Human-Following Mobile Robot in a Distributed Intelligent Sensor Network

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***Abstract*—The robots that will be needed in the near future are human-friendly robots that are able to coexist with humans and support humans effectively. To realize this, humans and robots need to be in close proximity to each other as much as possible. Moreover, it is necessary for their interactions to occur naturally. It is desirable for a robot to carry out human following, as one of the human-affinitive movements. The human-following robot requires several techniques: the recognition of the target human, the recognition of the environment around the robot, and the control strategy for following a human stably. In this research, an intelligent environment is used in order to achieve these goals. An intelligent environment is a space in which many sensors and intelligent devices are distributed. Mobile robots exist in this space as physical agents providing humans with services. A mobile robot is controlled to follow a walking human using distributed intelligent sensors as stably and precisely as possible. The control law based on the virtual spring model is proposed to mitigate the difference of movement between the human and the mobile robot. The proposed control law is applied to the intelligent environment and its performance is verified by the computer simulation and the experiment.**

***Index Terms*—Distributed sensors, intelligent environment, mobile robot, tracking control.**

I. INTRODUCTION

IN RECENT years, robot technology has advanced significantly. However, conventional robots are only used for industrial use in some restricted places, including factories, and intelligent robots for our general daily use have yet to be achieved. The robots that will be needed in the near future are human-friendly robots that are able to coexist with humans and support humans effectively. One of the most important aspects in the development of human-friendly robots is to realize cooperation between humans and robots.

In order for humans and robots to coexist and to perform a certain amount of cooperative work, robots and humans have to interact closely. The human-following robot in this research is a method of maintaining a certain relative positional relationship between the human and the robot. The following are examples of the sorts of services that human-following mobile robots are able to provide. The robot can carry loads that are required by people working in hospitals, airports, etc. The robot can work as an assistant for humans in various situations. Moreover, since such a robot always accompanies a human, the robot is able to easily acquire detailed information associated with target people. It has been reported that the approach of a human and a mobile robot leads to mutual interactions [1]. Several research groups have presented work on robots designed to follow humans. reference [2] describes a mobile robot which always faces humans and acts as an assistant robot. The mobile robot shown in [3] is a human-following robot for assisting humans. This robot is aimed at guiding a wheelchair in a hospital or a station and has the ability to estimate the position and velocity of humans and to avoid obstacles. In [4], four-legged mobile robots for following humans were considered. However, these studies only addressed the problem of how to follow humans, not how to detect the presence of humans. They developed their studies on the premise that human detection is possible.

Some technology which includes the recognition of humans, a position estimation technique for a mobile robot and humans, and a control strategy for following humans who are walking in a stable way, is required in order to realize robot human-following behavior. In order to recognize humans, most human-following robots are mounted with many sensors, such as charge-coupled device (CCD) cameras, ultrasonic sensors, etc. These sensors detect the relative position from the mobile robot to the target human. The mobile robot in [1] recognizes a human's skin color using a CCD camera, and traces the target human by combining pan-tilt control of a CCD camera. In addition to the vision sensor, a voice recognition sensor is mounted in the mobile robot in [5], and is able to follow humans in an outdoor environment. An LED is installed on the human as a beacon and the position of the LED is detected by the CCD camera of the human-following robot in [6]. Most of the proposed human-following robots burden the target human with special equipment. It is very difficult for a mobile robot to continue following a human while avoiding other obstacles, without missing the target while walking at a natural speed, since the stand-alone robot has limitations in terms of recognition performance. Moreover, the control methods of a mobile robot for following a walking human have not been taken into consideration, especially in these studies. Therefore, it is unlikely that the proposed robots are actually able to follow walking humans.

In this research, an intelligent environment is used in order to solve these problems. A mobile robot cooperates with multiple intelligent sensors, which are distributed in the environment. The distributed sensors recognize the target human and the mobile robot, and give control commands to the robot. The mobile robot receives the necessary support for human-following

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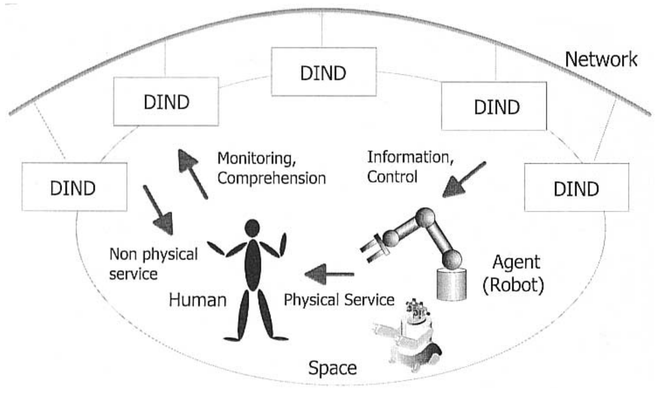


Fig. 1. Intelligent space.

control from the environmental sensors. We aim to achieve a human-following robot without applying any burden to the human with a mobile robot that is simple in structure. We propose intelligent space (ISpace) as an intelligent environment with many intelligent sensors, and are building an environment where humans and mobile robots can now coexist. The human-following robot of this research is one of the physical agents for human support in ISpace.

This paper is organized as follows. In Section II, the concept of ISpace and the role of the human-following robot in it are explained. Section III describes the tracking method of humans and mobile robots in ISpace, and the configuration of a mobile robot for human following. In Section IV, the control law of the mobile robot for following humans is proposed, and the model of the mobile robot and the characteristics of a control system are described. Section V explains the control method of a mobile robot using many intelligent sensors. In Section VI, the proposed control law is applied to ISpace. The experiment of human-following control is performed and the effect of the proposed method is verified. Conclusions and directions for future work are described in Section VII.

II. HUMAN-FOLLOWING ROBOT IN ISPACE

A. *Concept of ISpace*

ISpace [7] is a space where many intelligent devices are distributed throughout the whole of the space, as shown in Fig. 1. These intelligent devices have sensing, processing and networking functions, and are named distributed intelligent networked devices (DINDs). These devices observe the positions and behavior of both humans and robots coexisting in the ISpace. The information acquired by each DIND is shared among the DINDs through the network communication system. Based on the accumulated information, the environment as a system is able to understand the intention of humans. For supporting humans, the environment/system utilizes machines including computers and robots.

Up until now, the position estimation of human and mobile robots [8], human behavior recognition [9], and mobile robot control under ISpace [10] have been studied. These are the basic functions of space information understanding and human support by robots. One DIND consists of a CCD camera for acquiring space information, and a processing computer which has the functions of data processing and network interfacing. It becomes easy to install new technology as a new module to the ISpace if the protocol and data structure between the DINDs and modules are decided in advance. In an intelligent space, this enable the achievement of a flexible system based on this feature. The human-following robot introduced in this paper is a new module for ISpace, as it is one of the applications located in a level higher than the mobile robot position estimation module.

B. *Human-Following Robot in ISpace*

In this section, the expected effects of the human-following robot in ISpace are described. The first feature is that human following can be realized without being influenced by the mobile robot's performance. Not the intelligence of the robot itself but the intelligence of the ISpace is mainly used for the navigation of a mobile robot in ISpace [11]. For this reason, it is possible to perform human-following operations in ISpace with any type of mobile robot, even though the robot lacks sensors and intelligence.

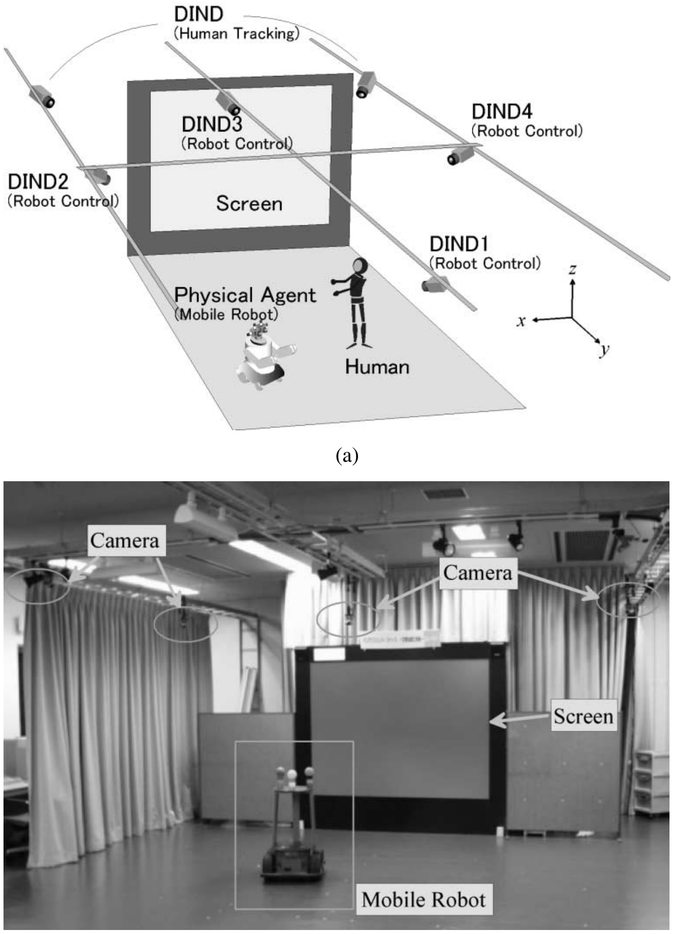
The second feature is that human following is possible even in a complicated environment. ISpace always acquires information about objects such as people, robots and obstacles in the space. Since mobile robots are managed by DINDs from the environment side, ISpace is able to generate each robot's path such that they do not collide with each other. Therefore, the robots are able to move smoothly, even if they are in a complicated environment.

The third feature is that ISpace has various functions; individual attestation, gesture recognition, behavior recognition, a record of the situation in ISpace, etc in addition to the control of the mobile robot. When these functions and the human-following robot system are combined, a more meaningful action of a mobile robot will be achieved. For example, ISpace recognizes a human who is beckoning by a gesture-recognition function, and a mobile robot is sent to him based on information from ISpace.

When a robot, which has advanced functions, is in an ordinary space, the robot is able to afford similar functions as the robots in ISpace. However, its serviceable area is limited to a range near the robot. It is difficult to provide services for people who are far from the robot. In such a case, a human is required to approach the mobile robot in order to receive services from the robot. Therefore, in order to achieve useful robot service, a human-following mobile robot in ISpace is one of the best candidates.

III. CONFIGURATION OF THE ISPACE

In ISpace, the CCD camera is adopted as the sensor for DINDs, and the tracking of target objects is performed. There are two advantages in using CCD cameras. One is that the position measurement of the target is a noncontact method. The other is that the human doesn't have to carry any special devices for the DINDs to be able to measure his position. This section describes the configuration of the tracking system and a mobile robot in ISpace.



(a)

(b)

Fig. 2. Experimental environment.

A. Tracking System

Currently, our laboratory room, which is about 5 m in both width and depth, is used for the ISpace. The ISpace has a mobile robot as a human-following agent, six DINDs which can obtain the situation in the environment, and a projector and a screen which present suitable information to the human. Each module is connected through the network communication.

Four DINDs are used in order to recognize the mobile robot and to generate the control commands. The other two DINDs are used to recognize the position of the human. DINDs are placed as shown in Fig. 2(a). Fig. 2(b) is a picture of the actual ISpace. The placement of the two DINDs for human recognition is optimized to expand the viewable area of the cameras [12] so that the head and hands of the human can be recognized over a wide area. On the other hand, the placement of DINDs for the mobile robot has to be decided by trial and error. It is desirable that the DINDs for the mobile robot recognize the whole of the area covered by two DINDs for human recognition in order to achieve the human-following system and reliable mobile robot control. Thus, four DINDs are placed so that the area for human recognition is completely covered. Human walking information is extracted by background subtraction and by detecting the skin color of a face and hands on captured images. A three–dimensional (3-D) position is reconstructed by stereo vision using two cameras.

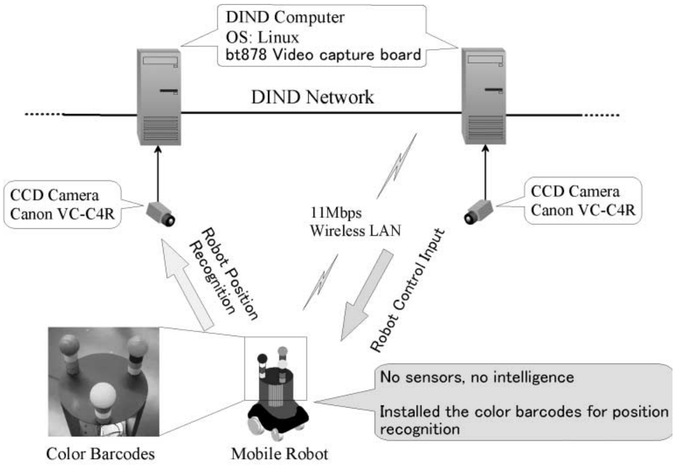


Fig. 3. Mobile robot in ISpace.

In the coordinate system of the ISpace, the x axis is parallel to the screen, the y axis is perpendicular to it, and the z axis follows the right-hand system. Each DIND measures 3-D positions, which are based on this coordinate system.

B. Mobile Robot in the ISpace

In this research, a differential wheel velocity-type mobile robot is used for the human-following robot. Since the DINDs take charge of the sensing and processing in ISpace, the mobile robots do not need any special functions nor devices, except for an ability to move and a wireless network device to allow for communication with the DINDs. Moreover, since this type of robot has a simple and compact structure, it is suitable for a physical agent that has to interact with humans in complicated environments. Our mobile robot is based on the Pioneer2-DX by ActivMedia Robotics [13].

This mobile robot is connected to the DIND network via wireless LAN, as shown in Fig. 3, and shares the resources of the DIND's. For estimating the position of the robot, three color barcodes are installed around the mobile robot. The pattern of the color barcode is recognized by the DIND and it estimates the posture and position of the robot. Since the height of the mobile robot is already known, the position of a mobile robot is reconstructed from one camera image. Details are written in [14]. Three color bar codes are installed so that these construct an equilateral triangle on the top of the mobile robot. Since the center of this equilateral triangle is calculated from the positions of these color barcodes, the position and posture of a mobile robot are achieved. Although all of the three color barcodes cannot be always recognized, it is possible to calculate the position and posture of the robot when at least two of them are detected.

IV. Mobile Robot Control for Human Following

A. Tracking Control

In order to follow a human, tracking control is performed. Many studies have been performed in the field of the tracking control. However, the trajectory which a mobile robot tracks is limited in most cases to continuous and smooth ones. A human-following robot should be able to track actual human walking

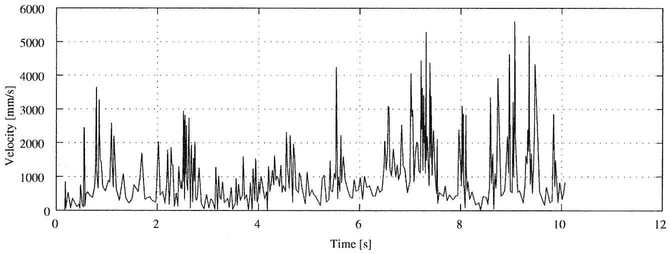


Fig. 4. Human walking as measured by ISpace.

trajectories, including abrupt changes in velocity and direction. Therefore, stable tracking may not be achieved when conventional tracking control is used. A special control method for the mobile robot to follow humans is required.

In the control of a nonholonomic mobile robot, Brockett's theorem proved that a smooth state feedback law for an asymptotically stable to one point of the state space does not exist [15]. However, it is necessary to construct a closed-loop control system in which the error between the reference point and the state vector of a mobile robot should become zero for the tracking control of a mobile robot. In recent years, various closed-loop control systems which can overcome the feedback stabilization impossibility of Brockett's theorem, have been proposed. Reference [16] proposed piecewise-continuous controllers which neglect the "smoothness" and [17] proposed tracking control in which a mobile robot follows the trajectory planned as a function of time. These techniques are very effective in tracking control.

In ISpace, since a human walking trajectory is newly generated in every step, it can be considered that it is a function of time. Therefore, the application of tracking control is effective. However, although the target trajectory of a mobile robot is continuous and smooth in the usual tracking control, a human-following robot tracks the actual human walking trajectory that is generally unstable. Stable human following may not be achieved when the usual tracking control is used. In the following subsection, a tracking control method in ISpace for following humans is proposed.

B. Design of Human-Following Control

Fig. 4. shows a human's walking velocity actually measured by ISpace. The estimated human position data by DIND is not the proper control input required for a mobile robot to follow a human since estimated position data contains errors in the form of calibration error and image processing error. When the heads of humans are measured by vision sensors in a short sampling period, their velocity and direction also change drastically.

Both the estimated position of humans and human walking action are unstable. The direction and velocity of human walking sometimes changes suddenly and unpredictably. In this case, the mobile robot may fail to follow the human and lose the stable movement by a sudden change in the velocity input. When conventional control law is used, which is derived only from the distance between the human and the mobile robot, it is considered that a mobile robot cannot follow the human. In order to solve such problems, a special control method for human following is required.

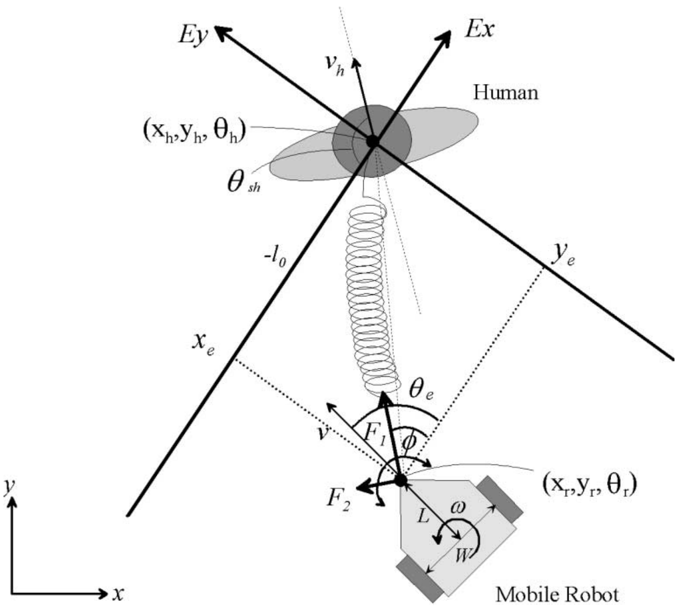


Fig. 5. Control variables.

The following need to be considered in the derivation of a new control law for human following: There are fundamental differences between a mobile robot and a human in the level of motion. A human is able to move freely by foot. However, since a differential wheel velocity type mobile robot of nonholonomic constraints is adopted as the agent of the ISpace in the current system, the robot cannot move as freely as does a human. To trace a human who walks freely, a control strategy that overcomes the limitations imposed by the nonholonomic constraints of the robot is needed. Solutions for establishing a control strategy for human following are considered as follows: One solution is that the control law absorbs the kinematic difference between the human and the mobile robot. Another solution is that the presumption based on the detailed analysis of the human's motion characteristic is included into the control law. In the latter solution, a detailed human model is needed for the human's motion analysis. In addition, since an intention of the human is closely related to the human's motion, it is difficult to presume the human's walking course. The first solution is adopted in this research.

In order to overcome the above problems, we propose a virtual spring model. The proposed control law is derived from the assumption that a human and a mobile robot are connected by a virtual spring. The input velocity to a mobile robot is generated on the basis of an elastic force of a virtual spring in this model. In the proposed control system, the virtual spring works as a low pass filter and absorbs adverse fluctuations. The proposed virtual spring model is able to absorb the gap between the motion of the human and that of the mobile robot. Since the point of application of the elastic force differs from the rotation center of the mobile robot, as shown in Fig. 5, the nonholonomic restriction of the mobile robot is overcome.

C. Virtual Spring Model

Fig. 5 describes the virtual spring model. The world coordinate of the ISpace is converted into a coordinate system whose origin is at the target human. The direction of a virtual spring at the human side corresponds to the negative direction of the X axis in the converted coordinate system. In the following notation, the superscript refers to the coordinate system. W is the world coordinate of the ISpace, and E is the coordinate system after conversion. Equations (1) and (2) represent the state vector of the mobile robot and human in the world coordinate system

$$ {}^{W}\boldsymbol{x}_r = [x_r \; y_r \; \theta_r]^T \tag{1} $$

$$ {}^{W}\boldsymbol{x}_h = [x_h \; y_h \; \theta_h]^T. \tag{2} $$

(x_r, y_r, θ_r) represents the position and direction of the mobile robot, but it is not on the center of the robot. It is the world coordinate of the joint, which connects the mobile robot to the virtual spring. L is the length from the mobile robot's center of rotation to the joint. Both of these coordinates are measured by the ISpace. The angle between the virtual springs connected to the human and the human's facing direction is expressed as θ_{sh}. This parameter is adjustable, and when it is set to $\theta_{sh} = 180°$, a robot directly follows a human. The details about θ_{sh} will be explained later. The state vector of the mobile robot in the converted coordinate system is expressed as (3)

$$ {}^{E}\boldsymbol{x}_r = [x_e \; y_e \; \theta_e]^T. \tag{3} $$

Here, the coordinate system is converted to (4)

$$ {}^{E}\boldsymbol{x}_r = \boldsymbol{F}\left({}^{W}\boldsymbol{x}_r - {}^{W}\boldsymbol{x}_h - [0 \; 0 \; \theta_{sh}]^T\right) \tag{4} $$

where $\boldsymbol{F}$ is

$$ \boldsymbol{F} = \begin{bmatrix} \cos(\theta_h + \theta_{sh}) & \sin(\theta_h + \theta_{sh}) & 0 \\ -\sin(\theta_h + \theta_{sh}) & \cos(\theta_h + \theta_{sh}) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{5} $$

The dynamic equations are derived for the case where the elastic power of the virtual spring is applied to the mobile robot, and the input value of the velocity and the angular velocity are determined from the equations. The state (l, ϕ) of the virtual spring is given from the physical relationship between the human and the mobile robot. It is assumed that the virtual spring transforms ideally and makes a curve which passes along the position (x_e, y_e) of the robot and the origin of the E coordinate system. The deformed length l of the virtual spring is approximated as (6). ϕ is the displacement angle between both ends of the spring, and is represented as (7)

$$ l = \sqrt{x_e^2 + y_e^2} \tag{6} $$

$$ \phi = \arctan\frac{y_e}{x_e}. \tag{7} $$

Here, the elastic force which the virtual spring effects on the mobile robot is obtained. Elastic force F_1 is proportional to $(l - l_0)$ and acts in the direction of the translational deformation, and F_2 is proportional to ϕ and acts in the direction of bending. l_0 is the free length of the virtual spring, and represents a set interval between the target human and the mobile robot. F_1 and F_2 are as follows:

$$ F_1 = k_1(l - l_0) \tag{8} $$

$$ F_2 = \frac{k_2}{\phi}. \tag{9} $$

Here, k_1 and k_2 are the virtual spring coefficients of the direction of expansion and bending. The dimensions of the spring coefficient are N/m and N·rad], respectively. Based on these virtual elastic forces F_1, F_2, the dynamic equations are derived as follows:

$$ M\dot{v} = -F_1\cos(\theta_e - \phi) - F_2\sin(\theta_e - \phi) - k_3 v \tag{10} $$

$$ I\dot{\omega} = (F_1\sin(\theta_e - \phi) + F_2\cos(\theta_e - \phi) - k_4\omega)L \tag{11} $$

$$ \begin{bmatrix} \dot{v} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{k_3}{M} & 0 \\ 0 & -\frac{k_4 L}{I} \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} + \begin{bmatrix} -\frac{F_1}{M}\cos(\theta_e - \phi) - \frac{F_2}{M}\sin(\theta_e - \phi) \\ (F_1\sin(\theta_e - \phi) + F_2\cos(\theta_e - \phi))\frac{L}{I} \end{bmatrix} \tag{12} $$

$$ \dot{\boldsymbol{q}} = \boldsymbol{H}\boldsymbol{q} + \boldsymbol{G}(\boldsymbol{x}_e). \tag{13} $$

M is the mass and I is the moment of inertia of the mobile robot. k_3 and k_4 are the viscous friction coefficients of translation and rotation, respectively, and each dimension is $\mathrm{N \cdot s/m}$ and $\mathrm{N \cdot s/rad}$], respectively. Equation (10) is a dynamic equation about the mobile robot's translational motion. The left-hand side of (10) is the product of the mass and the derivative of the translational velocity. The first and second terms on the right-hand side are the translational factors of F_1 and F_2. The third term is the viscous friction term of both of the forces. Equation (11) is a dynamic equation about the mobile robot's rotational motion. The left side of (11) is the product of the moment of inertia and the derivative of the angular velocity. The first and second term on the right hand side are the rotational factors of F_1 and F_2. The third term is the viscous friction term of the torque. The torque, which influences the angular velocity, is calculated from the product of L and the resultant. Here, v and ω are the translational and angular velocities of the mobile robot. Equations (10) and (11) can be expressed as (12). The vector and matrix of (12) is replaced with $\boldsymbol{q}$, $\boldsymbol{G}$, and $\boldsymbol{H}$ of (13).

V_r and V_l are the velocity of the right and left wheel, respectively, and W is the distance between both wheels. Their relationship is shown in (14). Based on $\dot{v}$ and $\dot{\omega}$ from the dynamic equations, V_r and V_l are the input to the mobile robot as actual control input for following the target human:

$$ \begin{bmatrix} V_r \\ V_l \end{bmatrix} = \begin{bmatrix} 1 & \frac{W}{2} \\ 1 & -\frac{W}{2} \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}. \tag{14} $$

k_1, k_2, k_3, and k_4 in (10) and (11) are optimized empirically by a simulation based on information about the human; the maximum walking speed, the maximum acceleration, etc. The whole

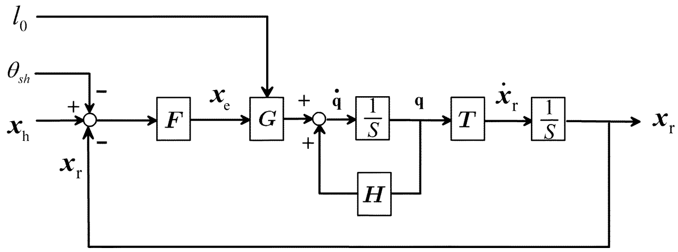
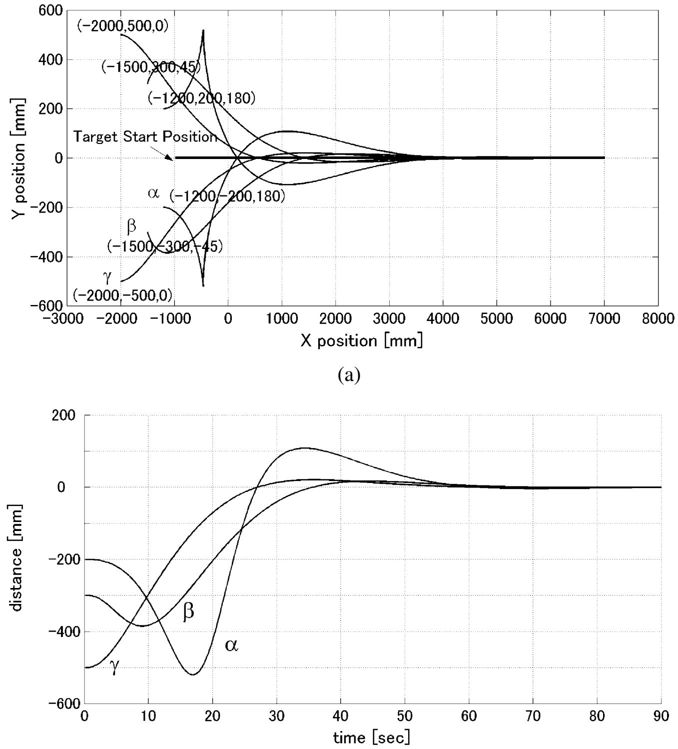


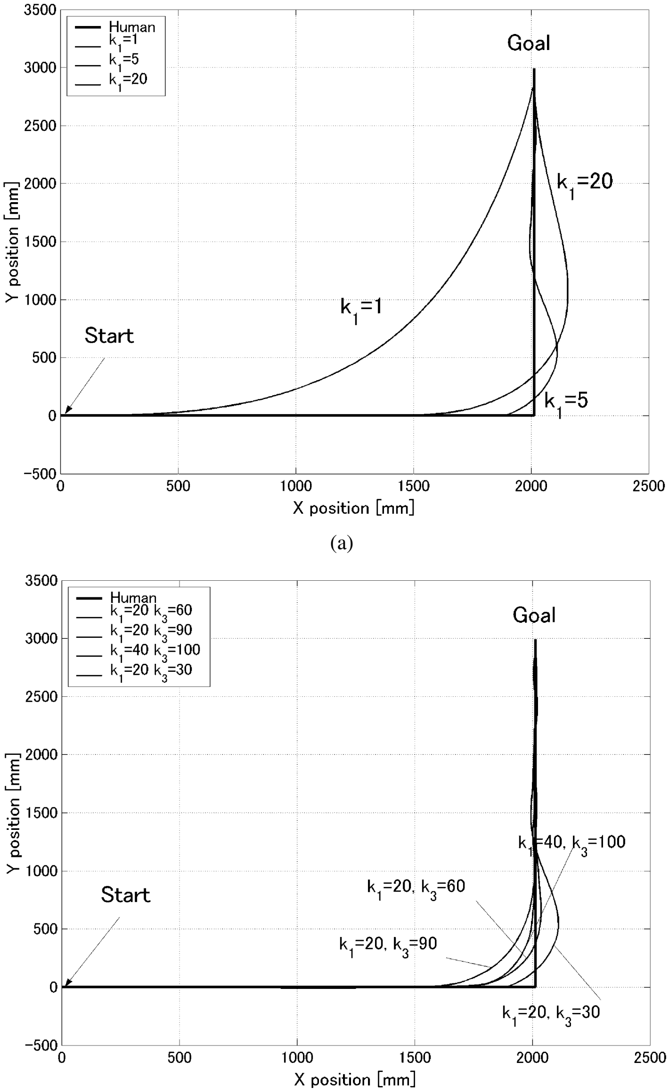
Fig. 6. Control block diagram.



(a)

(b)

Fig. 7. Convergence evaluation.



(a)

(b)

Fig. 8. Changes in the parameters.

of the control system is depicted using a block diagram shown in Fig. 6. Here, T is as follows:

$$\boldsymbol{T} = \begin{bmatrix} \cos\theta_r & 0 \\ \sin\theta_r & 0 \\ 0 & 1 \end{bmatrix}. \tag{15}$$

D. Tracking Evaluation

The tracking performance is evaluated through a computer simulation with various initial states of a mobile robot. It is assumed that a target human is walking parallel to the positive direction of the X axis. The initial state vector of the human $(-1500, 1000, 0)$ and θ_{sh} is set to 180°. The trajectories of the human and the mobile robot are shown in Fig. 7(a). Fig. 7(b) shows how long it takes before convergence on the trajectory of the human is achieved. α, β, and γ in Fig. 7(a) correspond with Fig. 7(b). Although the mobile robot starts from various initial states, it is able to track the target and converge on the human trajectory in a reasonable length of time. From the results, it can be concluded that the proposed control law is valid.

According to changes in the parameters, the mobile robot's trajectory changes, as shown in Fig. 8. In this simulation, the target human makes a right-angled turn, as shown in figure. k_2 and k_4, which are related to the spring bending, are set constant through all of this simulation. Fig. 8(a) is the trajectory of the mobile robot when k_1 is changed and k_3 is constant. A small k_1 makes the performance on the right-angled turn worse. On the other hand, the mobile robot strays from the human trajectory with a large k_1. If k_1 increases, the trajectory of the robot after turning becomes oscillatory. In Fig. 8(b), both k_1 and k_3 are changed. The performance as a result of a right-angled turn is improved by adequately setting up k_1 and k_3. The adequate parameters are tuned experientially by performing this simulation so that the mobile robot does not stray from the trajectory of the human and the motion of the mobile robot does not oscillate.

E. Various Following Patterns

Based on the control law as described above, a mobile robot is able to follow a walking human. It is possible for a robot to follow a human from behind as well as from other positions.

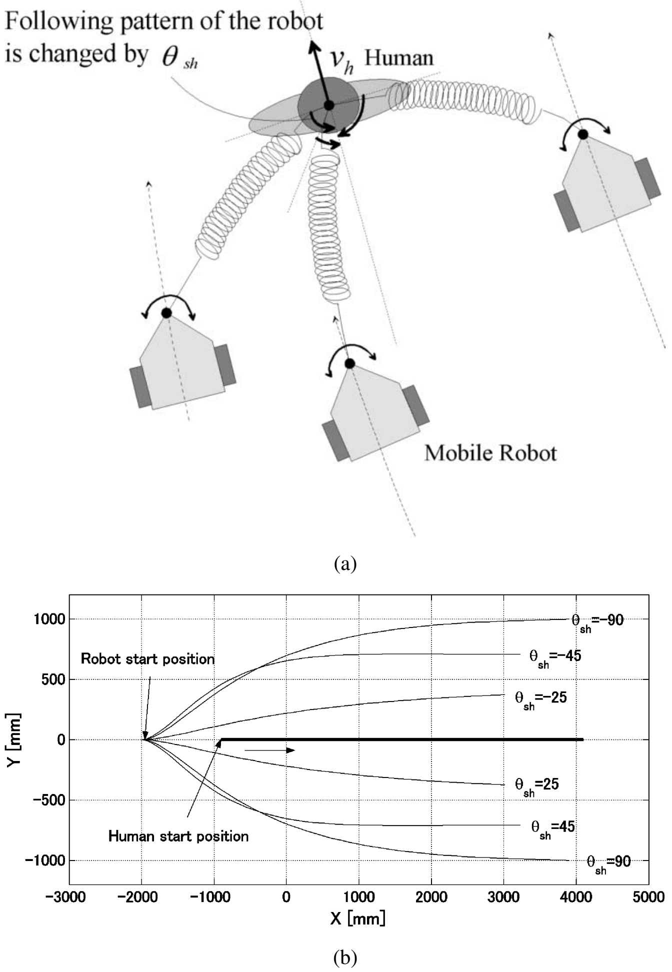


Fig. 9. Various following patterns.

As an example, a robot is able to move alongside a human. Such following patterns can be achieved using the proposed control method. A fixed angle θ_{sh} between the virtual springs and the human's walking direction can be set to various patterns [Fig. 9(a)].

Fig. 9(b) shows the results of computer simulation with various following patterns of the mobile robot. In this computer simulation, the target human walked in a straight line. The values of θ_{sh} were set to -90, -45, -25, 25, 45 and 90 degrees in this simulation. The results clarified that the human following pattern changed based on θ_{sh}. It is possible to avoid local obstacles when the active changing of this following pattern and the obstacle recognition by ISpace are combined.

V. ROBOT CONTROL BY DIND

A. Robot Position Estimation

Due to the processing time and the network communication time, there is a position gap between the robot at the time of performing the control and the robot at the time of capturing the image with the CCD camera, since the robot moves. The processing time includes clustering, 3-D reconstruction, etc. Therefore, it is necessary to estimate the robot's position and posture at the time at which the control is performed.

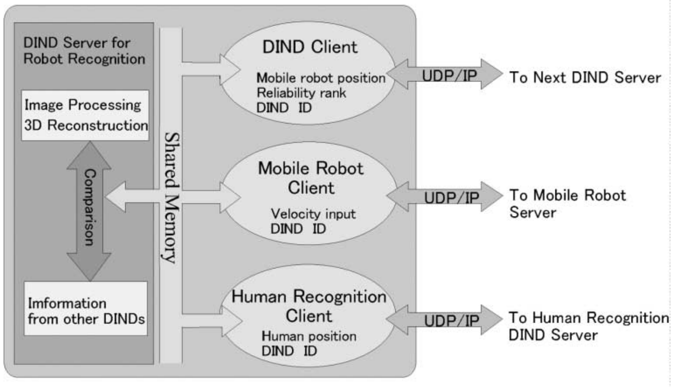


Fig. 10. Network software configuration of the DIND.

A mobile robot controller exists in the DIND side, and the modified velocity input signal to the mobile robot is determined before the network communication.

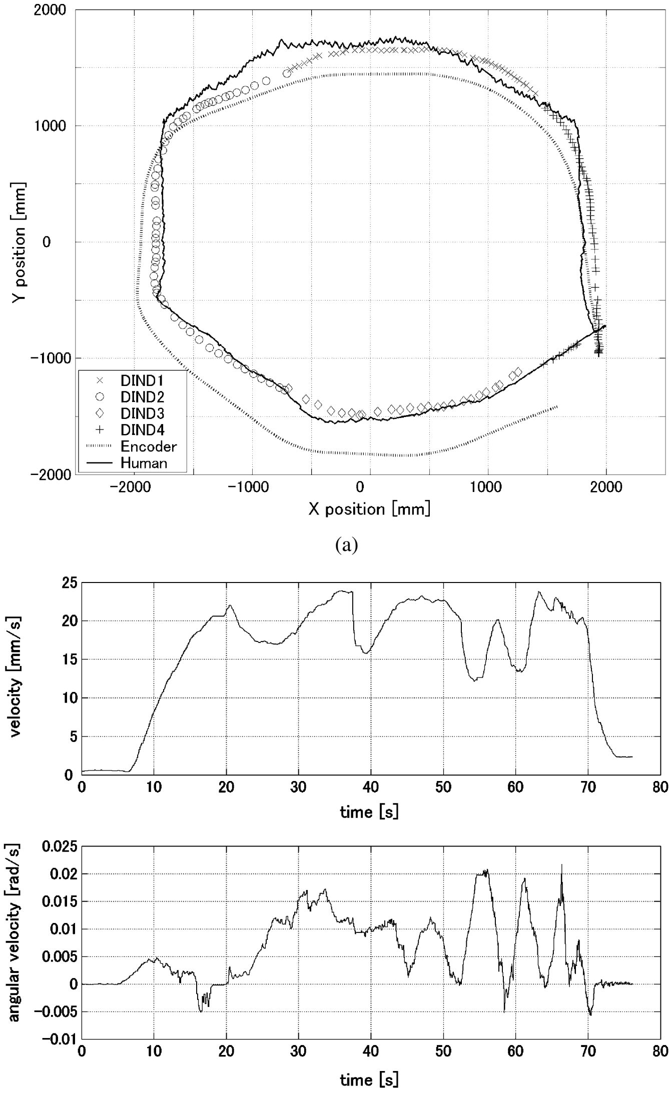
B. Robot Control in the Environment Where Many DINDs Exist

The network of six DINDs, which consist of four DINDs for the mobile robot and two DINDs for the human, is used in the experimental environment. Since the area that each DIND is able to cover is limited, the DINDs must share information acquired by themselves, in order to realize human following in the whole of the experimental environment.

In this environment, the DINDs are required to cooperate with each other. Effective communication and role assignment are required for the cooperation of the DINDs. We define a DIND that has the control authority of a robot as the dominant DIND for the robot. Each DIND compares the reliability rank based on measurement error and so on. When a robot moves from one area to a different area, the dominant DIND for a robot needs to be changed automatically to the DIND that has the higher reliability rank. This is called handing over of the control authority. The dominant DIND has the control authority of the robots, and only one dominant DIND exists for a given robot at any one time. Details about the handing over are described in [18]. In order to achieve a definite handover, the monitoring areas need to overlap. Moreover, in the proposed control law, the past velocity input is required in order to calculate the new velocity input. When the control authority moves to another DIND, information about the input velocity also has to be transmitted from the last dominant DIND to the new dominant DIND. Therefore, it is possible to input a continuous velocity into the mobile robot. The information which the DINDs share is defined as follows:

- ID of the DIND and control authority of the DIND;
- position and posture of the mobile robot;
- reliability rank of the DIND;
- ID of the mobile robot which the DIND is controlling;
- input velocity to the mobile robot.

The human-following module of a DIND is realized with the software configuration as shown in Fig. 10. A DIND basically makes connections to other DINDs with the client/server method of UDP protocol. A server program of each DIND is



(a)

(b)

Fig. 11. Experimental results.

always running in order to receive requests for passing the control authority from other DIND's. The client programs are executed according to the situation, such as DIND requests to other DIND's, and so on. When the DIND transmits the velocity input to the mobile robot, the client program for making a connection to the mobile robot will become active if the DIND has the control authority.

VI. EXPERIMENTS

A. Human-Following Experiment

The results of the experiment are shown in Fig. 11(a). The control parameters were tuned empirically to $M = 30.0$ kg, $I = 1.5$ kg·m^2, $k_1 = 3.0$ N/m, $k_2 = 0.001$ N·rad, $k_3 = 30$ N·s/m, $k_4 = 20.0$ N·s/rad, and l_0 is set to 60 cm. A human walked along a hexagonal path.The mobile robot followed him along the course plotted by four kinds of signs in Fig. 11(a). Fig. 11(b) shows the velocity control inputs for the mobile robot from the DINDs in this experiment.

In spite of the unstable human position estimation, the mobile robot was controlled smoothly and there were no abrupt changes in the control inputs. The low-frequency fluctuations in the human trajectory were cut off by the virtual spring and the robot was controlled smoothly. It is found from the results that the proposed algorithm allows the robot to follow the target without excessive motions.

In Fig. 11(a), the dashed line represents the position measured by the encoders in the robot. The dashed line deviates significantly from the trajectory of the robot measured by the DINDs. This is mainly caused by slips of the wheels and the wrong internal parameters of the robot. It is also an advantage for the human-following robot realized in ISpace to be robust against various errors that disturb the robot's navigation.

Although this human path is simple from a global point of view, complex motions, such as variations in the velocity and direction of humans are included in the human's actual movement. The validity of the proposed control method was verified from this experimental result.

B. Handing Over Experiment

Fig. 11(a) shows the results of the handing over between four DINDs. At the beginning, the mobile robot was located in the monitoring area of DIND number 4. Four kinds of signs of Fig. 11(a) show the ID of the DIND from which the mobile robot receives the control command. According to the position of the robot, the dominant DIND changed in the order of DIND 4, 1, 2, 3, 4. It turned out that the mobile robot continued the human-following operation smoothly, even when it's dominant DIND changed. The estimated positions of the mobile robot were discontinuous at the point where the dominant DIND changed. This was caused by position measurement error resulting from camera calibration and image processing. However, the maximum in error was about 10 cm and the error hardly influenced the control of the mobile robot since the proposed virtual spring model suppressed the abrupt change of motion. In wide ISpace where many DINDs are placed, it is possible to continue recognizing and controlling the mobile robot seamlessly.

VII. CONCLUSION

In this paper, a human-following mobile robot in ISpace was presented. First, a control algorithm using a virtual spring model was proposed for a mobile robot in order to follow a walking human whose position is estimated incompletely. The proposed model is able to absorb the gap between the motion of the human and the mobile robot. It was shown that various following patterns are possible in the proposed control algorithm. Next, cooperation between the multiple DINDs was described. The position of the human and the mobile robot in ISpace was measured with DINDs. To control a mobile robot in a wide area, cooperation of the DINDs, effective communication and role assignment are required. The handing-over protocol for a mobile robot control and the communication method with DIND for human recognition were explained. Finally, an experiment into the human-following control of a mobile robot was performed using the proposed control algorithm. It was shown that human following is easily achieved in ISpace. As a result, this research shows that the proposed control algorithm is effective in assisting a mobile robot to follow a human. Moreover, the fundamental human-following system is achieved in ISpace where many DINDs are arranged in the space.

Future studies will involve applying this system to complex environments where many people, mobile robots and obstacles coexist. Since the proposed algorithm absorbs the kinematic differences between humans and robots, any kind of mobile robot, including legged robots, can be used as human-following robots, as long as the robot is able to move at the speed of human walking. Moreover, it is necessary to survey the influence of the mobile robot which maintains a fixed distance between it and the human, and introduces the knowledge of cognitive science and social science.

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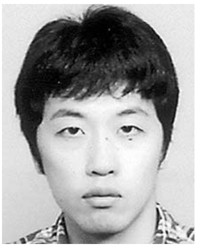

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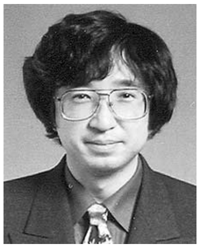

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