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Multisensory Data Fusion for Ubiquitous Robotics Services

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1. Introduction

Real time human tracking in indoor environment is highly demand and important to many applications for ubiquitous robotics services. There are several technologies for human tracking in the indoor environment, such as vision, pressure, infrared, and ultrasonic have been proposed. However, some technologies are costly, or have many restrictions when they are applied. For example, implant several cameras around indoor environment through real time image processing for tracking people is frequently discussed. However, the computer vision method does not function in dark situation and the privacy issue also generated.

Recent advances in radio frequency, microprocessor and sensor technologies enable the wireless sensor network (WSN) system. Wireless sensor network system used for target tracking can be found (Liu, J. et al., 2007); (Hua Li et al., 2008); (Djuric, P. M. et al., 2008). In general, the smart home aims to provide appropriate intelligent services to assist the resident's living. Autonomous and multi-functional robots plays important role in the smart home. However, if robots depend on their own sensors, the applications will be limited. Sensor network system uses multi sensor combined with microprocessor and radio transmission into a device and deploy in the monitoring environment. With the ambient information provided by sensor network based ubiquitous robotics services system, robots can serve people more quickly and accurately.

There are a lot of researches discuss sensor network theories or applications. However, these researches (Yoon Gu Kim et al., 2006); (Taehong Kim et al., 2008) deal with implement sensor network in indoor environment just implant additional sensor nodes on the desks or ceiling. We propose a solution on implementing the sensor network system for ubiquitous robotics services in the indoor environment.

Since most building have implant traditional smoke detector on ceiling for fire detection. We try to implement sensor network system in indoor environment and modify these smoke sensors. We developed a prototype of wireless multi-functional detector; the sensor consists of pyroelectric infrared (PIR) sensor for detecting human radiation, temperature sensor for measuring the ambient temperature and smoke sensor to replace the original smoke detector function on ceiling. With this multi-functional detector, robot can locate the remote people in the environment and provide the services.

2. Related work

The are some technologies used for tracking targets: Vision based algorithm using sequences of images from cameras that moving people can be tracked(Q. Cai & J. K. Aggarwal, 1998) or the number of people can be found(D. B. Yang et al., 2003). The infrared also can be used to facilitate the location of people. However, they can only record the count of people enter or exit in a certain area such a the door of a room (ACOREL Corp.). And this technology requires careful and dense deployment, and dose not work in a more complicated envrionment. Some localization technologies adopt the acceleration and air pressure sensors to detect the location of people (R. J. Orr & G. D. Abowd, 2000). The obvious drawbacks of this technology are costly and need careful deployment. Some researches use ultrasonic sensor technology and adopt time of flight (TOF) method to obtain the location information. The "cricket" localization system uses a combination of ultrasonic and radio frequency (RF) to provide a location support service(Yunbo Wang et al., 2007).

3. Ubiquitous service space for smart home

Realize smart home, identification card with radio frequency transceiver on it which called "iCard" are needed as in Fig.1. iCard is a simple IEEE 802.15.4 (ZigBee) protocol transceiver and can be made as identify card.
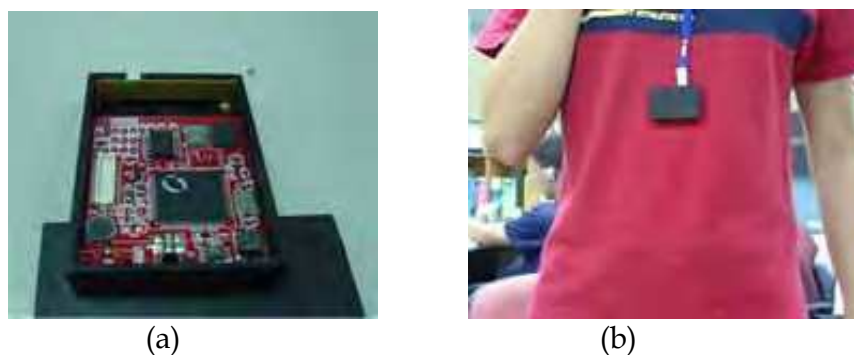

| (a) | (b) |

Fig. 1. (a) iCard (b) Wear on human

ZigBee protocol provides the unique ID information in the same ZigBee wireless environment, thus it can easy identify people with their own ID code.

Since the pyroelectric sensors are suffered from multi target tracking, therefore the assistance from radio frequency signal contain with the people ID information is needed for sensor network multi human tracking system.

iSensor is a multi-functional detector composed with ZigBee protocol transceiver, microprocessor, pyroelectric sensor, temperature sensor and smoke sensor. ZigBee protocol is designed as low-cost and low-power for home automation or hospital care. Pyroelectric sensor can detect the radiation from human body; with multi pyroelectric sensors the accuracy of people localization can be improved by data fusion technique. Temperature sensor data can be provided to HVAC system and adjust the temperature of environment. Smoke sensor is the original function and designed to detect fire disaster. The Architecture of iSensor is illustrated in Fig. 2.

Recent researches discuss on human tracking use pyroelectric sensor or radio frequency signal alone. However, the pyroelectric signal might suffer from tracking multi-targets, and accuracy of radio frequency tracking method might not be reliable. The iSensor will

integrate two types of radio and pyroelectric signal that can trace multi targets and the fidelity also can be guaranteed.

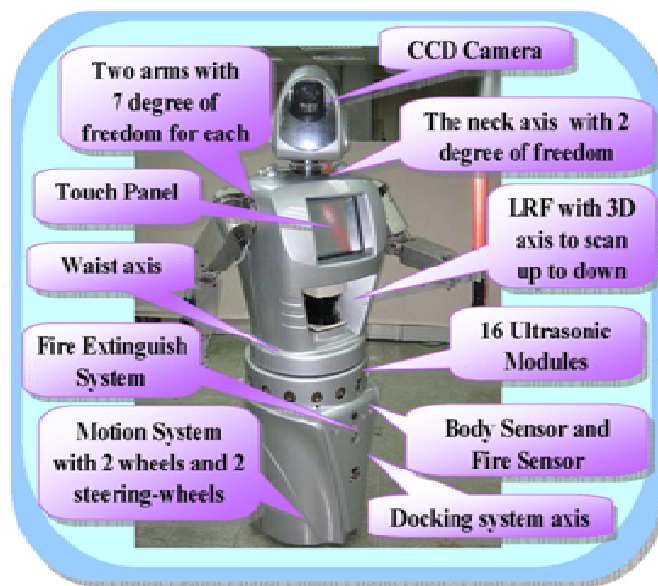

Fig. 2. Architecture of iSensor

Fig. 3. System architecture of NCCU security warrior robot (Luo, R. C. et al., 2007).

We have developed a multisensor based intelligent robotics system as shown in Fig. 3.The multi-functional service robot can provide various services locally, however if remote area need services, how to cooperate with robot is an important issue. For example, as shown in Fig.4 people in the room 3 require services, if there are no sensor network system how the robot to determine and locate the service target?
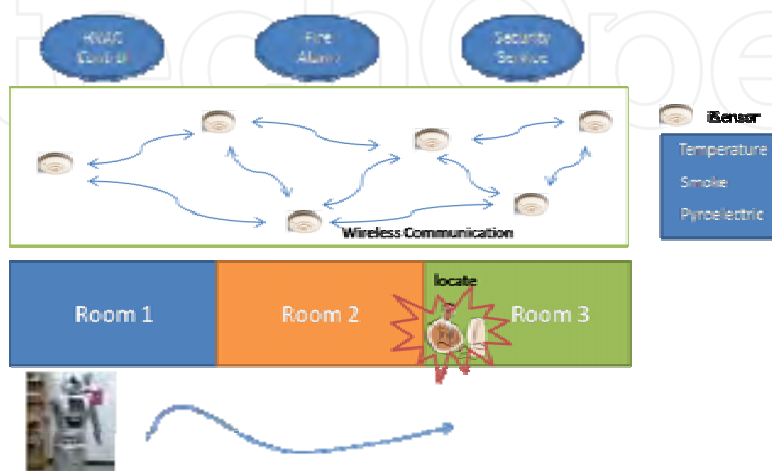

Fig. 4. Architecture of ubiquitous robotics services environment

The robot is equipped with ZigBee compatible communication module for communicating with sensor network. The iSensor network system installed in the ceiling, they collects ambient information and reports to the multi-functional robot. Robots can perform the tasks such as fire fighting, resident following or intruder detection.

4. Pyroelectric sensor

The indoor tracking system should be implemented with many sensors installed in rooms; therefore low cost is the main consideration of smart home service. Since each room is different in shape and size, the location of obstacles which prevent the normal operation of sensors are also varied. A good localization system must be robust from noise and reduce the influence of surroundings.

The PIR sensor can detect the infrared wavelength emitted from humans. They are robust to their surroundings. iSensor are easily installed on the ceiling, where they are not easy affected by the structure of rooms or obstacles.

4.1 Working principle

For a linear sensor, the response signal of n sensors $S(t) \in R^n$ is given by

$$S(t) = h(t)^* \int_\Omega v(r)\Psi(r,t)dr \tag{1}$$

where * represents convolution operation, $h(t)$ is the impulse function of a sensor, Ω is the object, $v(r)$ is the positive visibility function between n sensor and the object space, $\Psi(r,t)$ is the radiation from the target.

The visibility $v(r_1,r_2)$ denotes the contribution by the field at point r_2 to the field at r_1.
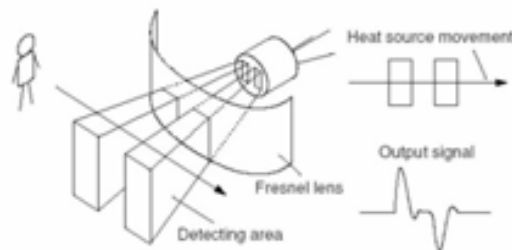

Fig. 5. Pyroelectric sensor behavior

Pyroelectric sensor signals are proportional to the change in temperature of the crystal rather than the temperature of environment. Fig. 5 shows a human walking through a pyroelectric sensor and the corresponding output signal. The response time of the transducer amplifier of the detector limits the maximum frequency. The resultant transfer function turns to be a bandpass one.

Fig. 6. pyroelectric detector

4.2 Pyroelectric sensor deployment and overlapping issue

In order to determine the location of residents within the monitoring area, an array of PIR sensors is used as shown in Fig. 7.
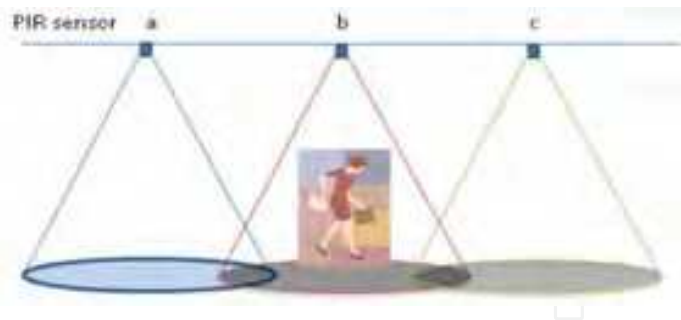

Fig. 7. The localization for PIR sensors

We find some interested questions when developing pyroelectric sensor system. A field of view of our sensor is 100° on directivity-horizontal and 60° on directivity-vertical, as shown in Fig 8. In other words, a field of view is an ellipse, and we must discuss this issue when deploying sensor nodes.
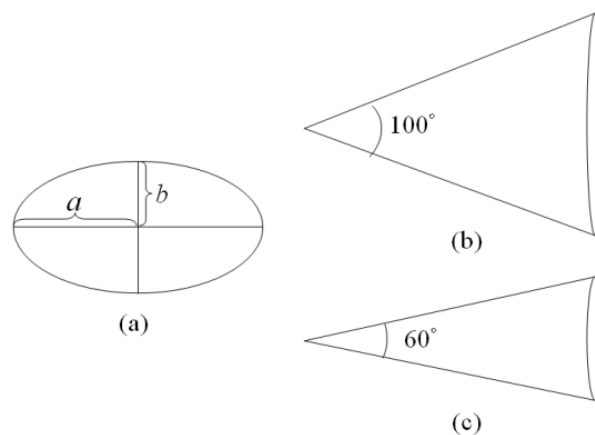

Fig. 8. The general architecture of sensor network system

Given an interested sensing field A, our approach is to get the signal of human radiation in an indoor environment. According to a specification of PIR sensor, a field of view of PIR sensor is an ellipse. And function of an ellipse is expressed as

$$(x-n)^2/a^2 + (y-m)^2/b^2 = 1 \qquad (2)$$

and $\begin{cases} x = a * \sin\theta + n \\ y = b * \cos\theta + m \end{cases}$

Where n, m are coordinate of node; a, b are major and minor axis of an ellipse, respectively. When deploying node, calculate the relationship of distance between each node should be afresh. Fig. 9 illustrates the deployment of node without overlap; we find that an overlapping issue of ellipse is not like that of a circle. A graph that is account by three center of a circle is an isosceles triangle, not an equilateral triangle.

Assume that coordinate of n1, n2, and n3 is (0, 0), (0, 2a), and (a, a tanθ), respectively and ∠n3n1n2=θ. And centre of gravity of the triangle can be obtained as (a, $\frac{1}{3} * a * \tan\theta$)in Fig. 9.
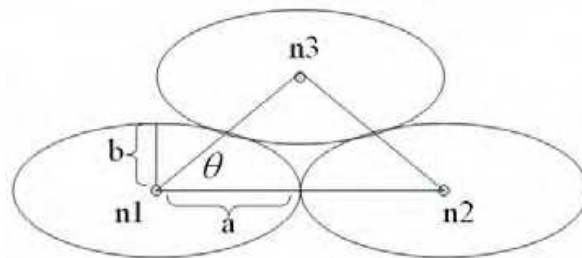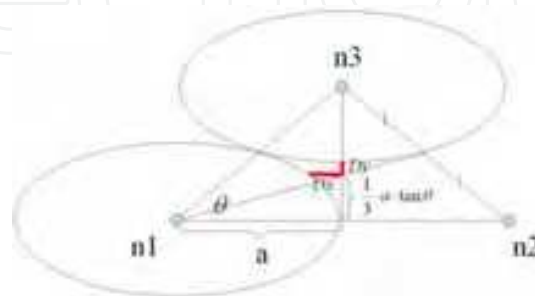
Fig. 9. Normal deployment without overlapping

Fig. 10. The concept of D_x and D_y

Consider the distance between nodes should be corrected by decreasing red and boldface lines (D_x, D_y) to reach a minimal overlap.
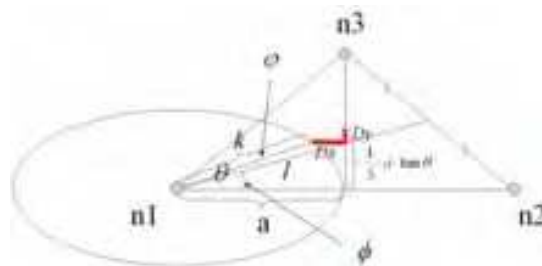

Fig. 11. Geometry of each angle and length

Use approximation theory to get a length of D_x, a degree of angle φ is narrow enough that a length of ($k+D_x$) is similar to a length of l (i.e. $D_x \cong 1 - k$) in Fig 9. A length of l is expressed as

$$l = \frac{1}{3}a * \tan\theta * \csc\emptyset \tag{3}$$

where $\emptyset = \tan^{-1}(\frac{1}{3} * \tan\theta)$

And function of length k is as (4); because a degree of φ is smaller than that of $\emptyset$ (i.e. $(\emptyset + \varphi) \cong \emptyset$), approximate function can be obtained as (5).

$$k = \sqrt{[a \cdot \sin(\phi + \varphi)]^2 + [b \cdot \cos(\phi + \varphi)]^2} \tag{4}$$

$$k = \sqrt{(a \cdot \sin\phi)^2 + (b \cdot \cos\phi)^2}$$

Combining function of (3) and (5), get a function of length of Dx that we want to decrease and correct a distance between nodes in (6).

$$Dx = (l - k)$$
$$= \frac{1}{3} \cdot a \cdot \tan\theta \cdot \csc\phi - \sqrt{(a \cdot \sin\theta)^2 + (b \cdot \cos\theta)^2} \qquad (6)$$

And function of length of D_y is expressed as

$$D_y = \frac{2}{3}a * \tan\theta - b \qquad (7)$$

Combining (6) and (7), the distance between each node can be corrected. In this issue, we discuss questions of deployment and overlapping, and a discussion is not identical among ellipse and circle.

5. Localization through radio frequency signal

5.1 ZigBee radio frequency transceiver

Our indoor RF localization system utilizes the CC2420 chip. The CC2420 is a single-chip IEEE 802.15.4 compliant and ZigBee™ ready RF transceiver. It provides a highly integrated, flexible low-cost solution for applications using the world wide unlicensed 2.4 GHz frequency band. The mobile user also equips with CC2420 transceiver and floods the beacons every 50 ms.

For the direct line of sight propagation path, according to the free space model, the power received by the receiver is given by the Friis space equation(T. S. Rappaport, 2002) as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \qquad (8)$$

Where P_t is the transmitted power in watts, P_r is the received power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the wave length in meters, and d is the distance from transmitter to receiver.

5.2 Received signal strength

In order to locate residents, the estimated distance between sensor nodes and users is needed. Taking consideration of the estimation distance into localization algorithms; the coordination of ZigBee transceiver can be obtained. Radio signal propagation is easily influenced by diffraction, reflections, and scattering of radio induced obstacles in a building, thus the RSS signal measurement is contaminated by the measuring error and NLOS error. The measurement error results from the measuring processes in a noisy channel and can be improved with better signal-to-noise ratio (SNR). NLOS errors depend on the multi path dominated environments and change from time to time.

We record the received signal strength index (RSSI) and distances between the sensor nodes and users. By using maximum likelihood method the propagation model can be found for fading channel. This model provides the mean RSS(d) that received from mobile user, and equation (8) state that. The $RSS(d_0)$ is the received signal strength in dB at a reference distance, and n is denoted the path loss exponent. The measured RSS is calculated by ML and find the parameter $RSS(d_0)$ and n. The measured RSS fit into channel model is obtained by using the equation (8). $\hat{d}$ is the estimation of the distance from equation (9), and X_σ is the random variable that denoted the estimation error with variance σ^2 from equation (10). We find that random variable X_σ increases with distance between the sensor node and mobile user.
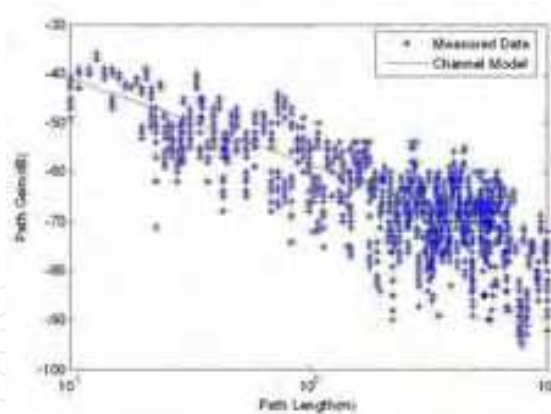
Fig. 12. The measured RSSI of radio signal

$$RSS(d) = RSS(d_0) - 10n\log(d/d_0) \tag{9}$$

$$\hat{d} = d_0 10^{RSS(d_0)-RSS(d)}/_{10n} \tag{10}$$

$$\hat{d} = d + X_\sigma \tag{11}$$

6. Covariance intersection method

In the distributed environment such as sensor network, we cannot keep track on "which node received estimations from which level nodes". Thus we do not know the degree of redundant information exists in an estimation a node received. It means that the error between predicted and actual position covariance will be underestimated. The covariance information must keep consistency to avoid the disastrous consequences of redundant data on Kalman filter type estimators. However, it is not possible to maintain cross covariance consistent with distributed. This makes the estimated state based on the assumed state model with little correction from the new measurements. Thus, drifts the state estimate away from the actual state. The Covariance Intersection (CI) (S. Julier & J. Uhlmann, 2001) can be treated as a generalized Kalman filter. The primary advantage of CI is that it permits filter and data fusion to be performed on probabilistically defined estimates without knowing the degree of correlation among those estimates. Thus CI does not need assumptions of the dependency of the two data of information, when it fuses them. If the cross-variance of the data is unknown, it is not possible to compute the exact covariance matrix of the estimate, but still desirable to have a pair estimate-covariance that is consistent, as defined below.

Set Z a random variable with mean $\bar{z}$ and estimation $\hat{z}$. The estimation error can be given by $\tilde{z} = \hat{z} - \bar{z}$ and the covariance associated with this error is $P_{zz} = E\{\tilde{z}\tilde{z}^T\}$. Let P_{zz}, be an estimation of the covariance of $\hat{z}$, then the pair $\{\hat{z}, P_{zz}\}$ is said to be consistent if

$$P_{zz} \geq \overline{P_{zz}} \tag{12}$$

The proof can be found in (S. Julier & J. Uhlmann, 2001). The pair of estimate-covariance is consistent if the estimated covariance matrix is in the upper bound of the actual covariance of the estimate.

Set x and y be two random variables which have means and covariance matrices are E{x}=X, E{y}=Y separately

$$Cov\{x\} = P_{xx}, \ Cov\{y\} = P_{yy}, \ Cov\{xy\} = P_{xy} \tag{13}$$

Define the estimate Z as a linear combination of x and y: where x and y might represent either a prior estimate of Z with certain covariance matrix or a measurement which has its own uncertainty.

The covariance intersection method is a data fusion algorithm which uses a convex combination of the means and covariances in the information field. This approach is referenced on a geometric interpretation of the Kalman filter process. The general form of the Kalman filter is

$$\hat{z} = W_x X + W_y Y \tag{14}$$

$$P_{zz} = W_x P_{xx} W_x^T + W_x P_{xy} W_x^T + W_y P_{yx} W_y^T + W_y P_{yy} W_y^T \tag{15}$$

The weights W_x and W_y are chosen to minimize the trace of P_{zz}. If the estimates are independent ($P_{xy}=0$), the form of the conventional Kalman filter can be reduce.

The Covariance Intersection method provides estimation and a covariance matrix which their covariance ellipsoid encloses the intersection region. The estimate is consistent independent of the unknown value of P. Given the upper bound $P_{xx} \geq \overline{P_{xx}}$ and $P_{yy} \geq \overline{P_{yy}}$, the covariance intersection estimator are defined as follows:

$$Z = P_{zz} \left\{ w_x P_{xx}^{-1} X + w_y P_{yy}^{-1} Y \right\} \tag{16}$$

$$P_{zz}^{-1} = w_x P_{xx}^{-1} + w_y P_{yy}^{-1} \tag{17}$$

$$w_x + w_y = 1 \ , \ 0 \leqq w_x, w_y \leqq 1. \tag{18}$$

The parameter w_i gives the relative weights assigned to x and y. Different choices of w_i can be used to optimize the covariance estimate with different performance criteria such as minimizing the trace or the determinant of P_{zz}.

$$\text{Let } \ \alpha \equiv \sqrt{tr\{W_x P_{xx} W_x^T\}} \tag{19}$$

$$\beta \equiv \sqrt{tr\{W_y P_{yy} W_y^T\}} \tag{20}$$

$$\text{Thus } \ P_{zz} = \left(\frac{\alpha}{\alpha+\beta} p_{xx}^{-1} + \frac{\alpha}{\alpha+\beta} p_{yy}^{-1} \right)^{-1} \tag{21}$$

and the gains are

$$W_x = \frac{\alpha}{\alpha + \beta} P_{zz} P_{xx}^{-1} \quad W_y = \frac{\alpha}{\alpha + \beta} P_{zz} P_{yy}^{-1} \tag{22}$$

This theorem presents the advantage of the optimality of the best w_i in CI algorithm.

The main benefit of parallel estimation for each measurement type is the independence of the data fusion method for the location estimation calculation that has different measurement type each. The estimation calculations can be substituted with another location estimate calculation with an associated error covariance estimate and the data fusion technique can still be used.

7. Simulation and experimental results

The experimental test with investigation area is 5x5m². The prototype of iSensor is installed on the ceiling. The red circles indicate the multiple sensor units in Fig. 13.

Fig. 13. Experiment geometry

The tracking strategy in our experiment for wireless pyroelectric sensor includes event detection, event digitization, covert sampled signals into event index, motion inference, fuse measurements from pyroelectric sensor and radio frequency signals, trajectory smoothing and estimate the trajectory of users.

An event is defined as an occurrence of thermal radiation detected by a pyroelectric sensor above a threshold value, and the thermal signal will be associated with motion across one detection region, we define such signal as an event.

When a human passes through the Fresnel modulated lens, the response signals are generated. Fig.14 illustrates the event time windows which generated from pyroelectric sensor.

Fig. 15 shows the signal when human user walked along the diagonal of the room, the response of 4 elements of a pyroelectric sensor module. After process the signals, we can convert those signals into angular and distance displacement.

Fig.16 shows the relation between RSS and the distance from mobile user to reference sensor node. The red line named "regression function" is a linear regression function calculated from mean value of measured data. The distance from mobile user to reference sensor node can be predicted accordingly by entering a measured RSS value to the regression function(22).

$$RSS = c_{m-1}d_{RSS}{}^{m-1} + c_m d_{RSS}{}^m + ... + c_2 d_{RSS}{}^2 + c_1 d_{RSS} + c_0 \tag{23}$$

where

$$c = [-0.009\ 0.944 - 3.2332 - 18.6146]^{T}$$
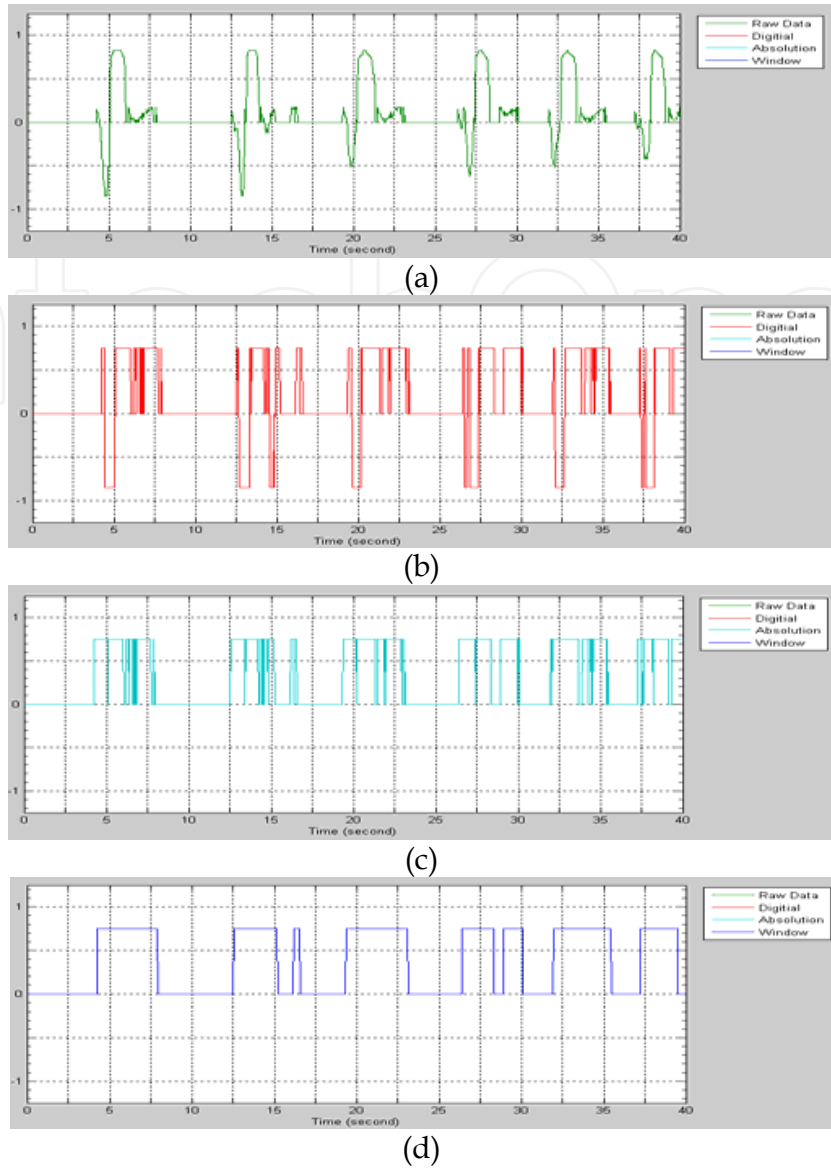
(a)

(b)

(c)

(d)

Fig. 14. Event detection from matched filter (a) Raw data (b) Digitized signals (c) Logic signals (d) Event windows.
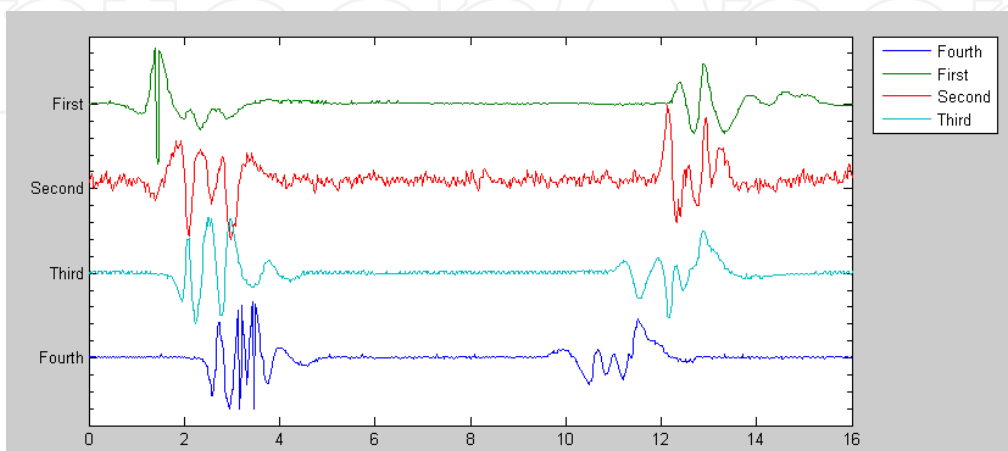

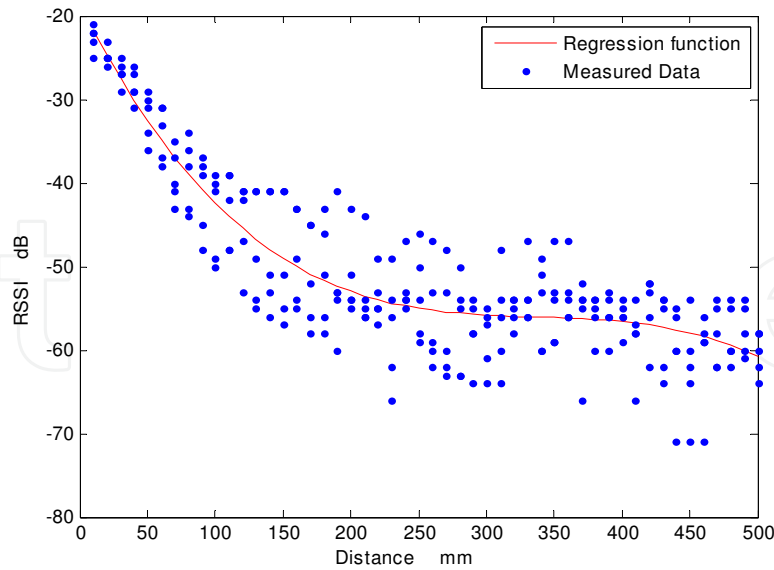Fig. 15. Four elements signal when human user walk pass the pyroelectric sensor system
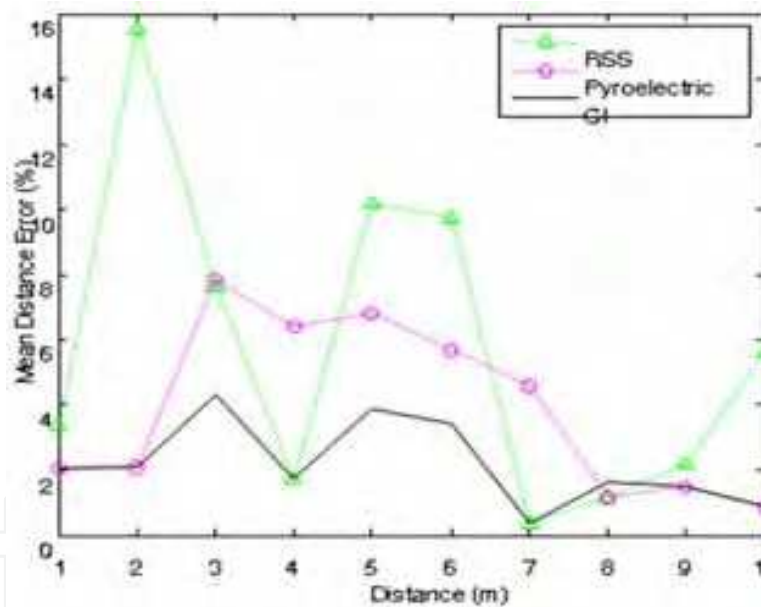
Fig. 16. RSS measured data

Fig. 17. Covariance Intersection with RSS and Pyroelectric measurement

Fig. 17 shows that covariance intersection fuses pyroelectric sensor and RSS localization estimation. The maximum mean distance error of RSS is near to sixteen percentages and the maximum mean distance error from pyroelectric measurement is near to eight percentages. Using covariance intersection algorithm, the mean distance error is below four percentages. The accuracy of locating residents under our system can be increased by using covariance intersection.

In the Fig. 18, the circle mark is the actual test trace, square is the measurement through pyroelectric sensor, triangular is the result from RSS and diamond is the fusion result from CI, The tracking error can be reduced through data fusion technique.
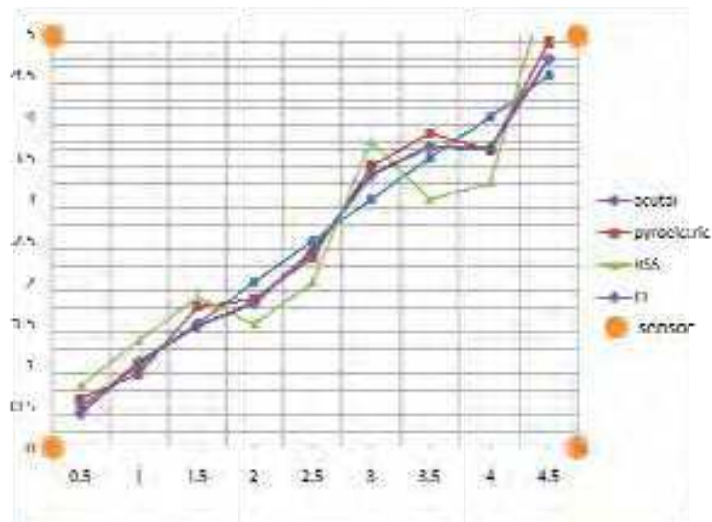
Fig. 18. Moving target tracking

8. Conclusion

This article presents a wireless multi-functional sensor call "iSensor" that is composed with radio transmission, microprocessor, pyroelectric, temperature and smoke sensor. With such device, the sensor network system can be implemented in indoor environment just replace original smoke sensor. This system can estimate the resident's location and cooperate with robots to provide ubiquitous service space. In this paper, we build a prototype of wireless human tracking system by using pyroelectric and radio frequency signal. The measurement error from pyroelectric and radio frequency signal can be reduced through covariance intersection data fusion method. This work should extend to tracking multi targets in the near future. The data obtain from pyroelectric, temperature and radio signals, are also considered provide to air condition and adjust the temperature of the room thus energy saving for building can be realized.

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Sensor and Data Fusion

Edited by Nada Milisavljevic

Data fusion is a research area that is growing rapidly due to the fact that it provides means for combining pieces of information coming from different sources/sensors, resulting in ameliorated overall system performance (improved decision making, increased detection capabilities, diminished number of false alarms, improved reliability in various situations at hand) with respect to separate sensors/sources. Different data fusion methods have been developed in order to optimize the overall system output in a variety of applications for which data fusion might be useful: security (humanitarian, military), medical diagnosis, environmental monitoring, remote sensing, robotics, etc.

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