Discrimination of Multiple Objects and Expanding Positioning Area for Indoor Positioning Systems Using Ultrasonic Sensors

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Abstract. This paper describes new concepts and techniques for an indoor positioning system that uses ultrasonic signals to enhance practicability. This indoor positioning system can be applied to the location detection of a moving object such as a person or a goods trolley over a wide indoor area. The proposed system works by means of ultrasonic signals. This makes it easy to avoid multipath effects because the propagation velocity of ultrasonic signals is much slower than that of radio waves. In addition, ultrasonic signals are not restricted by radio regulations that may differ from country to country. The main feature of our system, developed and presented last year, is that it does not require synchronization between the transmitting and receiving units. This paper describes a system for accommodating multiple moving objects and expanding positioning area. Two techniques, the allocation of a specific ID to each positioning object and the use of a virtual receiving point for ultrasonic signals, were investigated in order to realize the required functions and make the proposed system more practical. The effectiveness of these techniques was confirmed by experiments carried out using ultrasonic sensors installed in the ceiling and model railway trains acting as moving objects on the floor below.

Keywords: Indoor positioning, Ultrasonic signal, FPGA, Area expansion, Moving objects.

1 Introduction

The global positioning system (GPS) is widely used for determining position in outdoor areas. It has become a universal system and the location information provided by GPS is widely used in navigation devices and many other service systems [1]-[2]. However, for indoor positioning applications, no common system has yet been established and various possibilities are being investigated. Position information is an indispensable requirement for the realization of “smart space”, which can, for example, be used to assist navigation for the visually impaired and can supply helpful information to people

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regarding appropriate location and timing for various indoor activities. Many applications can make use of location information.

Fig.1 summarizes the different categories of indoor positioning system currently available, taking positioning accuracy and positioning range into consideration. The received signal strength of RF signals from wireless LANs (WLAN) etc., using the so called "Received Signal Strength Indicator" (RSSI), has been used to determine position in an indoor area [3]-[4]. However, signal strength is heavily influenced by multipath effects and it is quite difficult to accurately identify the distance between the receiving unit and the transmitting unit. Consequently, the positioning accuracy that is derived from such distance information is quite low. In addition, the actual multipath effects are dependent on the room layout. As a result, this type of system cannot be applied for practical use in situations where accurate positioning is required. An alternative system based on the propagation time difference and the use of ultra wide band (UWB) has been proposed, but accuracy is not yet adequate for pedestrian navigation and product tracking in indoor areas. A system using RFIDs could be one solution, but since the propagation distance is quite short a lot of RFID tags would be needed to construct a suitable positioning system over a wide area.

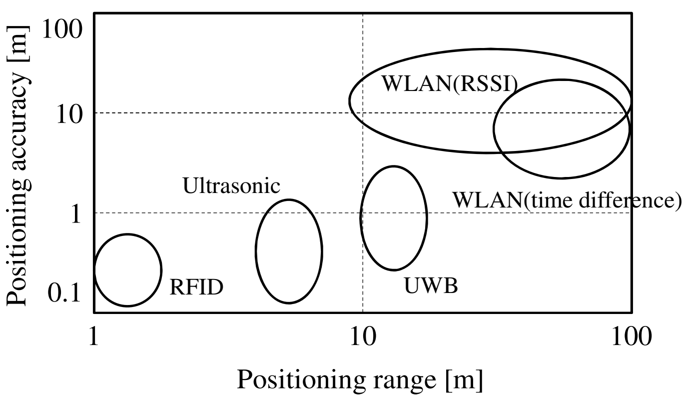


Fig. 1. Categories of indoor positioning systems

Positioning systems based on the use of ultrasonic signals seem to be a promising alternative. Conventional systems are usually based on the principle of trilateration [5], in which, the distance between two points is measured by the difference in propagation time of radio signals and ultrasonic signals [6]. The propagation time of radio signals can be neglected in this system. Therefore, the difference of arrival time between radio signals and ultrasonic signals become propagation time of ultrasonic signal between two points. Alternatively, time synchronization between transmitting and receiving units can be implemented in order to detect the propagation time [7]. However, because these systems use radio devices, they are rather complicated and must satisfy existing radio regulations, which often differ from country to country.

Instead, we have adopted inverse GPS methods [8], in which the arrangement of transmitting and receiving units is the reverse of that used in GPS. We have developed an indoor positioning system based on this method and its effectiveness and positioning accuracy have been evaluated [9]. This paper describes the techniques used to realize the proposed system and the steps needed to make it more practical.

First, the use of ID transmission via an infrared signal was adopted to accommodate multiple moving objects and increase the application area of the system. This technique makes use of an ultrasonic transmitter that is installed on the moving object and only emits an ultrasonic transmission when it receives its own ID signal. Second, since it is desirable to expand the effective positioning area and enlarge the receiving field for ultrasonic signals (thereby reducing the number of ultrasonic detection ports required) the concept of a virtual reception point was also adopted. An experimental system utilizing infrared devices and ultrasonic receiving units was built to verify the effectiveness of these methods. Ultrasonic receiving sensors were installed in the ceiling and the model railroad trains moving on tracks on the floor below were used to evaluate the system experimentally.

2 Positioning Method and System Architecture

2.1 Positioning Method and System Architecture

The system configuration proposed involves the use of ultrasonic receiving sensors connected to a receiving unit embedded in the ceiling and an ultrasonic transmitter attached to a moving object below. The basic operating principle is shown in Fig.2 [9]. Conventional positioning systems are usually based on trilateration, in which time synchronization between the transmitting unit and the receiving unit is required in order to detect the propagation time between the two components. Consequently, some mechanism is needed to establish synchronization. However, in the proposed system, the clock of the transmission unit is independent of the receiving unit. Therefore, the propagation time cannot be obtained and only the delay times of each receiving sensor can be detected. Here, the delay time refers to the amount of time elapsed after the first receiving sensor detects the ultrasonic signal. Three delay times (t_1, t_2 and t_3) can be obtained from four receiving sensors as shown in Fig.2. The synchronization of all receiving sensors is maintained because they are all connected to a single receiving unit in which one clock governs all timing.

The following mathematical equations can be derived by considering the distance and propagation time. Here, x_i, y_i, and z_i are the positions of the receiving sensors and are determined when they are embedded in the ceiling. The constant, c, is the ultrasonic signal velocity (dependents on temperature). The variable, t, is the propagation time from the transmitter to the receiving sensor that is the first of all the receiving sensors to receive the ultrasonic signal signal (an unknown value). The variables t_1, t_2 and t_3 are the delay time at each receiving sensor (determined as described above). The variables x, y, and z are the coordinates giving the position of the moving object that is attached to the transmitter (these values need to be solved). Since there are four unknown quantities (x, y, z and t), at least four receiving sensors are required in order to solve the following equations:

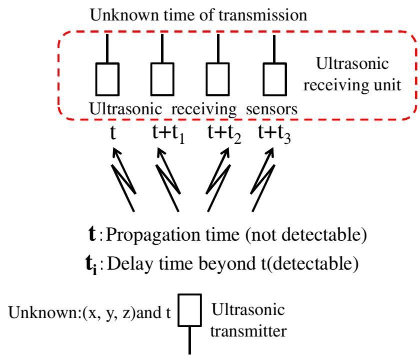


Fig. 2. Basic positioning principle

$$\begin{aligned}
\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2} &= ct \\
\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} &= c(t+t_1) \\
\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} &= c(t+t_2) \\
\sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} &= c(t+t_3)
\end{aligned} \tag{1}$$

2.2 Prototype System Configuration

The prototype system used for verifying the effectiveness of the design proposed in this paper is shown in Fig.3, which illustrates the three components of the positioning system: the ultrasonic receiving unit, the ultrasonic transmitters (#1, #2), and the signal processing PC used for position calculation.

The ultrasonic receiving unit consists of ultrasonic receiving sensors, a FPGA and a H8 microcomputer. The output signal of each receiving sensor (Murata MA40S4R units with a diameter and height of 10mm and 7mm, respectively) is amplified by each receiving unit using an amplifier and comparator, and is detected as the arrival of the ultrasonic pulse.

An FPGA captures the ultrasonic signals from each sensor via the receiving unit and generates count values which indicate the elapsed time between ultrasonic reception and the designated time. The FPGA is capable of receiving signals from a large number of ports. These values are then sent to the PC via the H8 microcomputer and the RS485 interface. A thermistor is used to monitor the ambient temperature since temperature information is needed to compensate for changes in the ultrasonic signal propagation velocity.

The ultrasonic transmitter installed on the moving object has an infrared light receiving sensor attached and each ultrasonic receiving unit also incorporates an infrared light emission unit. The role of this receiver and transmitter is described in the next section.

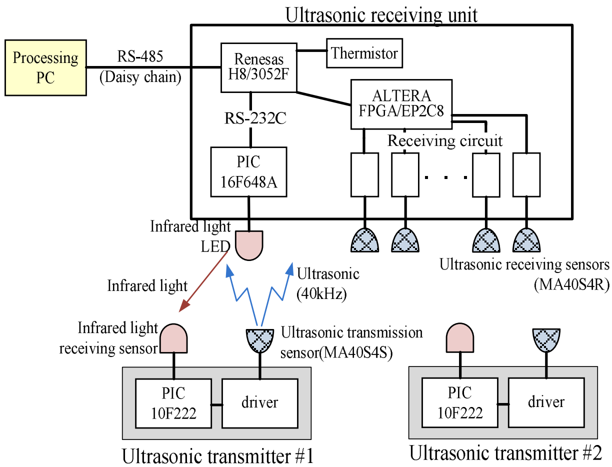


Fig. 3. System configuration

3 Accommodation of Multiple Objects

If the system proposed above is to be of any practical use, it must be able to accommodate multiple moving objects. Distinguishing each individual object is essential in order to satisfy this requirement. Therefore, an infrared signal is used to transmit a designated ID from the ultrasonic receiving unit and the ultrasonic transmitter emits ultrasonic pulses when it receives its own ID. This enables the system to distinguish each individual ultrasonic transmitter that is installed on each positioning object.

The system sequence used to obtain the received times (count values) from multiple moving objects in order to derive the delay time in expression (1) is indicated in Fig.4. The count starts when the ultrasonic receiving unit sends a trigger signal to the ultrasonic transmitter causing it to emit an ultrasonic signal. The count values are then stored in the FPGA in the receiving unit when the associated sensor connected to the receiving circuit receives the ultrasonic signal. These values are sent to the PC via the H8 microcomputer which calculates the delay times that are then used for the positioning calculations. Although only one input capture sequence is described in this figure, multiple count values are obtained from the corresponding ports connected to each ultrasonic sensor.

The delay times, t_i, shown in expression (1) are calculated from these count values by taking the clock time of the receiving unit into account. Each count value is reduced by the count value of the first sensor to receive the ultrasonic pulses (i.e., the minimum count value) in order to convert the counts into delay times. The position calculation is then carried out by taking account of the temperature, obtained as a voltage value from the thermistor, in order to determine the ultrasonic signal velocity, c. The entire sequence, from trigger signal to position calculation, is then repeated for all subsequent iterations, as shown in Fig.4.

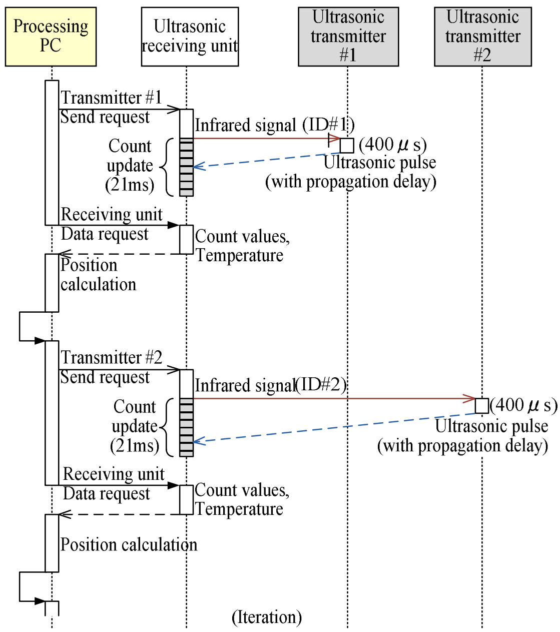


Fig. 4. System sequence

4 Expansion of Receiving Region

In order to make such a system cost effective, it is necessary to expand the receiving region. The receiving region for a single ultrasonic sensor is restricted by the receiving angle. However, if multiple sensors are combined the receiving range can be expanded. The method we used is shown in Fig.5, which illustrates how the receiving range can be expanded without having to increase the number of receiving ports for the FPGA and the number of connections from the receiving unit to the FPGA. This simplifies system installation because multiple sensors can be dealt with just as easily as a single sensor. The signals that are received from all four sensors are then composed by an OR circuit. Therefore, if anyone of the four sensors receives the ultrasonic signals, this is detected by the receiving unit.

Pre-evaluation testing confirmed that this configuration enlarges the receiving area 1.7 times, compared with the conventional method using a single sensor, when measured at a distance of 2 m from the transmitter.

When this technique is applied to the system described above, the concept of a virtual receiving point is used for position calculation. This means that although the real receiving point is the actual sensor location, a virtual receiving point is used for the positioning calculation, as shown in Fig.6. This virtual receiving point represents the location of the four receiving sensors. The following expression (2) needs to be solved whenever the receiving unit is changed in order to expand the receiving area. Here, r refers to the sensor attachment radius and r/c refers to propagation time from

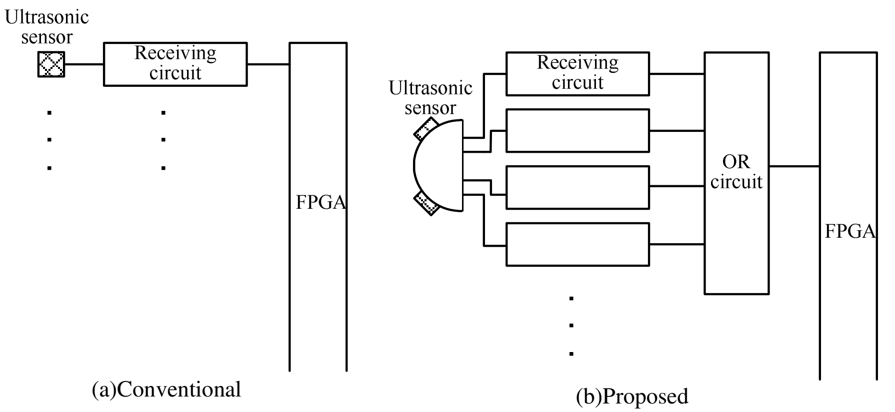


Fig. 5. Proposed method for expansion of the reception field

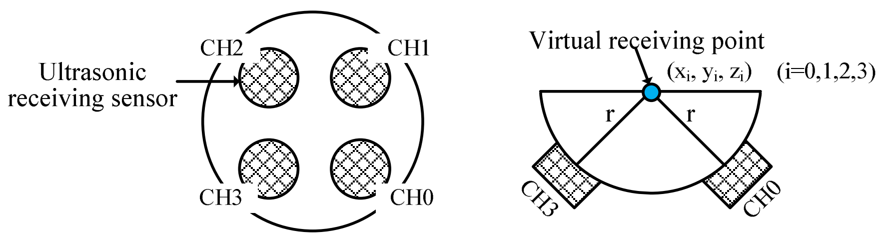


Fig. 6. Virtual receiving point

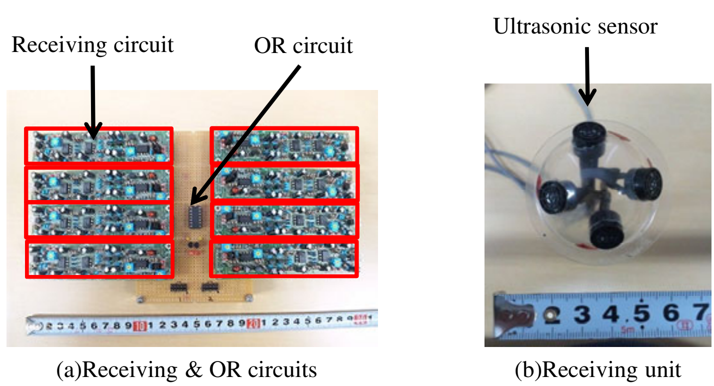


Fig. 7. Receiving circuits and receiving unit

the receiving sensor and the virtual point. The virtual point is set at the center of the sphere to which the four sensors are attached.

An illustration of the receiving circuits and the OR circuit is shown in Fig.7 (a). The four receiving sensors are built into a single receiving unit, as indicated in Fig.7 (b). The OR circuit composes the output signal from the four sensor outputs and its signal is sent to the FPGA to provide the reception timing for the ultrasonic pulse.

$$\begin{aligned}
\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2} &= ct \\
\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} &= c(t+t_1+\frac{r}{c}) \\
\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} &= c(t+t_2+\frac{r}{c}) \\
\sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} &= c(t+t_3+\frac{r}{c})
\end{aligned} \tag{2}$$

5 Confirmation Experiment

5.1 Static Test for Accuracy Evaluation

The validity of the methods proposed above was confirmed by experiment. A comparison of the obtained, using expression (1) and expression (2), is shown in Table 1, including the averaging error and standard deviation. The measurement target was set up on the floor and its position was measured using the two methods described earlier. Five fixed points were set for evaluation purposes. The results indicate that positioning accuracy is not degraded by the introduction of virtual receiving points.

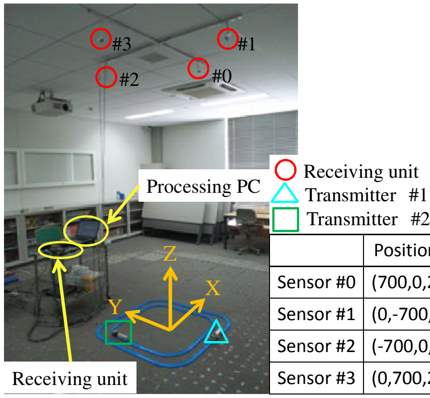
Table 1. Positioning accuracy

Position	Conventional(one sensor)			Proposed(four sensors)		
	Average	Positioning error	Standard deviation	Average	Positioning error	Standard deviation
X = 0	3.6	3.6	3.6	19.9	19.9	8.9
Y = 0	-18.5	18.5	4.5	-39.4	39.4	11.3
Z = 50	50.1	0.1	0.0	50.3	0.3	0.1
X = 0	12.8	12.8	3.4	-32.9	32.9	8.5
Y = 700	819.1	119.1	11.0	669.3	30.7	9.6
Z = 50	56.4	6.4	0.4	52.1	2.1	0.2
X = 0	-19.4	19.4	4.4	-48.8	48.8	10.5
Y = -700	-777.1	77.1	2.8	-720.3	20.3	15.4
Z = 50	59.4	9.4	0.1	57.7	7.7	0.4
X = 700	777.6	77.6	7.2	678.8	21.2	6.2
Y = 0	21.0	21.0	1.2	-44.3	44.3	10.5
Z = 50	59.0	9.0	0.3	56.3	6.3	6.3
X = -700	-763.8	63.8	6.5	-717.6	17.6	6.6
Y = 0	9.2	9.2	0.3	-9.4	9.4	11.1
Z = 50	55.0	5.0	0.2	53.3	3.3	0.2
						(mm)

5.2 Dynamic Test for Moving Object

The practical usefulness of positioning for multiple moving objects was confirmed by experiment. The experimental apparatus used is shown in Fig.8. In this system, two model trains, each with a transmitter attached, are used as moving objects on a model railway track. The virtual positions of each receiving sensor are as indicated in the figure. The z position of the sensors installed on the frame has four locations because positioning accuracy degrades if all sensors are put in the same plane.

The experimental results obtained using this apparatus are shown in Fig.9, which illustrates the shape of the railway tracks and the positioning results (with an output



	Position(mm)
Sensor #0	(700,0,2725)
Sensor #1	(0,-700,2675)
Sensor #2	(-700,0,2625)
Sensor #3	(0,700,2575)

Fig. 8. Experimental apparatus

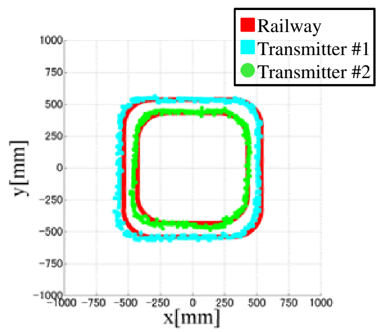


Fig. 9. Experimental results for moving objects

interval of approximately 0.5 seconds/object). The PC used in this experiment incorporated a Celeron processor and a 1.86 GHz clock rate. Consequently, if we used a higher clock rate, the output interval would be reduced because positioning calculation time is dominant. It was confirmed that the positioning error was within about 100mm in the xy plane. This should be sufficiently accurate to monitor the location of a moving person or goods trolley in an indoor area.

The possible causes of positioning error also (as shown in Table 1) are thought to be the fluctuation in count values from the FPGA that indicates the time delay, and attachment errors for the receiving sensors in the ceiling. Overall, it has been verified that the proposed system architecture and methodologies make it possible to apply the techniques described to the position detection of multiple moving objects and to expand the positioning area without degrading accuracy or increasing the number of FPGA receiving ports.

6 Conclusions

We have proposed a new positioning system for indoor use over a wide area. This system can be used to detect the position of people or moving vehicles in a factory.

The main feature of this system is that it does not require synchronization between transmitting and receiving units. Two different methods have been considered in order to make the system more practical. One of these methods involves improved discrimination to cope with the presence of multiple objects. This can be is realized by allocating a specific ID to each object and transmitting these IDs as IR signals. In addition, the concept of a virtual receiving point has also been proposed in order to expand the receiving area without increasing the number of FPGA receiving ports. A verification system was built and the validity of these methods was confirmed by experiment. This verified that the level of accuracy is sufficient to monitor the location of a person or goods vehicle within a factory, etc. The application of this system to indoor navigation for the visually impaired is a topic deserving further study. In order to produce an effective indoor navigation system, however, further expansion of the positioning area, an increase in the number of receiving sensors, and further evolution of the IR communication function used for sending navigation information will be required.

References

1. Harpter, A., Hopper, A., Steggles, P., Ward, A., Webster, P.: The Anatomy of a Context-Aware Application. Wireless Networks 8, 187–197 (2002)
2. Khalid, M., Xiaodong, L., Yuji, H., Kinji, M.: Autonomous Pull-Push Community Construction Technology for High-Assurance. IEICE Transactions on Information and Systems E92.D(10), 1836–1846 (2009)
3. Xiang, Z., Song, S., Chen, J., Wang, H., Huang, J., Gao, X.: A Wireless LAN-based Indoor Positioning Technology. IBM Journal of Research and Development 48, 617–626 (2004)
4. Gwon, Y., Jain, R., Kawahara, T.: Robust Indoor Location Estimation of Stationary and Mobile Users. In: Proceedings of the IEEE Conference on Computer Communications (INFOCOM 2004), Hong Kong, China (2004)
5. Berle, F.J.: Mixed Triangulation/trilateration Technique for Emitter Location. IEE Proc. 133(F.7), 638–641 (1986)
6. Priyantha, N., Miu, A., Balakrishnan, H., Teller, S.: The Cricket Compass for Context-aware Mobile Applications. In: Proceedings of the 7th Annual International Conference on Mobile Computing and Networking (MobiCom 2001), Rome, Italy, pp. 1–14 (2001)
7. Ward, A., Jones, A., Hopper, A.: A New Location Technique for the Active Office. IEEE Personal Communications 4(5), 42–47 (1997)
8. Homma, Y., Moriya, J., Hasegawa, T.: Comparative Experiments on Inverse GPS Based Systems Using Audible Sound or Ultrasonic Waves. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences J91-A(1), 139–142 (2008) (in Japanese)
9. Hada, T., Sunaga, H., Akiyama, M., Ioroi, S., Tanaka, H.: Investigation and Demonstration of Local Positioning System Using Ultrasonic Sensors for Wide Indoor Areas. In: de Ruyter, B., Wichert, R., Keyson, D.V., Markopoulos, P., Streitz, N., Divitini, M., Georgantas, N., Mana Gomez, A. (eds.) AmI 2010. LNCS, vol. 6439, pp. 280–284. Springer, Heidelberg (2010)