International Journal of Fuzzy Logic and Intelligent Systems, vol. 5, no. 3, September 2005 pp. 246-252

Human Centered Robot for Mutual Interaction in Intelligent Space

TaeSeok Jin*, Hideki Hashimoto**

***, **Institute of Industrial Science, University of Tokyo,**
4-6-1 Komaba Meguro-ku Tokyo 153-8505, Japan

Abstract

Intelligent Space is a space where many sensors and intelligent devices are distributed. Mobile robots exist in this space as physical agents, which provide human with services. To realize this, human and mobile robots have to approach each other as much as possible. Moreover, it is necessary for them to perform interactions naturally.

It is desirable for a mobile robot to carry out human affinitive movement. In this research, a mobile robot is controlled by the Intelligent Space through its resources. The mobile robot is controlled to follow walking human as stably and precisely as possible. In order to follow a human, control law is derived from the assumption that a human and a mobile robot are connected with a virtual spring model. Input velocity to a mobile robot is generated on the basis of the elastic force from the virtual spring in this model. And its performance is verified by the computer simulation and the experiment.

Key Words : Mobile robot, intelligent space, position detection, spring model, Kalman filter

1. Introduction

Intelligent space (ISpace) is a space where many sensors and intelligence are distributed [1]. Mobile robots exist in this space as agents, which offer physical service to human. In order to realize this, human and mobile robot have to approach each other to certain range as much as possible, and it is required for human and a mobile robot to perform an interaction naturally. In this research, the function of the ISpace is used for extraction of walking human, and control of mobile robots. Human walking action is extracted by using the human position information measured from the vision sensors in the ISpace.

Since measurement error and fluctuation peculiar of a human walking is contained in position detection results, it is not appropriate to use the results directly as control input for a mobile robot. This paper describes how to extract a walking of human correctly first. In addition, the method for estimating position of mobile robot is described. Next, the control method of the mobile robot using above results is described. At last, simulation and experimental results are shown. In [2], human is followed by a robot using the vision sensor carried on the robot. Furthermore, since the direction, where man is facing, is measured, a mobile robot and human are able to face mutually. In [3] and [4], mobile robots follow each other. It is considered as a mean of realizing cooperative work. Based on the accumulated information in the DINDs, the position estimation of human and mobile robots based on the tracking of color marker[5], human behavior recognition[6] and mobile robot control under ISpace[7] have been studied.

In this research, such a function is realized with the interaction of a mobile robot and Intelligent Space. A mobile robot does not need to have complicated processing functions. The ISpace is always able to catch the information of the objects which exist there, such as robots or obstacles. Therefore, even when environment is complicated, a mobile robot is afforded by the ISpace to accomplish given task.

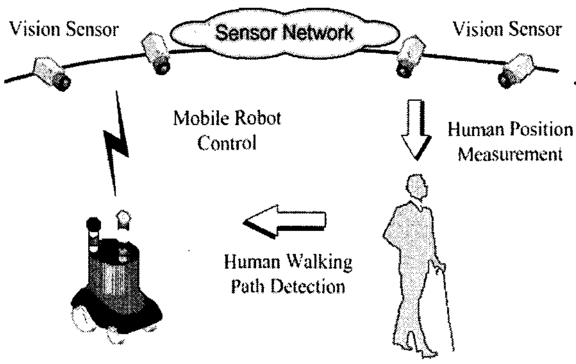


Fig. 1. Human following system in ISpace.

2. Importance of Human Following in ISpace

2.1 Human Following Mobile Robot

In recent years, the technology about the man-machine interface becomes important. Especially, it is required to realize cooperated operation of man and robot in the field of robotics. However, at present, intelligence of the robot is limited. It is difficult for human and robot to understand each other and work together. Human's intelligence is required in cooperated operation of human and robot.

First, it is required to distinguish the role of human and a robot clearly. The system that a role assignment has clarified is considered to be suitable for cooperation of man and a

Manuscript received Aug. 5, 2005; revised Sep. 6, 2005.

robot. A mobile robot approaches human who receives support from it, and a human is followed by it.

Followings can be realized as cooperated operation using this human following system.

- Conveyance of the load in being accompanied by human in a factory, a hospital, etc.
- Assistant of human in the office.
- The guidance robot in an art gallery, a museum, etc.

Besides, the environment where human and a robot are always able to perform cooperative operation in this way is considered to be the first step which realizes a future life. The interaction of a human and a robot is more activated by realization of such environment, and we consider that this environment is close to the ideal coexistence environment of human and a robot.

2.2 Human Following Robot in ISpace

In this section, advantages and meanings of realizing a human following robot system in Intelligent Space are explained. Not the intelligence of robot itself but the intelligence of ISpace is mainly used to realize navigation of a mobile robot in the ISpace [11]. For this reason, it is possible to perform human following operation in the ISpace with any kinds of mobile robots, even though the robot lacks of sensors and intelligence. In addition to control of a mobile robot, ISpace has various functions; Human individual attestation, Gesture recognition, Behavior recognition, Record of the situation in ISpace, and so on. When these functions and human following robot system are combined, more meaningful action of a mobile robot will be achieved. For example, ISpace recognizes the human who is beckoning by gesture recognition function, and a mobile robot is sent to him based on the information through ISpace.

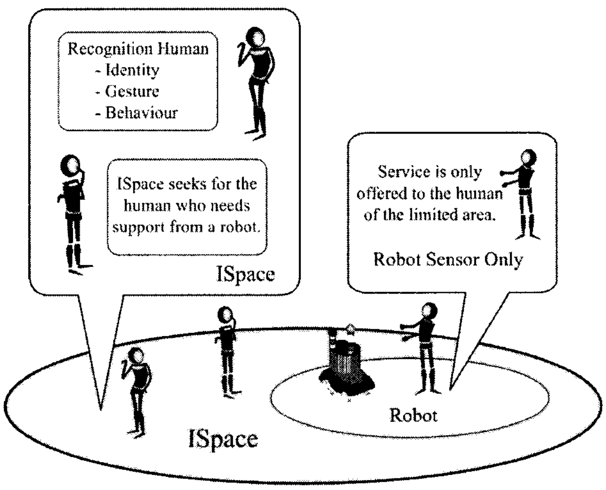


Fig. 2. Merit of human following in ISpace.

When only the functions of a robot is used, it is difficult to provide services for all the human that are in the place distant from a mobile robot (Fig.2.). A human must approach a mobile robot and receives services from a robot. It is not so desirable because a human receives the impression that a robot takes the lead in a living environment. Therefore it is considered effective to realize a human following mobile robot in the Intelligent Space.

3. 3D Position Detection

3.1 Distributed Intelligent Network Device

A mobile robot which follows walking human in the ISpace is realized with the composition shown in Fig.1. Many Distributed Intelligent Network Device (DIND) are arranged for sharing information through network communication for understanding of the situation in the ISpace. These DINDs perform image processing and recognition in space. Each DIND is connected to the network [12].

Human walking information is extracted by recognizing the skin color of a face or hands on a captured image. A 3D position is reconstructed by stereo vision using two cameras. Because the results include typical motion feature of ambulation and measurement error, the raw results are very noisy. Even a man walked straight, the observation results by the ISpace is not straight at all.

The raw results are not able to be used as control input of a mobile robot to follow human. When extracting a mobile robot position, three color barcodes are installed around a mobile robot. The pattern of the color barcode is recognized by DIND and it estimates posture and position of the robot. Since the height of a mobile robot is known, the position of a mobile robot is reconstructed from one camera image. Details are written in [8]. The raw results are processed to be meaningful data in this research. A filter is utilized to eliminate all possible noises. As the results of the filter, position estimation of both human and robot becomes accurate.

3.2 Error Feature

The error of the estimated position of an object changes with the distance from and pose of camera. The error is influenced by several factors; the performance of each camera, the method of image processing, etc. Currently, image processing is utilized for localization, mainly using a color information. Since the camera pixel position of target object is not stable, estimated world position of target object is not determined to one position. In other words, deviation of the position on image frame influences deviation of world position. Influence of error can be estimated by reconstructing the position with error on image frame to the position in world coordinates. The range of measurement error in 3-dimensional position can be calculated by the following methods (Fig.3.).

When world coordinates (x_w, y_w, z_w) are given, a camera pixel position (X_f, Y_f) is determined by using the camera parameters through the camera calibration. Here, it is assumed that 1 pixel is shifted in the direction of the X-axis from (X_f, Y_f). The world coordinates at this time are drawn by inverse calculation procedure. If the result is $(x_w+\varepsilon_x, y_w+\varepsilon_y, z_w+\varepsilon_z)$, then $(\varepsilon_x, \varepsilon_y, \varepsilon_z)$ is the range of error in each 3-dimensional coordinates.

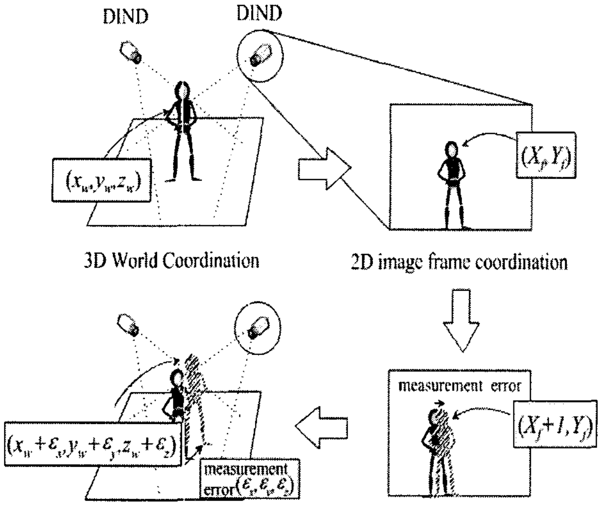
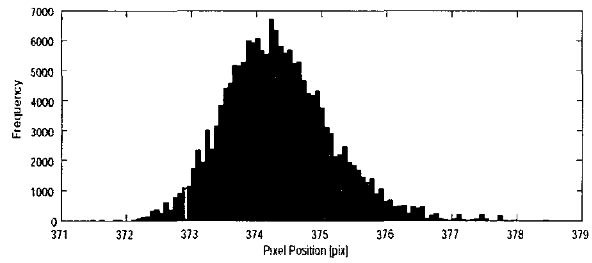
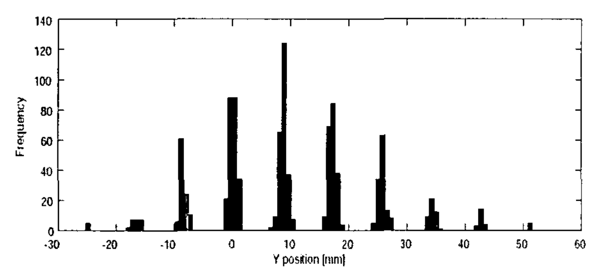


Fig. 3. Calculation of measurement error.

The object was put on certain point in the ISpace and the world coordinate of it was measured several times. The appearance frequency of measured value on the image frame is shown in Fig.4(A). Horizontal axes of Fig.4(A) shows Y-coordinates of measured position. These values follow the Gaussian distribution function. When 3D reconstruction is performed with these data, 3D positions with error are generated. At this time, the appearance frequency of reconstructed 3-dimensional values are shown in Fig.4(B). Reconstructed values are divided into some groups at certain interval. $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are equivalent to the interval between each group which appears in measured values, and amplify the error of only few pixels in a image. Although Fig.4(B) is data of the Y-coordination of world coordinates, the same tendency is also measured on X and Z-coordination.



(A) Tracking position on camera image



(B) 3D reconstruct position spread

Fig. 4. Measurement error variance.

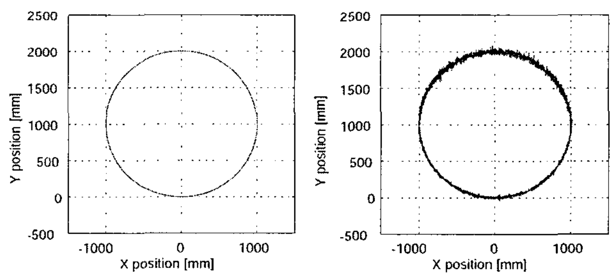
3.3 Kalman Filter based Human Tracking

Kalman filter is applied to this system and measurement errors are made flat and smooth. The measurement errors of a 3-dimensional position changes according to the position based on $\varepsilon_x, \varepsilon_y, \varepsilon_z$ as mentioned above. Here, filtering in consideration of change of the error variance is proposed. The covariance matrix W of measurement noise is defined as follows. Based on measurement data mentioned above w_{ai} and w_{bi} are decided according to the position of target.

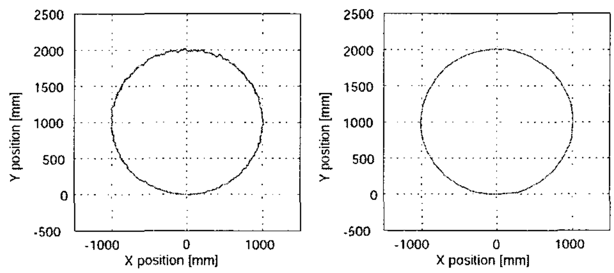
$$W=\begin{pmatrix} w_{xx} & 0 & 0 \\ 0 & w_{yy} & 0 \\ 0 & 0 & w_{zz} \end{pmatrix} \tag{1}$$

$$w_{ij}=\begin{cases} w_{ai}+w_{bi}\varepsilon_i(i_t) & (i=j) \\ 0 & (i\neq j) \end{cases} \quad (i,j=x,y,z) \tag{2}$$

The simulation was performed in order to verify efficiency of proposed filter. The results are shown in Fig.5. In the simulation, the measurement noise according to the position was generated first. $\varepsilon_x, \varepsilon_y, \varepsilon_z$ mentioned above are used for this. As a human walking route, the circle with a radius of 1000mm was assumed (Fig.5(A)). Estimated positions including noise are shown in Fig.5(B). Two DINDs are installed, and each position is (1000,-3000,2200) and (-1000,-3000,2200). The visual axis of two DINDs is the direction of Y axis. In Fig.5(C) and (D), smoothing was performed by using Kalman filter. Fig.5(C) is the case when an uniform error covariance matrix was used. Error covariance matrix was dynamically changed according to the position in Fig.5(D). In the case of (D), as compared with (C), it turns out that the measurement errors are mitigated and the trajectory is smoothened.



(A) Human walking path (B) Measurement result



(C) Kalman filter (uniform error covariance) (D) Kalman filter (dynamic error covariance)

Fig. 5. Human walking trajectory in ISpace.

4. Mobile Robot Control

4.1 Tracking Control

In order to follow a human, tracking control is performed. Much research is performed on the field of tracking control [9], [10]. The simulation of the human tracking control in ISpace was performed in this section.

Control law is derived from the assumption that a human and a mobile robot are connected with a virtual spring. Input velocity to a mobile robot is generated on the basis of the elastic force from the virtual spring in this model. Position data of walking human is unstable and is not desirable as a control input to a mobile robot, since the unstable input often cause bad influence to speed input of a mobile robot. Even though dynamic error covariance Kalman filter is applied, low frequency fluctuation still remains. Moreover, differential wheel velocity type mobile robot, adopted as agent of the ISpace in current system, has restriction in its motion. Thus the virtual spring model is considered to control non-holonomic mobile robot to follow human. Since the point of application of elastic force differ from rotation center of a mobile robot as shown in Fig.6, non-holonomic restriction is overcome. To trace human who walks freely, a control strategy that absorbs limitation of non-holonomic constraint is needed. The proposed virtual spring model is able to absorb the gap between motion of human and a mobile robot. Control variables are shown in Fig.6.

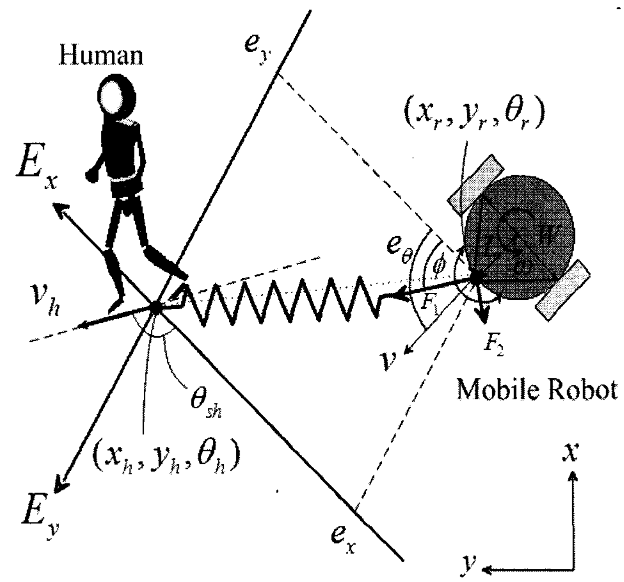


Fig. 6. Control variables in human tracing.

(x_h, y_h, θ_h) is world coordinate of joint, which connects the mobile robot to the virtual spring. (x_r, y_r, θ_r) is the position and posture of the mobile robot. These both vectors are measured by the ISpace. First, the coordinate system of ISpace is changed into the coordinate system on the basis of the human followed by the mobile robot.

$$\begin{pmatrix} e_x \\ e_y \\ e_\theta \end{pmatrix} = \begin{pmatrix} \cos\theta_h & \sin\theta_h & 0 \\ -\sin\theta_h & \cos\theta_h & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_r - x_h \\ y_r - y_h \\ \theta_r - \theta_h \end{pmatrix} \tag{3}$$

Next, the dynamic equations are derived in case the elastic power of the virtual spring is applied to a mobile robot. The input value of velocity and angular velocity is determined by following equations.

$$M\dot{v} = -k_1(l - l_0)\cos(e_\theta - \phi) - \frac{k_2\phi}{l}\sin(e_\theta - \phi) - k_3 v \tag{4}$$

$$I\dot{w} = (k_1(l - l_0)\sin(e_\theta - \phi) + \frac{k_2\phi}{l}\cos(e_\theta - \phi) - k_4 w)L \tag{5}$$

M, I are mass and inertia moment of the mobile robot respectively. l and l_0 are deformed length and free length of the virtual spring respectively. l_0 becomes the equilibrium distance between the target human and the mobile robot. ϕ is displacement angle between both ends of the spring. These are expressed with the following equations. l_0 is the desirable interval of a human and a mobile robot. k_1 and k_2 are the elastic coefficients of a spring. $k_3 v$ and $k_4 \omega$ are viscous friction term for both force and torque.

$$\phi = \arctan\frac{e_y}{e_x} \tag{6}$$

$$l = \sqrt{e_x^2 + e_y^2} \tag{7}$$

k_1, k_2, k_3 and k_4 are tuned up empirically with some information of human; maximum speed of walk, maximum acceleration, etc.

4.2 Convergent evaluation

The tracking performance is checked in a simulation of various initial states of the mobile robot.

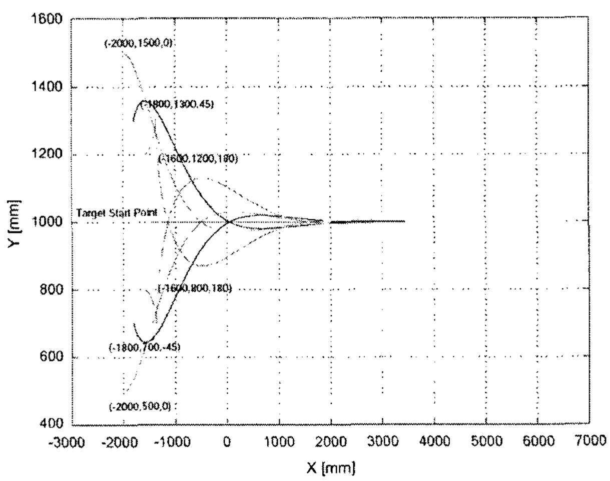


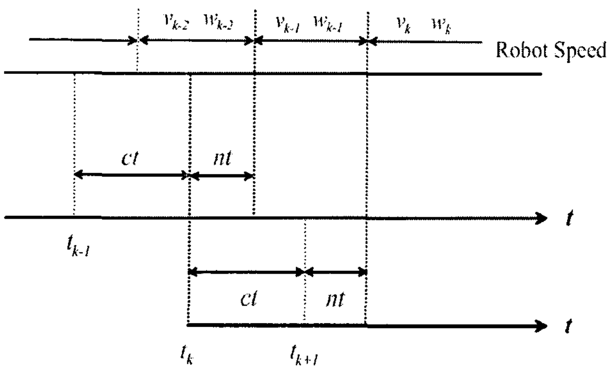
Fig. 7. Convergent evaluation.

It is assumed that target human is walking in parallel to the positive direction of x-axis. Human walking speed is fixed at 400 [mm/s], the initial state vector of human is (-1500, 1000, 0). The trajectories of the human and the mobile robot are shown in the Fig.7. Although a mobile robot starts from any initial position, it is converges into the target. From this simulation results, the validity of proposed control law is verified.

4.3 Robot Position Estimation

When the position of the mobile robot at the time of performing control is compared with the position measured with CCD camera, a gap between these two positions is produced under the influence of calculation time, such as 3-dimensional reconstruction, and network communication time. Therefore, it is necessary to estimate a robot's position and posture at the time of performing control.

While a robot position is detected by DIND, its calculation time and the network communication time can be expressed with a time schedule in Fig.8. A mobile robot controller exists in DIND side, and the following speed input signal to a mobile robot is determined before network communication. In such a case, an estimated position is updated using the functions are shown below. It is necessary to memorize the speed input value of past 2 steps to perform this. Here, x_k, y_k, θ_k are estimated positions. x_c, y_c, θ_c are the positions detected by the camera image.



t_{k-1}, t_k, t_{k+1} : Camera Image Caputure Time

ct : Calculation Time (3D Position,Kalman Filter)

nt : Network Time (from DIND to Robot)

Fig. 8. Time schedule in network communication.

$$x_k = x_c + \int_{tk}^{t_k+ct+nt} v_i(t) \cos\theta dt \tag{8}$$

$$y_k = y_c + \int_{tk}^{t_k+ct+nt} v_i(t) \sin\theta dt \tag{9}$$

$$\theta_k = \theta_c + \int_{tk}^{t_k+ct+nt} w_i(t) dt \tag{10}$$

$$i = k-2 \quad \text{for} \quad t_k < t \le t_k + ct$$
$$i = k-1 \quad \text{for} \quad t + ct < t \le t_k + ct + nt$$

5. Simulation and Experiment

Here, the simulation that a mobile robot follows an actual walking human by using the proposed control law is performed, and the possibility of realization of the human following system in the ISpace is verified. As simulation environment, we assumed a space with two DINDs, and the measurement noises, mentioned previous section, exist in the position estimation function. Time delay caused by its calculation time and the network communication time is also included in this simulation. Time delay was set to ct=200[ms], nt=10[ms] based on the measurement results of network communication time and sampling time of image processing. The actual human walking trajectory is extracted by the method mentioned above. This trajectory is used as a target human. In this environment, all the 3-dimensional positions of a robot and human are measured by DINDs, and a mobile robot is controlled by DIND. A simulation results are shown in Fig.9. (A) is the raw data of human's trajectory. (B) is comparison of trajectory of human after filtering and trajectory of a robot. (C) and (D) show the motions of x,y axis as for the time. This figure shows that the mobile robot is following the human walking well. Low frequency fluctuation in human trajectory was cut off by virtual spring and the robot was controlled smoothly. Moreover, input of the velocity and angular velocity of the mobile robot are shown in Fig.10. It can be found that there is no abrupt change in input values.

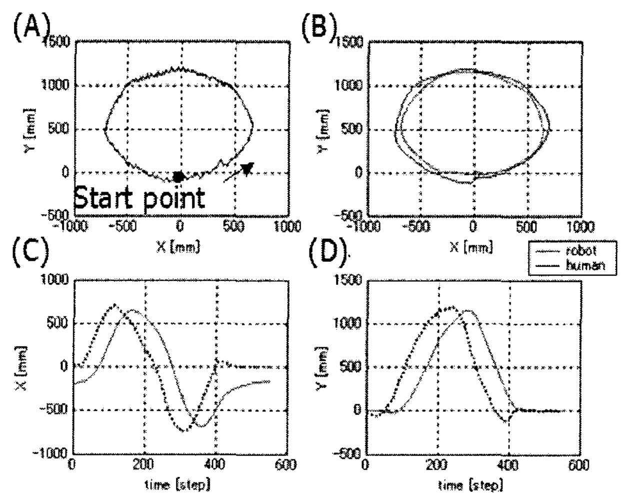


Fig. 9. Robot simulation results.

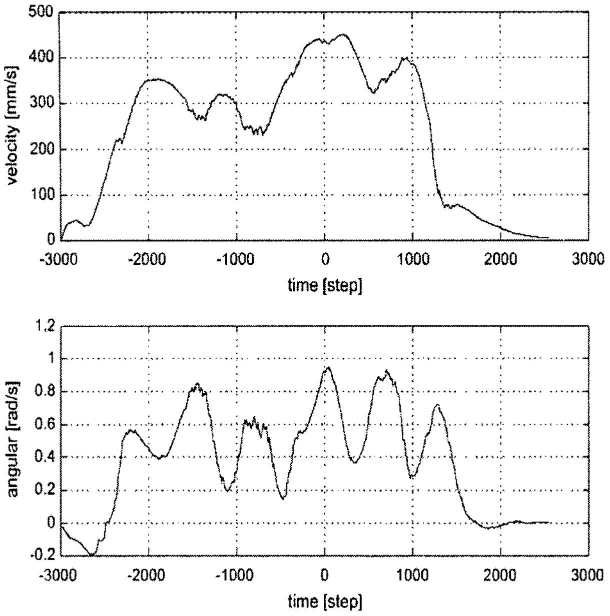


Fig. 10. Robot velocity and angular velocity input.

Next, an experiment was performed in the environment as Fig.11. The network of 5 DINDs, which consisted of 3 DINDs for mobile robot and 2 DINDs for human, were used in this experiment. We assumed that only one human and one mobile robot existed in this ISpace. Human trajectory was extracted by human tracking DIND with the pair of two CCD cameras. To control a mobile robot, 3 DINDs were used and each of DIND monitored different area. The control parameters were tuned to M=30.0[kg], I=1.5[kg·m^2], k_1=3.0, k_2=0.001, k_3=30, k_4=20.0 empirically.

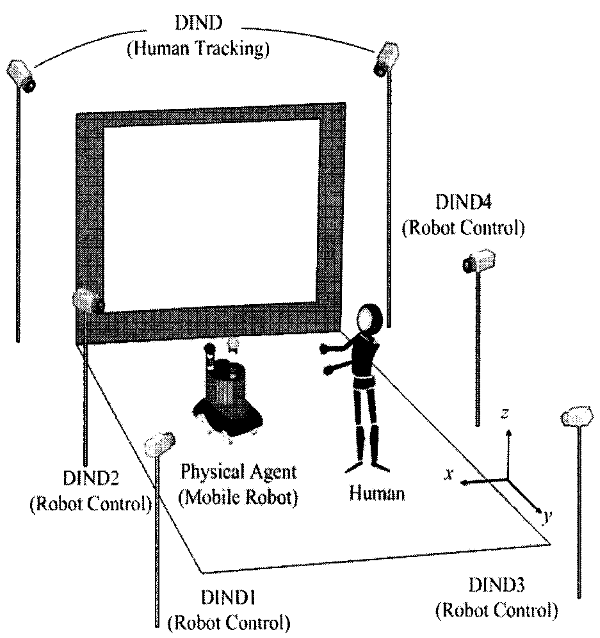


Fig. 11. ISpace experimental environment.

The results of experiment are shown in Fig.12. A human walked along a square path and the mobile robot followed him. The robot deviated from the target human's trajectory when the robot was passing left area. Since the area was just mid of both DINDs and the recognition rate was very low occasionally, the position of the robot was mismeasured. However even if the robot was deviated largely from the trajectory of the target human, it is found from the results that the proposed algorithm make the robot to follow the target again without excessive motions.

6. Conclusion

In this paper, a mobile robot following human in ISpace is explained. The position of the human and the mobile robot in ISpace was measured with DINDs. Since it measures the position by the camera image, measurement noises are included in the detected position. The position dependability of the measurement errors in world coordinates was calculated, and the features of this noise was discussed. Kalman filter was designed based on this, and measurement error was sharply reduced. The control law using the virtual spring model was proposed for a mobile robot in order to follow human. The proposed model is able to absorb the gap between motion of human and a mobile robot. The simulation and experiment of human following control of a mobile robot were performed by using this control law. It was shown that human following is possible in an environment governed by DINDs. As a future work, it is necessary to apply this system to the complex environment where many people, mobile robots and obstacles exist.

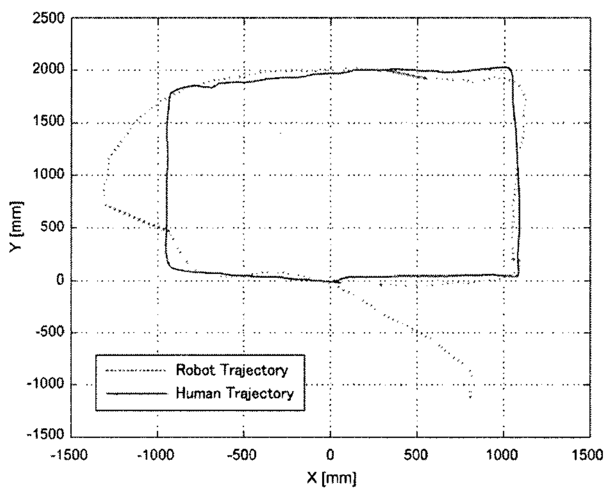


Fig. 12. Experimental result of human following robot.

References

[1] Joo-Ho Lee, Hideki Hashimoto, "Intelligent Space," Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2000, pp.1358-1363.

[2] Sung-On Lee, Hwang-Bo Myung, Bun-Jae You, Sang-RokOh, and Young-Jo Cho, "Vision Based Mobile Robot Control for Target Tracking," IFAC Workshop on Mobile Robot Technology, 2001, pp.73-78.

[3] Y.U.Cao, A.S.Fukunaga, and A.B.Kahmg, "Cooperative Mobile Robotics," Autonomous Robots, Vol. 4, 1997, pp.7-27.

[4] J.P.Desai, J.Ostrowski, and V.Kumar, "Controlling Formations of maltiple Mobile Robots," IEEE Proceeding of Intl. Conf. Robotics and Automation, 1998, pp.2864-2869.

[5] G. Appenzeller, J.-H. Lee, and H.Hashimoto, "Building Topological Maps by Looking at People: An Example of Cooperation between Intelligent Space and Robots," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'97), 1997, pp.1326-1333.

[6] J.-H. Lee, T. Yamaguchi and H. Hashimoto, "Human Comprehension in Intelligent Space," IFAC Conference on Mechatronic Systems, 2000, pp.1091-1096.

[7] J.-H. Lee, H.Hashimoto, "Controlling Mobile Robots in Distributed Intelligent Sensor Network", IEEE Transactions on Industrial Electronics, Vol. 50, No. 5, 2003, pp.890-902.

[8] Joo-Ho Lee, Noriaki Ando, and Hideki Hashimoto, "Design Policy of Localization for Mobile Robots in General Environment," Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 1999, pp.1733-1738.

[9] Yutaka Kanayama, Yoshihiro Kimura, Fumio Miyazaki, and Tetsuo Noguchi, "A Stable Tracking Control Method for a Non-Holonomic Mobile Robot," Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 1991, pp.1236-1241.

[10] K.Yoshizawa, H.Hashimoto, M.Wada, and S.Mori, "Path Tracking Control of Mobile Robots Using a Quadratic Curve," Proc. of IEEE Intelligent Vehicles Symposium, 1996, pp.58-63.

[11] TaeSeok Jin, Kazuyuki Morioka, and Hideki Hashimoto, "Appearance Based Object Identification for Mobile Robot Localization in Intelligent Space with Distributed Vision Sensors," International Journal of Fuzzy Logic and Intelligent Systems, Vol. 4, No. 2, 2004, pp.165-171.

[12] TaeSeok Jin, Hideki Hashimoto, "Multi-Object Tracking using the Color-Based Particle Filter in ISpace with Distributed Sensor Network" International Journal of Fuzzy Logic and Intelligent Systems, Vol. 5, No. 1, 2005, pp.46-51.

TaeSeok Jin

He received the B.Sc. degree from Jinju National University, M.Sc. and Ph.D. degrees from Pusan National University, Busan, Korea, in 2000 and 2003, respectively, all in electronics engineering.

He is currently a Researcher at the Institute of Industrial Science, The University of Tokyo, Japan. His research interests include sensor fusion, mobile robots, computer vision, redundant manipulator, and intelligent control. Dr. Jin is a Member of the KSME, JSME, IEEK, ICASE, and KFIS.

Phone : +81-3-5452-6258
Fax : +81-3-5452-6259
E-mail : jints@hlab.iis.u-tokyo.ac.jp

Hideki Hashimoto (S'83-M'84)

He received the B.E., M.E., and Dr.Eng. degrees in electrical engineering from The University of Tokyo, Tokyo, Japan, in 1981, 1984, and 1987, respectively.

He is currently an Associate Professor at the Institute of Industrial Science, The University of Tokyo. From 1989 to 1990, he was a Visiting Researcher at Massachusetts Institute of Technology, Cambridge. His research interests are control and robotics, in particular, advanced motion control and intelligent control. Dr. Hashimoto is a Member of the Society of Instrument and Control Engineers of Japan, Institute of Electrical Engineers of Japan, and Robotics Society of Japan

Phone : +81-3-5452-6258
Fax : +81-3-5452-6259
E-mail : hashimoto@iis.u-tokyo.ac.jp