINDs are distributed in intelligent space provides sensory resources; and processing resources are also distributed around the space. Artificial clients including robots in the intelligent space are able to use the DIND resources through networks as if the resources are parts of the body of clients. This feature leads to resource saving since artificial clients of an intelligent system can employ resources that tend to overlap with other clients of a DIND.

C. Prototype DIND in Current Stage

A prototype of a DIND was developed. A cheap IEEE1394 interfaced CCD camera was adopted as the sensor part. For the processor, an industrial standard Celeron 2.7-GHz PC is used and a general 100baseT LAN card is used as the network device. Linux was adopted as the operating system for DINDs. All software algorithms are written in C++ and the GUI parts written in TCL/TK. The total cost to build a prototype DIND was about \$500 dollars U.S. Fig. 4 is a photo image of the prototype DIND.

V. Cooperation Among DINDs

Even though one DIND is able to provide services with its function modules, cooperation with other DINDs is necessary to achieve an intelligent space. Since one DIND monitors a restricted area, to provide services seamlessly and continuously through an entire space, DINDs should cooperate with each other. Moreover, in some functions, information from other DINDs is required so that cooperation among function modules can be prepared.

A. Localization of Humans

To localize a human in a space, at least two vision sensors are required. This means that a function module to localize humans requires information from other DINDs. Fig. 5 describes the composition of a function module for localizing humans. To reconstruct the three-dimensional (3-D) position of a human in an intelligent space, the human localization function module matches local clusters and clusters from other DINDs. During

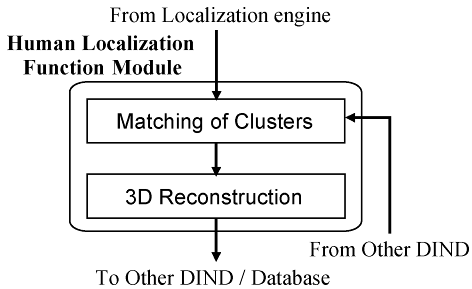


Fig. 5. Human localization function module.

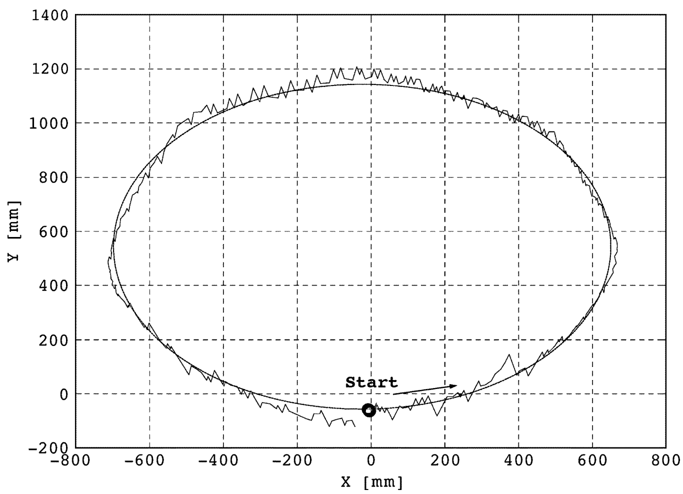


Fig. 6. Trajectory of a walking human monitored by DIND.

the cluster matching process, noises are filtered out in consideration of size, position, epipolar conditions, etc. On the basis of the calibration data of each DIND, including the absolute position of DINDs in intelligent space, 3-D reconstruction is performed. Fig. 6 shows an example of localizing a human in intelligent space. A man walked along a circular path with a diameter of about 1.4 m and the intelligent space traced him. The dotted line is the ideal path that the man tried to walk along.

B. Localization of Robot

Unlike the case of localizing humans, to localize a mobile robot in an intelligent space, only one DIND is required. Because the heights (z axis) of the targets are known, only one camera is needed for precise 3-D reconstruction. The information on heights of the robots and their identification color codes is stored in a DIND database in the intelligent space. Fig. 7 shows a robot with color codes. Each robot has a different arrangement of color codes so that a DIND is able to identify a particular robot and to calculate the facing direction and position of the robot.

This procedure is shown in Fig. 8. Based on the height of the robot from the database, the 3-D positions of the color codes are calculated. According to the DIND database, each color code, placed around a mobile robot, is checked. If a color-code, which is not in the database, is detected, it is removed from the candidates. From this process the DIND is able to recognize which robot it is and localize the robot by referring to the database. To get rid of errors, 2-D Euclidean distances between detected

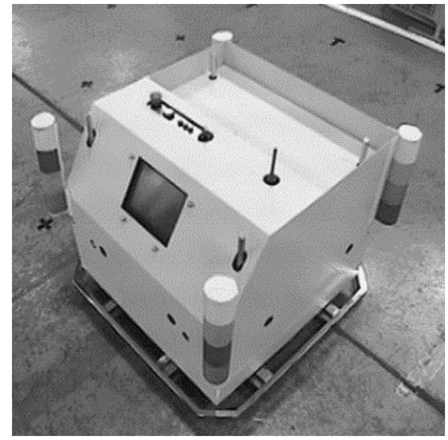


Fig. 7. Mobile robots with color bars.

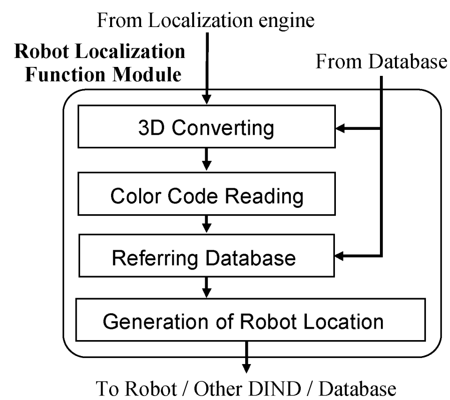


Fig. 8. Robot localization function module.

Fig. 9. Localization of a robot.

color codes are checked. If the distance is too long or too short, the detected color codes are neglected. The geometrical relations, stored in the database, are compared between color codes and the robot is localized from the geometrical relations of the color codes.

In Fig. 9, color codes are detected and read by a DIND. Based on the information of color codes in the database, the direction and position of the robot is calculated.

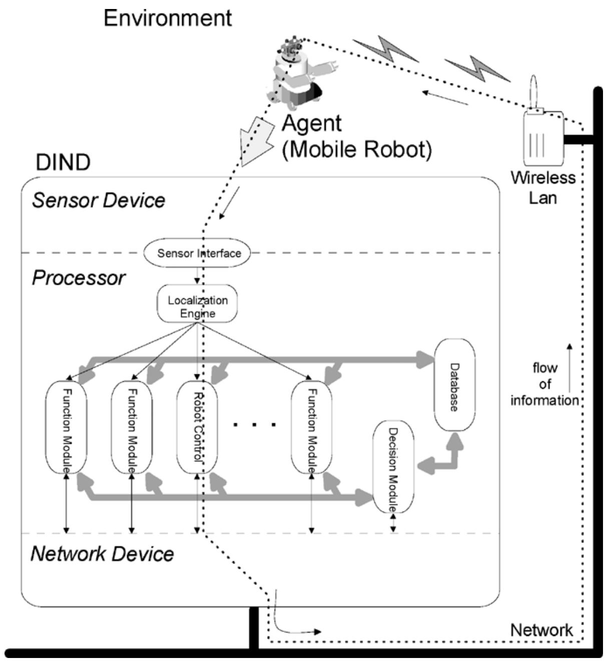


Fig. 10. Mobile robot control loop in the intelligent space.

C. Control of Robot

Mobile robots in intelligent space need neither range sensors to detect obstacles nor positioning sensors to localize themselves. The robots only require passive color bars-codes and a communication device to communicate with DINDs. Due to their communication with DINDs, robots are able to freely use the sensors in DINDs. This is a kind of resource sharing; a feature that leads to low cost robots, since the expensive sensors, such as gyroscopes, laser range finders, etc., are not needed. In intelligent space, robots are both client and agent of the space. As explained above, to provide physical service in intelligent space, a robot is used as an agent of the intelligent space.

A mobile robot control function module produces control input for mobile robots. A DIND senses the mobile robots, and the robot localization function module localizes them. According to the desired path and estimated position, control input for the mobile robots are generated and transferred to the mobile robots through a wireless LAN. The flow of information makes a closed loop, as shown in Fig. 10.

A DIND is an independent device, and its functions, including localization and control of mobile robots, are performed completely within it. Thus, if a mobile robot is moving in the area a DIND is monitoring, the robot is guided without any difficulty. However, to guide robots in a wider area, which a single DIND cannot cover, we define the DIND that has the control authority of a robot as the dominant DIND for the robot. When a robot moves from an area to a different area, the robot's dominant DIND should be automatically changed. This is called "handing over of control authority." A dominant DIND has the control authority of the robots and at one time only a single dominant DIND exists for each robot. Therefore, the control authority should be smoothly handed over to the next DIND at the proper time and location. To solve this problem, a reliability rank is devised. High reliability stands for that a DIND can guide a robot robustly and precisely. Generally, the area near a DIND and the center area of an image captured by a DIND, have the highest reliability rank; while the boundary of the image and the area far from the DIND have the lowest reliability. Since a vision camera is adopted as a sensor for a DIND. Fig. 11 sets out how the reliability rank is determined. Fig. 11(a) is an area monitored by a DIND and is divided into four parts according to the distance from the DIND. In Fig. 11(b), the image is divided into three areas. Even though a good calibration algorithm is adopted, the outskirts of the image suffer a large distortion since a vision sensor with a lens is used. Based on these two partition methods, the actual reliability ranks in the monitored area are determined as shown in Fig. 11(c).

Fig. 12 sets out the protocol for handing over of the control authority of a robot. First, $\mathrm{DIND}_{(n)}$ is the dominant DIND for the robot. $\mathrm{DIND}_{(n)}$ requests information from other DINDs about the reliability rank of the robot. The other DINDs reply with their reliability rank concerning the robot and the current dominant DIND, $\mathrm{DIND}_{(n)}$, compares these values with its own rank. If $\mathrm{DIND}_{(n+1)}$ has a higher rank than the rank of $\mathrm{DIND}_{(n)}$, then the current dominant $\mathrm{DIND}_{(n)}$ transfers the authority of control to $\mathrm{DIND}_{(n+1)}$, which has the higher rank from the robot. Then the new dominant DIND, $\mathrm{DIND}_{(n+1)}$, controls the robot. However, if authority of control is shifted to a new DIND with the condition

$$R_{d,\mathrm{robot}} > R_{\mathrm{other,robot}} \tag{1}$$

chattering may occur in the handing over of the control authority, where $R_{d,\mathrm{robot}}$ and $R_{\mathrm{other,robot}}$ are reliability ranks of the dominant DIND and the other DIND, respectively, for the target robot. Therefore, instead of (1), the following condition is used to avoid chattering:

$$R_{d,\mathrm{robot}} > R_{\mathrm{other,robot}} + \alpha \tag{2}$$

where α is an offset value to avoid chattering. Empirically, in actual system, α is set to 1. Since the robot has original color codes, and the reliability rank map is based on geometrical position and image positioning of the robot, the proposed system is able to simultaneously deal with multiple robots.

Fig. 13 has the results of controlling a mobile robot in an intelligent space. Two DINDs cooperated to complete the navigation of the robot. Fig. 13(a) and (b) are localized outputs of the robot from each DIND. The dashed line in each figure indicates the monitoring areas of DIND A and DIND B, respectively. Even though the DINDs failed in correct localization in some areas, the handing over of the control authority was properly performed and the robot was seamlessly and continuously controlled. Fig. 13(c) shows which DIND controlled the robot. "+" indicates that the robot was controlled by one DIND at that position and "×" denotes by the other DIND. The gray squares in the figure indicate the monitoring areas of the DINDs. It is verified that the hand over is performed in an area where both DINDs monitor. The trajectory is discontinuous at the position where the hand over occurs. However, due to (2), chattering does not occur and the robot is smoothly controlled. The dotted line

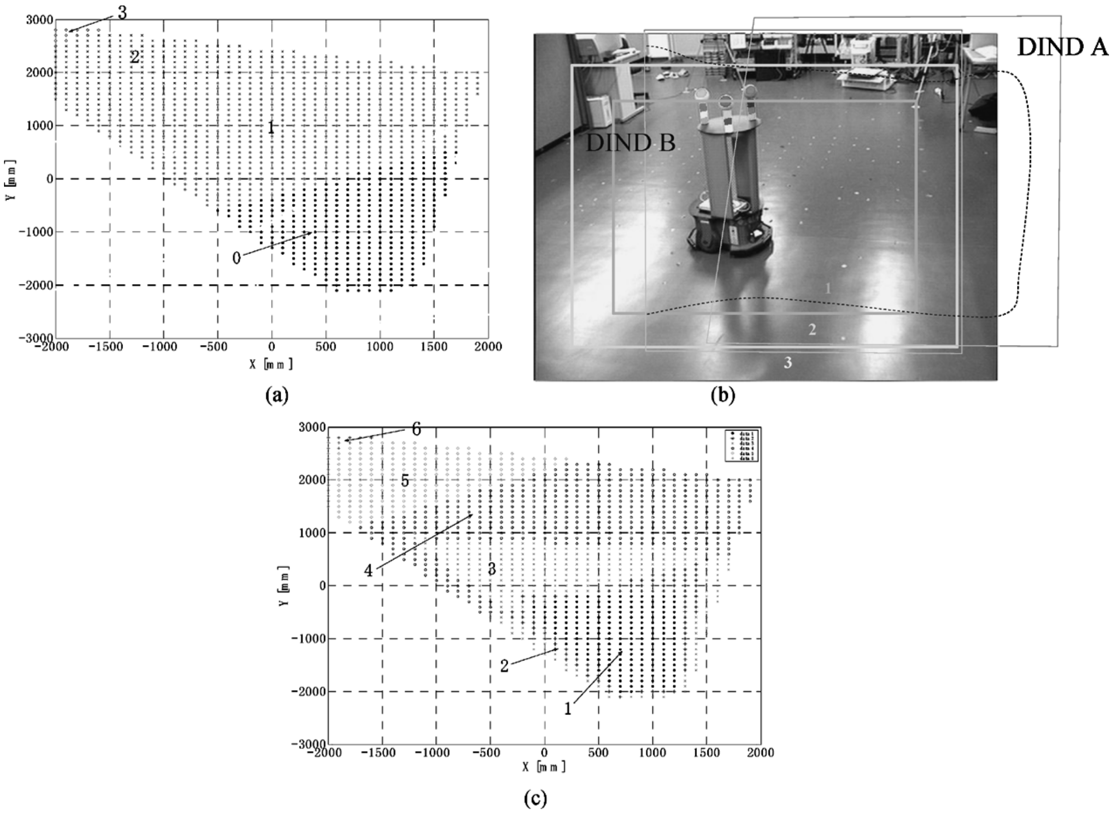


Fig. 11. Reliability rank map: (a) based on the distance from DIND; (b) based on captured image; and (c) the combined reliability map.

describes the real trajectory of the robot based on eye measurement and wheels traces.

D. Multi-Function Processing

Some function modules have been introduced above. In a real situation, a DIND should often simultaneously treat more than one function module. When a function module is activated by the decision module, it works regardless of the states of other function modules, whether it is activated or not, except for some function modules that are dependent on the outputs of other function modules. This feature enables function modules in one DIND to operate simultaneously.

A demonstration was performed. Two DINDs controlled two robots and DINDs also traced a man. When DINDs guide more than one robot, priority levels among the robots exist; and these are contained in the DINDs' databases. According to this priority, one robot should give way when it blocks another's path. A path, which the path planning function module generates, for the robot with a higher priority is modified to avoid the other robot, which waits for other robot to pass by. Similar situations occur when the ways of robots are blocked by a dynamic obstacle, mainly humans. Paths are modified or the robots stop for obstacles to pass according to the situation. In this demonstration; first, a man blocked the way of a mobile robot and then two mobile robots blocked each other's way. Cooperation between DINDs, and cooperation among function modules in the DINDs happened successfully and the robots could reach their goals without collision. Fig. 14 shows the monitor windows of the DINDs for the trajectories of the robots and the human. The red line represents the trajectory of the human. For the same reason as explained in Section V-C, some errors in the robot trajectory are found in each DIND monitor window.

VI. Future Works

Currently, only basic parts of intelligent space have been achieved. For it to be a useful system, intelligent space should be equipped with many useful function modules, which follow the proposed architecture. In the future, we will develop many function modules. Not only DINDs, but where to install them is an unresolved problem; ascertaining optimal dispositions of DINDs are in progress [13]. Further, more intelligent space agents are needed to enlarge the range of uses of intelligent space. In the current system, only robots and computers have been prepared as agents of intelligent space. Electronic appliances such as VCRs, air conditioners, and lights, are good candidates for agents of intelligent space. To use them in this way, a common interface, which can absorb differences needed to handle the appliances, is required so that the function modules in DINDs can easily access those agents [14]. As well, DINDs with other sensors are expected to be developed.

Another future work involves achieving complex cooperation among DINDs. Complex cooperation means that a task needs more than one DIND and is under time pressure. Sequential and parallel cooperation exist in such situations. For instance, if a task is "put a DVD into a recorder and download a television program" then the recording control should be undertaken by a robot after inserting the disc. This is sequential cooperation, where the sequence is important for pursuing the task. Parallel

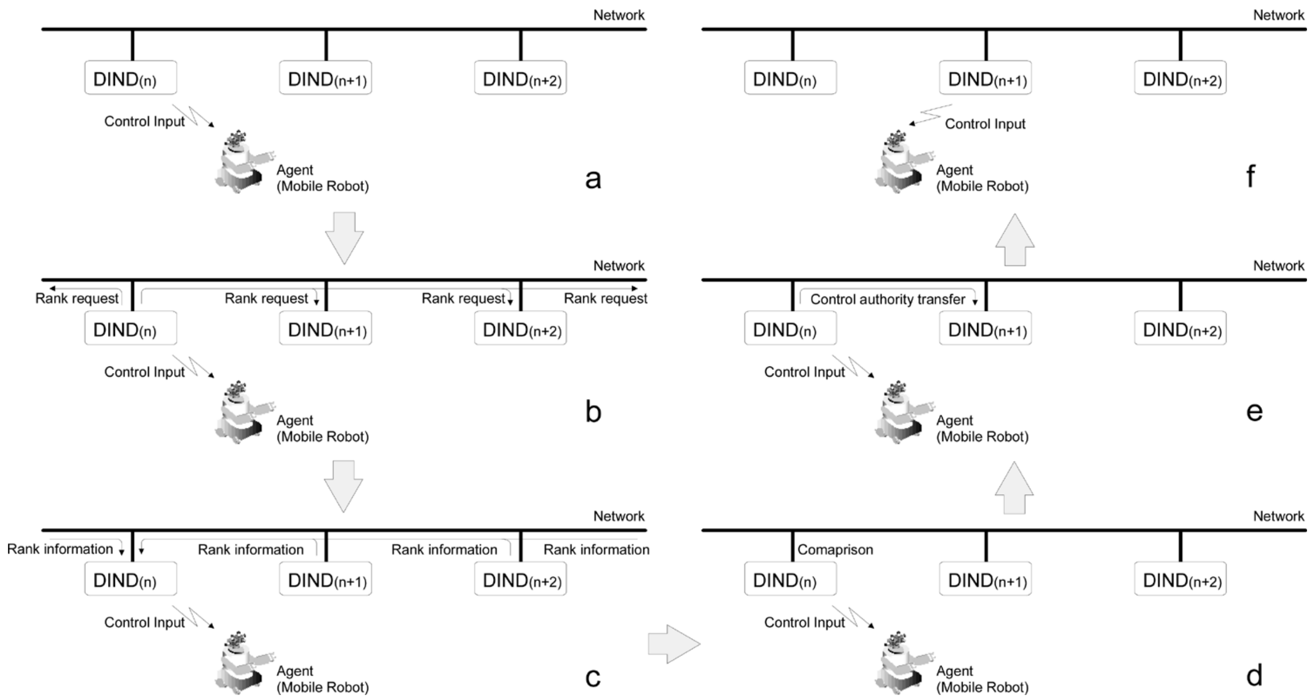
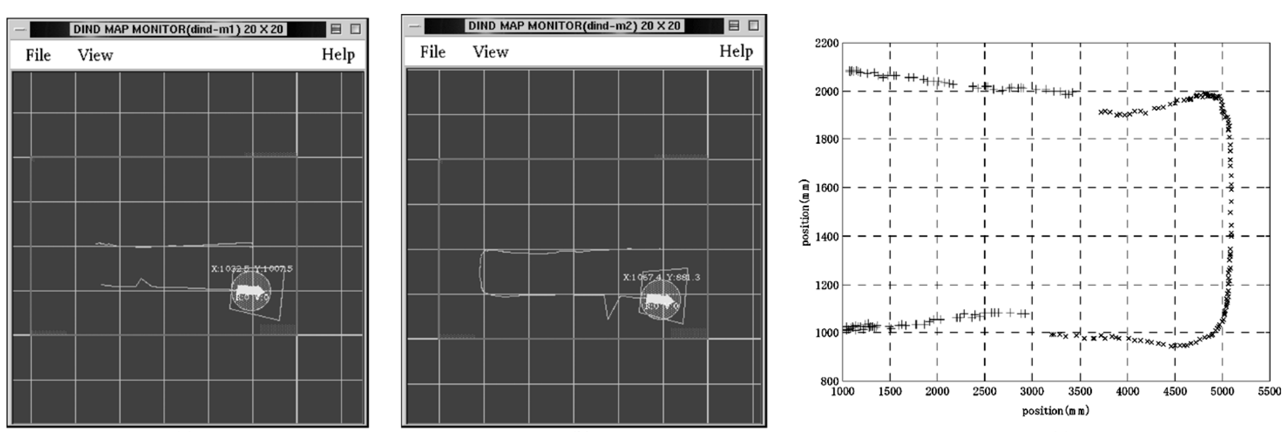
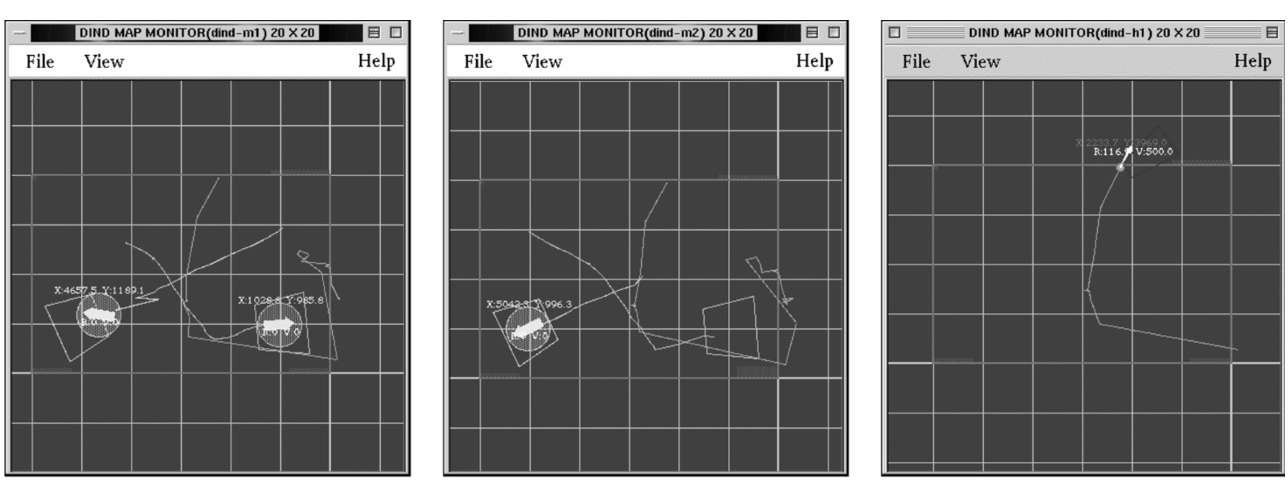


Fig. 12. Procedure of handing over of control authority.



(a) (b) (c)

Fig. 13. Handing over of control authority. (a) Monitor window of DIND A. (b) Monitor window of DIND B. (c) Estimated position of a robot.



(a) (b) (c)

Fig. 14. Trajectory of robots and a human. (a) Monitor window of DIND A. (b) Monitor window of DIND B. (c) Monitor window for the human.

cooperation is needed when a task requires simultaneous operations. To realize complex cooperation, one DIND rules other DINDs according to the situation; this is determined by negotiation among the DIND decision modules. Therefore, a decision module must be developed to cope with complex cooperation.

VII. Conclusion

Intelligent space is still in its early stage of development and somewhat far from being a practical system. For it to be practical and useful, many functions and agents remain to be developed. However, to effectively advance development and to apply intelligent space to a real environment, the most important issuer is the one of its architecture. In this paper, architecture for intelligent space based on intelligent sensors is proposed. The proposed architecture satisfies the requirements of intelligent space: scalability, reconfigurability, modularity, easy maintenance, affinity, etc. Since the proposed architecture works as a plank for new functions, the effort required from developers can be decreased and the development of functions made simpler. All information in intelligent space is handled based on position information as determined by distributed intelligent sensors that cooperate with each other to perform tasks in the proposed architecture. Some demonstrations of intelligent space with the proposed architecture have been described here.

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