Minimally Privacy-Violative System for Locating Human by Ultrasonic Radar Embedded on Ceiling*

Yoshifumi Nishida
Digital Human Research Center
AIST & CREST, JST
2-41-6, Aomi, Koto-ku, Tokyo
135-0064, Japan
y.nishida@aist.go.jp

Shin'ichi Murakami
Mechanical Engineering Department
Tokyo University of Science
2641,Yamazaki, Noda-shi, Chiba
278-8510, Japan
s-murakami@aist.go.jp

Toshio Hori
Digital Human Research Center,
AIST & CREST, JST
2-41-6, Aomi, Koto-ku, Tokyo,
135-0064, Japan
t.hori@aist.go.jp

Hiroshi Mizoguchi
Mechanical Engineering Department
Tokyo University of Science
2641, Yamazaki, Noda-shi, Chiba,
278-8510, Japan
hm@rs.noda.tus.ac.jp

Abstract – *Violating the privacy of individuals with systems that measure daily human activities is unacceptable in our society. In this paper, the authors propose a system using ultrasonic radar embedded in the ceiling of a room to locate human individuals with a minimum violation of privacy. It is expected that this system will be used in the prevention of accidents among aged persons suffering from Alzheimer's disease. The proposed system determines the three-dimensional position of a person's head by assuming that the human head is an object that will move at a relatively high vertical position within a living area. In this study, the method used to locate the human head is analyzed theoretically from the perspective of acoustics. The feasibility of the proposed system is confirmed by experimental results using a system constructed by the authors.*

Keywords: Minimum privacy violation sensor, Human location sensor, Ultrasonic radar

1 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.

Collecting rich information on individuals leads to an increased possibility of privacy violation. A more rigorous management of information is therefore required. This is expensive, however, and more importantly, such a rigorous management of information cannot be accomplished easily. The solution is to minimize the possibility of privacy violation.

In this paper, "minimum 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 processing 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.

The ultrasonic radar technology used in this study has been applied widely in such fields such as robot collision avoidance and medical diagnosis. It has not been applied, however, in locating persons in their daily living spaces. In this type of application, the area to be monitored and the distance from the radar system to the human subject will vary depending on the target area, and the amount of space available to install the ultrasonic radar system may be limited in some living spaces even when ceilings are used. To address this problem the authors developed a simulation method, described in this paper, with which the developer of human locating systems can analyze and determine an optimal configuration of ultrasonic transmitters and receivers appropriate to the target space.

2 Locating Humans by Ultrasonic Radar Embedded in a Ceiling

2.1 Ultrasonic Radar Embedded in a Ceiling

This paper proposes ultrasonic radar as a system for locating humans with minimal privacy violation. An ultrasonic radar system basically consists of several transmitters and receivers embedded in a ceiling. It is assumed in the system 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 system is considered a minimum privacy violation monitor because it merely detects the location of a human and infers behavior about the subject from this information. It cannot be easily used to reconstruct a high-resolution image.

2.2 Application as an accident prevention system

The authors believe this system can be applied as an accident prevention system for aged patients in nursing homes. Some of the behaviors of aged individuals in and around their beds, for example, can be inferred from the detection of head positions. Fig.1 shows some system-detectable behaviors that can be used to prevent accidents such as ”falling from the bed to the floor,” ”sitting up in bed,” ”moving about on the bed” and ”moving from the bed to another location.”

2.3 Principle of measurement

This section explains the principle used to measure and calculate, that is, to locate, the position of a human head.

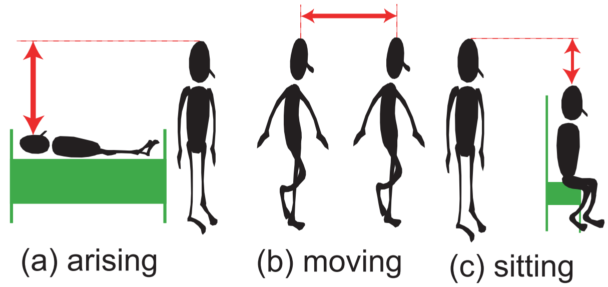

Figure 1: Examples of detectable behaviors

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 in Fig. 2, 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.

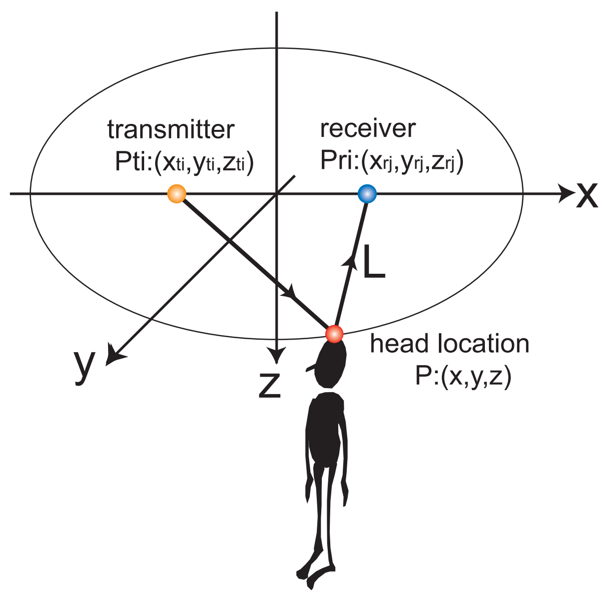

Figure 2: Principle used to locate human head by ultrasonic radar

2.4 Algorithm for estimating head position using redundant data

The following procedure for estimating the head position is adopted in the experimental system described in Section 4

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.
7. Select the position with the highest probability as the optimally estimated value for the head position.

3 Sensor Simulation for Adaptation of the Environment

3.1 Analysis for receiver configuration

3.1.1 Theory of ultrasonic reflection from a human head

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. This section describes a theory of ultrasonic reflection from the human head.

Figure3 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.

In the absence of a reflector, the velocity potential $\dot{\Phi}_s$ at a point P_s on the reflector is expressed by

$$\dot{\Phi}_s = \frac{U_0}{4\pi r} e^{-jkr}, \tag{2}$$

where U_0 , k and r denote the volume of the velocity of the sound source, the wave number of the sound wave and the distance of P_s from the sound source, respectively.

The particle velocity $\dot{V}_{ref}$ at P_s then becomes

$$\dot{V}_s = -\frac{\partial \dot{\Phi}_s}{\partial r} = \frac{U_0\left(1 + jkr\right)}{\partial r^2} e^{-jkr}. \tag{3}$$

If $kr \gg 1$, we can then write

$$\dot{V}_s = \frac{jkU_0}{4\pi r} e^{-jkr}. \tag{4}$$

If the reflector is placed in this sound field and P_s is on the surface of the reflector (i.e. $P_s = P_{ref}$), then particle velocity becomes 0.
Now, assuming the reflector has a reflection efficiency of 1.0, then the velocity potential generated by a reflected wave can be considered equivalent to that generated by the reflector

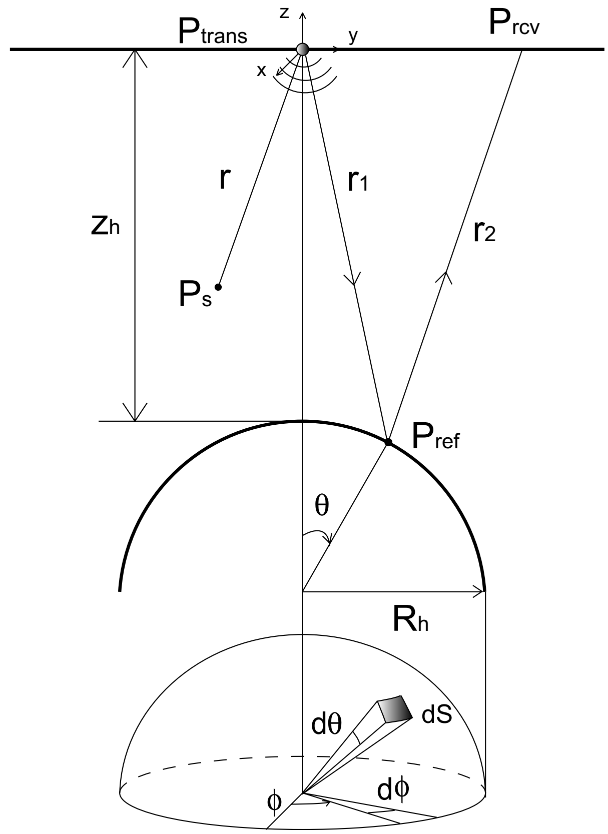

Figure 3: Model of ultrasonic reflection from human head

vibrating at particle velocity $-\dot{V}_s$.

According to Rayleight's theory[4], when only the small element dS situated at P_{ref} vibrates at volume velocity $\dot{V}_s \cdot dS$, while all other elements do not vibrate, then the velocity potential caused by the small element is expressed by

$$\dot{\Phi}_{dS} = -\frac{\dot{V}_{ref} e^{-jkr_2}}{2\pi r_2} dS, \tag{5}$$

where r_2 denotes the distance from P_{ref} of a point P_{rcv} on the ceiling. The velocity potential from the entire reflector $\dot{\Phi}_R$ is obtained by integrating $\dot{\Phi}_{dS}$.
Thus

$$\dot{\Phi}_R = \int \dot{\Phi}_{dS} = -\int \frac{\dot{V}_s e^{-jkr_2}}{2\pi r_2} dS, \tag{6}$$

from which, by eliminating $\dot{V}_s$ using Eq. (4), we obtain

$$\dot{\Phi}_R = -\int \frac{jkU_0 e^{-jk(r_1+r_2)}}{8\pi^2 r_1 \cdot r_2} dS. \tag{7}$$

Hence, the sound pressure $\dot{P}_R$ at P_{ref} becomes

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

where ω is the angular velocity and ρ is the density of air. Note that r_1 and r_2 depend on the position of the element dS. To prepare for numerical analysis, we must digitize Eq. (8). Now, P_{ref} is expressed by

$$P_{ref} = (R_h \sin\theta\cos\phi, R_h \sin\theta\sin\phi, z_c + R_h(1-\cos\theta)). \tag{9}$$

dS can be replaced by

$$\triangle S = R_h^2 \sin\theta \cdot \triangle\theta \cdot \triangle\phi. \tag{10}$$

and Eq. (8) is digitized as follows.

$$\dot{P_r} = \frac{k\rho\omega U_0 R_h^2}{8\pi^2} \Sigma\Sigma \frac{e^{-jk(r_{1i}+r_{2i})}}{r_{1i}\cdot r_{2i}} \sin\theta \cdot \triangle\theta \cdot \triangle\phi \tag{11}$$

3.1.2 Simulation of ultrasound reflection from a human head

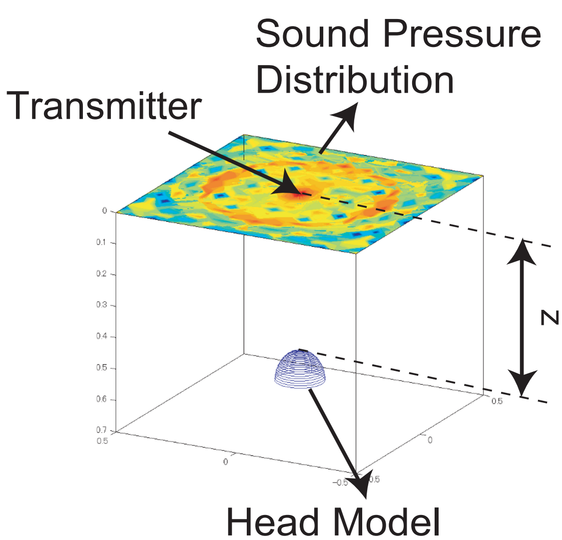

Figure 4: Example of simulation results

Using Eq. (11), we can create a simulation system for calculating sound pressure distribution on a ceiling. Figure 4 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.

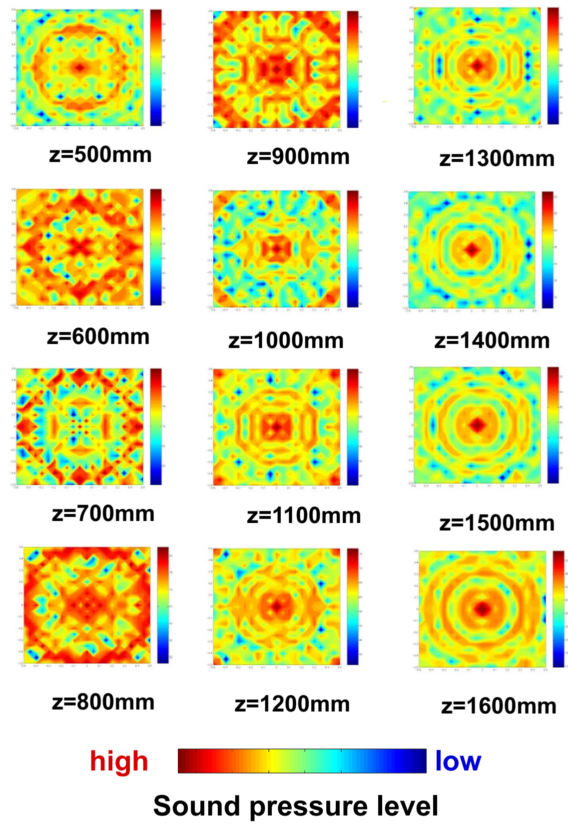

Figure 5: Results from a simulation of sound pressure distribution on ceiling

3.1.3 Discussion on proper receiver configuration

Figure 5 depicts the sound fields on the ceiling as the height of the head z varies from 50 to 160 cm. This figure shows how sound pressure on the ceiling changes as the head height changes.

By determining in advance the sound pressure levels detected by the receivers to be used, the developer can estimate which receivers can detect the reflected ultrasounds and thus configure the receivers properly through analysis. Figure 6(a) to (d) show examples in which the sound pressure level of each receiver on a ceiling is estimated for a ring arrangement as well as a lattice arrangement.

The lattice arrangement of receivers is adopted for the system described in Section 4.

4 Experimental System

4.1 Overview of experimental system

The authors constructed an experimental system based on ultrasonic radar. Figure7 is an overview of the system. Figure 8 shows the configuration of the ultrasonic radar. The system comprises 18 transmitters, 32 receivers, three transmitter-controllers, four receiver-controllers, a network device and a host computer. Component development for this system was based on an ultrasonic location sensor sys-

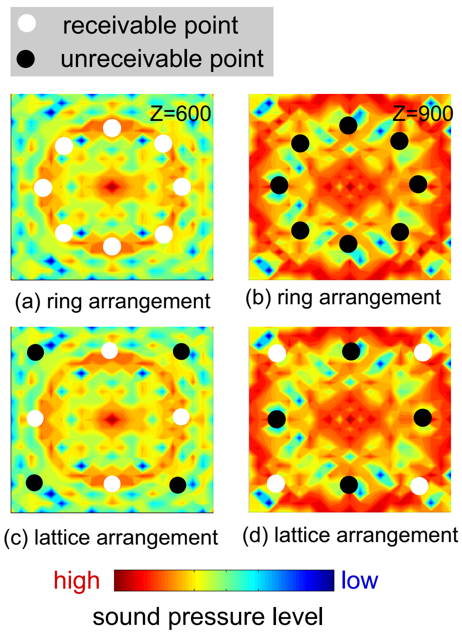

Figure 6: Proper arrangement of receivers

tem 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, and the sampling frequency of the system is 1 Hz. 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.

4.2 Evaluation of accuracy

Figure 9 shows examples of probability distributions for the detection of a human head, that is, the probability that a human head exists at a particular location, as calculated by the algorithm described in Section 2.4. The red areas indicate a high probability, and the blue areas indicate a low probability.

The authors evaluated the accuracy of the constructed system in terms of its ability to detect the location of a human head under the following conditions:

- A total of 50 measuring points were set at 15-cm intervals in the experimental area.
- The test subject stood at each of the measurement points.
- The position of the test subject's head was calculated at each measuring point and compared with the true position.

Figure10 shows the results of the evaluation, where the blue points indicate true locations of the head, and the red crosses indicate the measured locations of the head. From this figure we can see that the system could detect the position of a human head within an error of 5 cm.

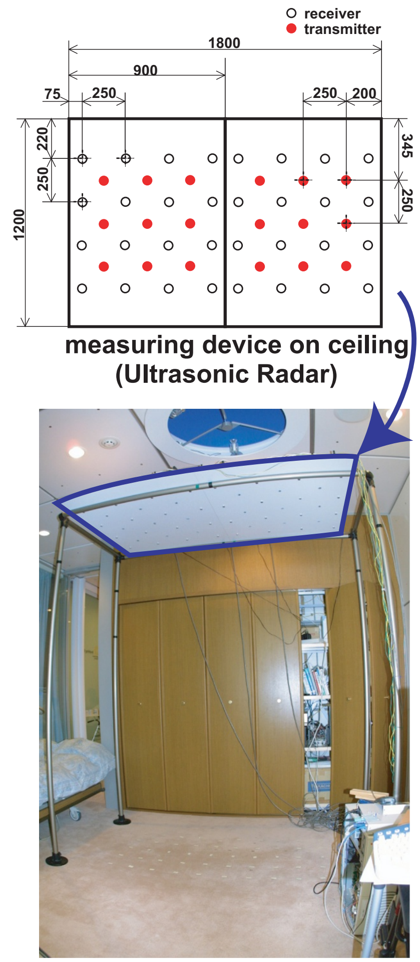

Figure 7: Experimental system for locating a human head by ultrasonic radar

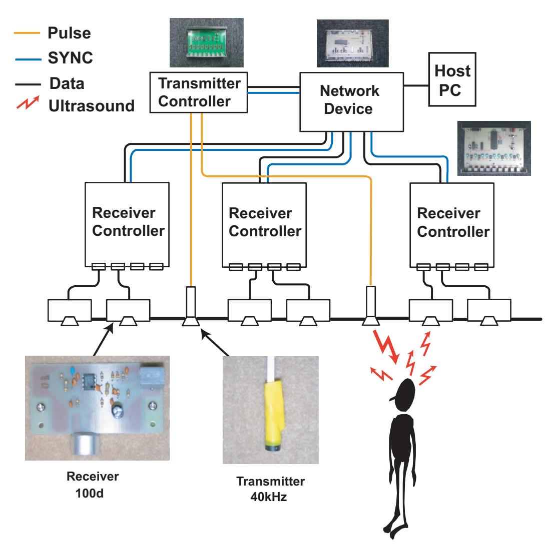

Figure 8: Configuration of the constructed ultrasonic radar system

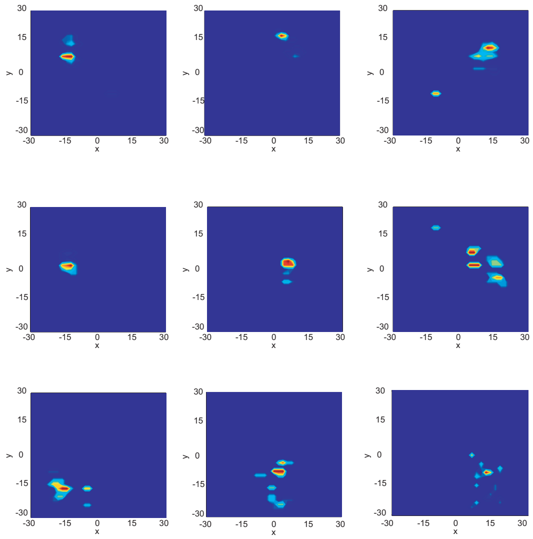

Figure 9: Example probability distributions for human head detection

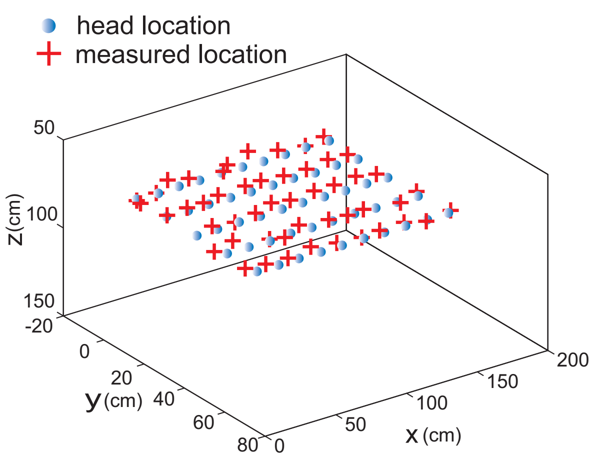

Figure 10: Evaluation of human head location accuracy

The upper part of Fig. 11 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.

5 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. In order to analyze an optimal configuration of ultrasonic receivers and transmitters in accordance with the target

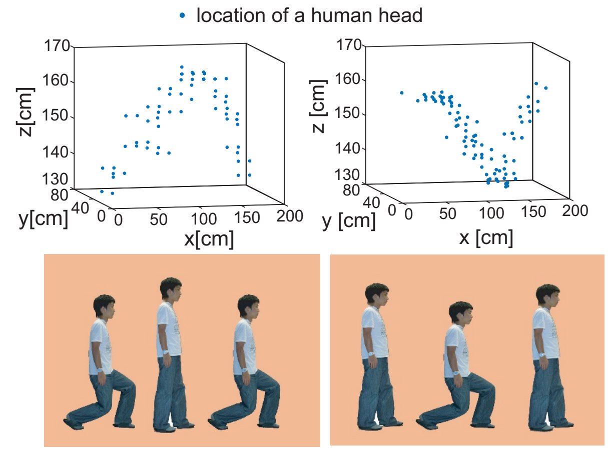

Figure 11: Tracking the position of a human head

space and target application, we presented a theory on the reflection of ultrasounds from the human head. The authors constructed an experimental system using ultrasonic radar technology comprising 18 transmitters and 32 receivers embedded in a ceiling. 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.

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References

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

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

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

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

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