Minimally Privacy-Violative Human Location Sensor by Ultrasonic Radar Embedded on Ceiling

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Abstract
A system observring human daily activities that may violate privacy is unacceptable in our society. This paper proposes a minimally privacy-violative system for locating a person using an ultrasonic radar embedded on a ceiling of a room. One of presumable applications is a system for preventing aged people suffering from Alzheimer's disease from accidents. The proposed system can determine the three dimensional position of a person's head by assuming that the human head is an object that will move at relatively high vertical position of a living area. The system doesn't input unnecessarily rich information such as images using a camera so that it can reduce the possibility for violating privacy. The authors constructed an experimental system that consists of 18 ultrasonic transmitters and 32 receivers which are embedded on the ceiling of a room. Experimental results confirmed the feasibility of the proposed system.

Keywords
Minimally privacy-violative sensor, Human location sensor, Ultrasonic radar

INTRODUCTION
Applications based on the observation of human activities are increasingly realizable due to the availability of inexpensive sensing systems[1] and the recent development of ubiquitous computing technologies[2]. There is a strong demand in some fields for the observation of human activities. A survey by the authors found that, in order to prevent serious accidents, caretakers at nursing homes must observe those patients who suffer from Alzheimer's disease.

In our society, however, systems that monitor daily human activity are unacceptable if the privacy of the individuals is violated. There are many problems in using privacy violative sensor such as a camera[3]. This point is particularly important in private home and nursing home environments where long-term, daily monitoring of human activity occurs.

On the other hand, measuring methods which involve devices or sensors attached directly to the human body are not suitable, since there exist a possibility of discouraging the human's natural behavior, not to mention the risk of the sensors being detached or broken in the course of the experiment.

To solve these problems, a system for observation of human activities needs to satisfy two conditions of "minimally privacy-violative observation" and "unconstrained observation". The authors have developed an ultrasonic radar system that satisfies the demands for observing human activity.

In this paper we propose an ultrasonic radar based system which can comply with the following: 1)minimal privacy violation, 2)unconstrained measurement of location for the human head, 3)easy calibration, and 4)position detection for the ultrasonic tags, which are compounding this human activities observing system.

ULTRASONIC RADAR SYSTEM EMBEDDED IN A CEILING

Minimally privacy-violative observation
In this paper, "minimal privacy violation" means that the possibility of violating one's privacy is minimized but not eliminated entirely. As such, the following design method is offered as one solution.

- The developer clarifies the information necessary to realize the target application.
- The developer designs a system in which unnecessarily rich information is not input and is not stored at the system layers, such as the sensor layer, signal process-ing layer, activity recognition layer and application layer.
- The resulting system should reduce the risk of information leaks, or should reduce the cost of an information management system that avoids the risk of information leaks.

This paper concerns a human location system that realizes a minimum of privacy violation in the sensor layer. The proposed system uses ultrasonic radar that is embedded in the ceiling of a room. The system does not collect unnecessarily rich information, such as the images taken by a camera, so as to reduce the possibility of violating individual privacy.

Unconstrained observation
A RFID and tagging system are the typical tools in observing the human activities. These methods however request to have a sensor attached to the human body, this sometimes compromising the results of the conducted experiment. The sensors may fall in the course of the experiment or their placement in the human body can discourage the natural behavior during the experiment's subject performance.

To successfully address and solve this problem, the condition of the unconstrained human behavior observation has to be satisfied. In this paper we propose an ultrasonic radar system as one of the elegant solutions for this problem. In general the ultrasonic radar system consists of several transmitters and receivers embedded throughout the measuring environment. In addition this system doesn't use any sensors attached to the subject's body.

Principle of measurement in ultrasonic radar system

In the ultrasonic radar system developed by the authors, it is assumed that the human head is an object moving at a relatively high vertical position in a living area, and the position of the head can be detected by emitting ultrasonic sounds and receiving them back as they are reflected from the head.
This section explains the principle used to measure and calculate, that is, to locate, the position of a human head with unconstraint.
If the positions of the i-th transmitter, j-th receiver and head are $\mathbf{P_{ti}} : (x_{ti}, y_{ti}, z_{ti}), \mathbf{P_{ri}} : (x_{rj}, y_{rj}, z_{rj})$ and $\mathbf{P} : (x, y, z)$, respectively, and the propagation distance is L , as shown in Fig. 1, then the following equation of a spheroid can be obtained.

$$L_{ti,rj} = |\mathbf{P_{ti}} - \mathbf{P}| + |\mathbf{P_{rj}} - \mathbf{P}| \quad (1)$$

If $\mathbf{P_{ti}}$ and $\mathbf{P_{rj}}$ are known, then the head position $\mathbf{P}$ can be calculated from the three equations of a spheroid.

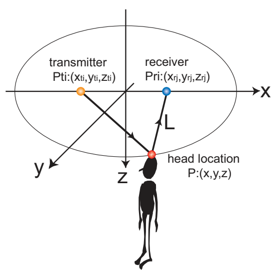

Figure 1. Principle used to locate human head by ultrasonic radar

Algorithm for estimating head position using redundant data

The following procedure for estimating the head position is adopted.

1. Emit ultrasounds with the i-th transmitter, and receive ultrasounds with all of the receivers.
2. Select three receivers from among all of the receivers that can detect ultrasounds.
3. Solve for the head position using Eq. (1).
4. Repeat Steps 2 and 3 for all combinations of receivers that can detect ultrasounds.
5. Repeat Steps 1 through 4 for all transmitters.
6. Calculate the probability distribution for the existence of a head in the target area. Figure 2 shows an example of calculated probability distribution.
7. Select the position with the highest probability as the optimally estimated value for the head position.

PROTOTYPE OF ULTRASONIC RADAR SYSTEM AND EXPERIMENTAL RESULTS

Experimental system

The authors constructed an experimental system based on ultrasonic radar. Figure 3 is an overview of the system. Figure 4 shows the configuration of the ultrasonic radar. The system is composed of 18 transmitters, 32 receivers, three

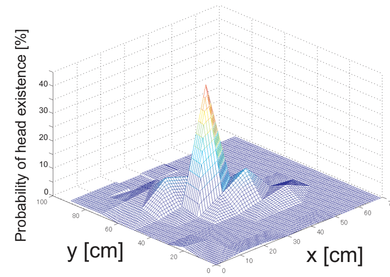

Figure 2. Example probability distributions for human head detection

transmitter-controllers, four receiver-controllers, a network device and a host computer. Component development for this system was based on an ultrasonic location sensor system developed previously by the authors[5]. The transmitters and receivers are embedded in a ceiling. The frequency of ultrasounds emitted from the transmitters is 40 kHz. The distance of ultrasound propagation is determined by measuring time-of-flight, and the transmitters and receivers of the system are synchronized for this purpose.

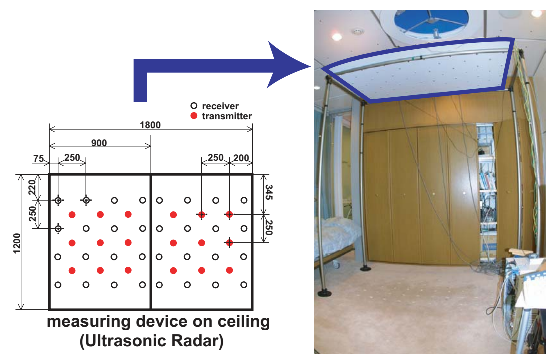

Figure 3. Experimental system for locating a human head by ultrasonic radar

The upper part of Fig. 5 shows the measured trajectory of the human head when the test subject moves as shown in the lower part of the figure. The figure shows that the system can detect the positions of the head at a frequency of 1 Hz.

Evaluation of accuracy

The authors evaluated the accuracy of the constructed system in terms of its ability to detect the location of a human head. Figure 6 shows the results of the evaluation of the system, where the blue points indicate true locations of the head, and the red crosses indicate the measured locations of the head. From the result of evaluation, we confirmed that this system could detect the position of a human head within an error of 54 mm.

FUNCTIONS FOR ACTUAL USE

Simulation software

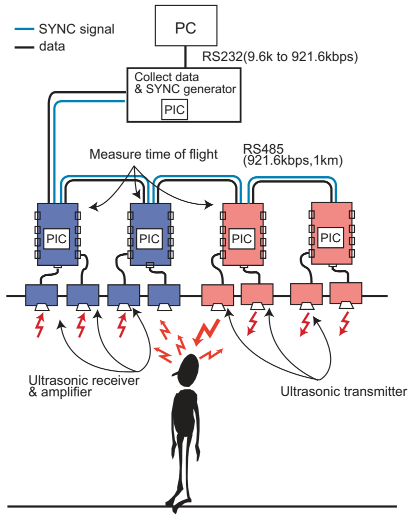

Figure 4. Configuration of the constructed ultrasonic radar system

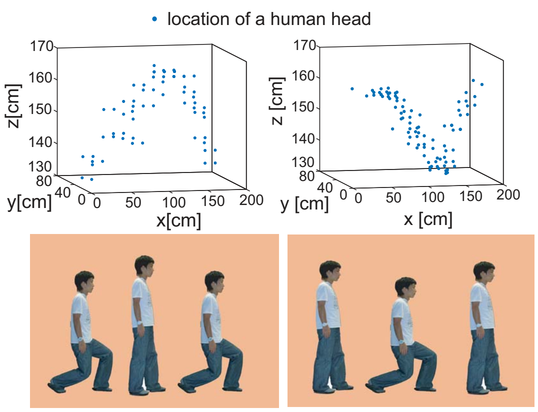

Figure 5. Tracking the position of a human head

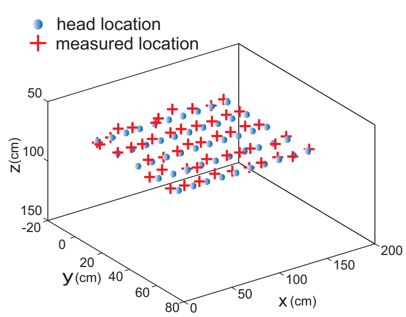

Figure 6. Evaluation of human head location accuracy

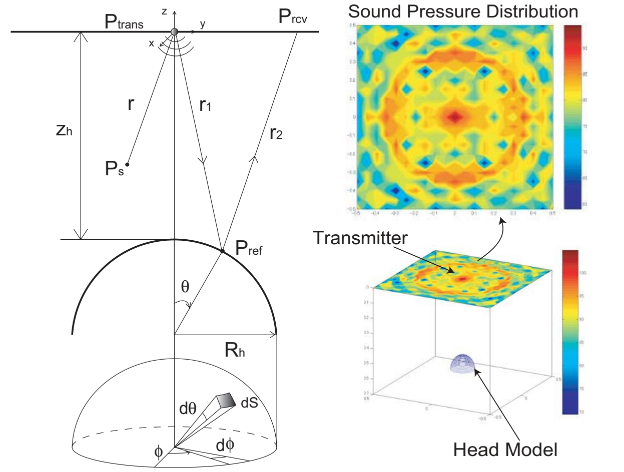

Figure 7. Model of ultrasonic reflection from human head and an example of simulation results

To robustly detect the position of a human head, receivers must be arranged appropriately according to the environment in which the ultrasonic radar is installed. The authors have developed a method of simulating sound pressure on the ceiling by modeling, from an acoustic perspective, the emitted ultrasounds and their reflections from a human head. This allows the proper configuration of ultrasonic transmitters and receivers to be determined by analysis.

The left part of Fig. 7 defines variables used to describe a human head, a sound source and other points. We assume here that the transmitter is a single sound source, and the human head is a hemisphere reflector. According to Rayleight's theory[4], the velocity potential from the reflector $\dot{\Phi}_R$ is expressed by

$$\dot{\Phi}_R = -\int \frac{jkU_0 e^{-jk(r_1+r_2)}}{8\pi^2 r_1 \cdot r_2} dS. \qquad (2)$$

Hence, the sound pressure $\dot{P_R}$ at P_{rcv} becomes

$$\dot{P_R} = j\omega\rho\dot{\Phi_R} = \int \frac{k\rho\omega U_0 e^{-jk(r_1+r_2)}}{8\pi^2 r_1 \cdot r_2} dS, \qquad (3)$$

where,

$$dS = R_h^2 \sin\theta \cdot d\theta \cdot d\phi. \qquad (4)$$

The right part of Fig. 7 shows an example of the analysis results from the simulation. The conditions for this simulation are: 1) The higher part of the sound pressure is assumed to be that part in which sound is available. 2)A transmitter is placed at the center of the ceiling. 3)A model of the human head is placed under the transmitter. By determining in advance the sound pressure levels detected by the receivers to be used, a developer can estimate which receivers can detect the reflected ultrasounds and thus configure the receivers properly through analysis. According to this analysis, the lattice arrangement of receivers is adopted for the system.

Integration with ultrasonic tagging system

We have developed a 3D ultrasonic tagging system which is able to track the three-dimensional motion of tagged objects within a error of 2 to 8 cm in real time [5]. The system uses a technology similar to the ultrasonic radar system, that is, the three dimensional positions of the tagged objects are calculated based on time-of-flight data. By integrating with the 3D ultrasonic tagging system, we can obtrain more advantages: 1) The system can detect not only a position of human head unconstrainedly but also positions of multiple tagged objects rubostly. Application of this function is described later. 2) A user can quickly calibrated positions of transmitters and receivers attached on the ceiling using a calibration method developed by the authors[6].

Figure 8 shows the configuration of the integrated system. The ultrasonic tags are synchronized and controlled via. wireless communication. The receivers are utilized for sampling ultrasonic waves that emited from the transmitters embedded on the ceiling as well as the transmitters of the ultrasonic tags.

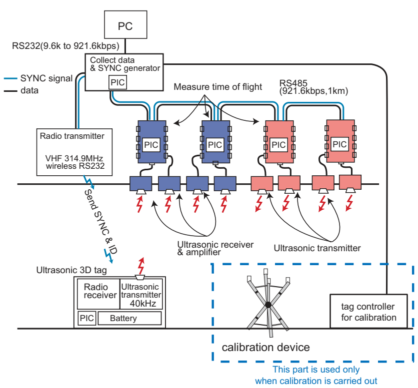

Figure 8. Configuration of integrated system

Presumable application

One of presumable applications by the integrated system is an observation of patients in nursing home and a hospital. A survey conducted by the authors, a patient never wants to have a special device even if the sensor can contribute to reducing the possibility of accident. However it is acceptable that caretakers attached a device to a patient's wheelchair. The integrated system can cope with such a case, namely, it can monitor the position of the patient on a bed using the ultrasonic radar function and monitor the position of the wheelchair using the ultrasonic tagging function as shown in Fig. 9. The system as shown in this figure would work as a component of a system for supporting accident prevention. The authors are developing such a system in cooperation with a nursing home.

CONCLUSIONS

In this paper, we described the concept of minimum privacy violation, in which the possibility of privacy violation is minimized but cannot be eliminated completely. We proposed an ultrasonic radar system embedded in the ceiling of a room as one example of a human location sensor that exhibits minimum privacy violation. The system does not input unnecessarily rich information, such as the images taken by a camera, so that the possibility of privacy violation is reduced. We constructed its experimental system composed of 18 transmitters and 32 receivers. The experimental results show that the constructed system can detect a human head within 5 cm of error and can track a human head at a frequency of 1 Hz. This paper also shows the ultrasonic radar system integrated with a ultrasonic location system that was also developed by the authors. The integrated system satisfies the following demands: 1)minimal privacy violation, 2)unconstrained measurement of location for the human head, 3)easy calibration, and 4)position detection for positions of tagged objects.

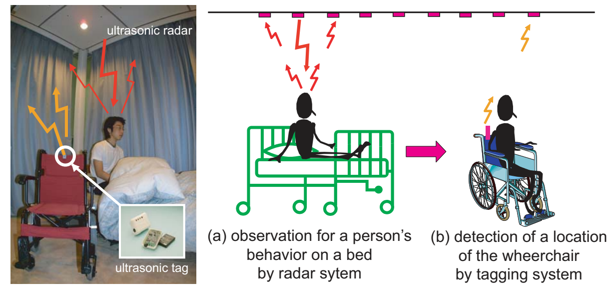

Figure 9. Application in nursing home

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REFERENCES

[1] Hori T. Overview of Digital Human Modeling *Proceedings of 2000 IEEE/RSJ International Conference on Intelligent Robotics and Systems(IROS2000), Workshop Tutorial Note* pp. 1-14, 2000

[2] Hansmann U., Merk L., Nicklous M.S. and Stober T., *Pervasive Computing Handbook. The Mobile World* Springer-Verlag Telos, 2001

[3] Hunter R. *World Without Secrets: Business, Crime and Privacy in the Age of Ubiquitous Computing* John Wiley & Sons, Inc., 2002

[4] Rayleigh J.W.S., *The Theory of Sound* Vol. 2, Dover Publications (New York), (original) 1877, (reprint) 1945

[5] Nishida Y., Aizawa H., Hori T., Hoffman N.H., Kanade T. and Kakikura M. 3D Ultrasonic Tagging System for Observing Human Activity *Proceedings of IEEE International Conference on Intelligent Robots and Systems (IROS2003)* pp.785-791, 2003

[6] Nishitani A., Nishida Y., Hori T. and Mizoguchi H. Portable 3D Ultrasonic Tag System Based on a Quick Calibration Method *Proceedings of 2004 IEEE International Conference on Systems, Man and Cybernetics (SMC2004)* 2004 (in press)