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Prototyping Sensor Network System for Automatic Vital Signs Collection

Evaluation of a Location Based Automated Assignment of Measured Vital Signs to Patients

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Keywords

Ubiquitous Computing, Context Awareness, Point of Care System, Sensor Network, Continua

Summary

Objective: Development of a clinical sensor network system that automatically collects vital sign and its supplemental data, and evaluation the effect of automatic vital sensor value assignment to patients based on locations of sensors.

Methods: The sensor network estimates the data-source, a target patient, from the position of a vital sign sensor obtained from a newly developed proximity sensing system. The proximity sensing system estimates the positions of the devices using a Bluetooth inquiry process. Using Bluetooth access points and the positioning system newly developed in this project, the sensor network collects vital sign and its 4W (who, where, what, and when) supplemental data from any Bluetooth ready vital sign sensors such as Continua-ready devices. The prototype was evaluated in a pseudo clinical setting at Kyoto

University Hospital using a cyclic paired comparison and statistical analysis.

Results: The result of the cyclic paired analysis shows the subjects evaluated the proposed system is more effective and safer than POCS as well as paper-based operation. It halves the times for vital signs input and eliminates input errors. On the other hand, the prototype failed in its position estimation for 12.6% of all attempts, and the nurses overlooked half of the errors. A detailed investigation clears that an advanced interface to show the system's "confidence", i.e. the probability of estimation error, must be effective to reduce the oversights.

Conclusions: This paper proposed a clinical sensor network system that relieves nurses from vital signs input tasks. The result clearly shows that the proposed system increases the efficiency and safety of the nursing process both subjectively and objectively. It is a step toward new generation of point of nursing care systems where sensors take over the tasks of data input from the nurses.

Introduction

The recent advancement of information and communication technologies (ICT), and a recent social demand for safety and efficiency of the health care services has resulted in the ongoing computerization of hospitals. Although the key for a successful process improvement through the introduction of ICT is an accurate and quick input of the entire information exchanged and its analysis, general information systems demand enormous human resources for data input. As hospital information systems (HIS) also depend on human beings, i.e. clinical staff, to collect the required information for the process improvement, the introduction of HIS deprives the clinical staff of time for direct treatment and care and, consequently, debases the quality of clinical services and clinical safety.

According to author's previous research [1], a nurse with seven patients would spend six out of his/her eight hour shift logged in as been in front of a HIS terminal. Taking account for the time nurses just browsing electric patient records (EPRs) and others, the actual time spent for data input may be three to four hours. Even so, HIS still demands half of the nurse's working time. Reducing the number of input tasks is indispensable in order to improve clinical processes, and consequently, to maximize the benefits of the introduction of ICT.

The point of care systems (POCS) using personal data assistants (PDA) [2] are expected to be a solution for the speedy and accurate data input of information at the patient's bedside. However, POCS that depends on clinical staff to collect data does not eliminate the need for input. Moreover, some researches [3-5] point

out the limitations of PDAs and laptops as input tools at the bedside as it may decrease subjective productivity as well as objective performance of nurses. Foregoing researches on the productivity improvement depict a high correlation between subjective productivity measures and objective performance measures [6-9]. Additionally, researches on the technology acceptance model [10-12] tell that “the perceived usefulness” is a decisive factor. Therefore, to eliminate input tasks, not only objectively but also subjectively is the key issue to achieve an improvement in the productivity and quality of care by a newly introduced IT system.

The most successful POCS is the auto-ID / barcode enabled medication administration (ABMA) system [13-16], especially the barcode based nursing checkup. Although a FDA review pointed out that the introduction of ABMA decreased productivity in the initial stage [16], the clear perceivable usefulness of the reduction of input tasks and benefits of increased clinical safety was warmly welcomed by nurses.

Sensor networks [17-24] where sensors provide obtained data for certain information system over mainly wireless communication channels may be the solution to make whole vital signs input task quicker and more efficient. However, a simple introduction of sensor networks will not reduce the input tasks, because the sensors themselves cannot provide any information about the data source, that is, a patient from whom the vital sign is obtained. Although RFIDs or barcodes attached to patients may provide information, to equip them on conventional vital sign sensors such as thermometers is not cost effective. To overcome this problem, the sensor network itself should provide certain methods to provide the information of the data source of each obtained vital signs.

Real Time Location Systems (RTLS) [25-26] could be a mechanism to obtain the data source. As all the inpatients are mapped to a certain bed within wards, the position of vital sign sensors taken by the RTLS can be mapped to a certain patient. RTLS is widely used for asset management of medical devices [27-29] or for nursing process improvement [30]. Some researches apply RTLS for security management of nurses [31], outpatient management [32] or for information service for patients’ family members [33]. As a matter of course, patient identification based on the location of beds is discussed [34]. However, the authors’ previous work [1] shows that conventional RTLS does not have enough

positioning accuracy for expected intra-hospital information services. Some solutions such as differential global positioning system (GPS) [35] or a combination of multiple sensors [36] may provide sufficient accuracy. However, a sensor network system needs to interpret absolute positions given by a conventional RTLS into logical positions such as “in operation room 1” or “around bed 222,” when they provide data for HIS. Therefore, the authors [1] claim that sensor networks should equip a referential positioning system that provides positions relative to logical reference points.

Objectives

The objective of this research is to design and to prototype a sensor network system in order to relieve nurses from vital signs input by providing a mechanism for automatic data-source acquisition based on a newly designed referential RTLS.

The following sections describe the system design of the proposed clinical sensor network system, and an evaluation of the prototype in a clinical environment.

Methods

1. System Design

In order to free nurses from vital signs input task, the sensor network system should provide 4W supplemental information that is who (nurse), where / whom (bed / patient), what (data type / sensor device), and when, together with obtained vital signs. To provide the information, the system needs to equip the following three functions as shown in Fig. 1.

1. Automatic collection of vital signs and logical place of the sensor device.
2. Automatic pairing of the obtained vital signs and logical place.
3. Semi-automatic store of the paired data into EPR after nurse check.

This paper does not discuss function 3, because the design of the function that is strongly affected by the connecting EPR cannot be universal.

A recent increase of social consciousness of health promotes the introduction of personal health record (PHR) [37-38] systems. The expansion of PHR has initiated several attempts to connect vital sign sensors with information systems such as Continua Health Alliance [39-41], which defines the standard connection protocol via Bluetooth. Therefore, once HIS provides Bluetooth access points, any Continua-ready vital sign sensors can transmit their obtained data for EPR.

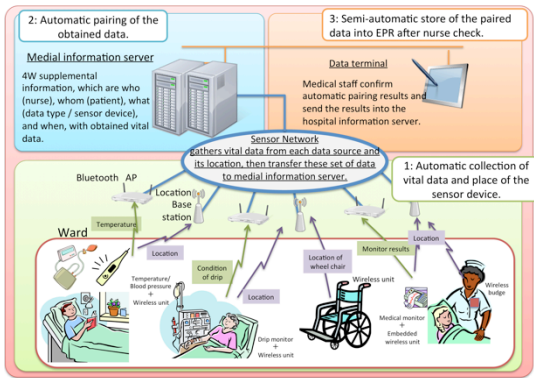


Figure 1. Functions required for the sensor network system

As discussed in the introduction, RTLS for clinical sensor network systems should provide positions relative to logical reference points such as beds. The referential RTLS should sense proximities to the logical reference points. Naya et al [42] proposed proximity sensing systems utilizing the inquiry process of Bluetooth and successfully demonstrated the sensing of the nearest bed using beacons placed on each bed. This approach enables the sensor network to handle any Continua-ready equipment without hardware modification.

Fig. 2 shows the system design of the proposed clinical sensor network system. The system tracks the positions of Bluetooth equipped devices using Bluetooth beacons at each bedside, and collects the obtained vital signs via Bluetooth access points. Once identification badges for nurses are equipped with Bluetooth transponders as demonstrated by Naya et al [42], the system can also obtain the positions of the nurses. Thus, the proposed system can obtain both vital signs and 4W supplemental information via a single communication channel.

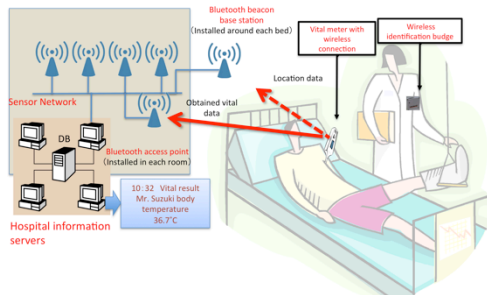


Figure 2. Overview of the proposed clinical sensor network system

2. Prototyping

The authors developed a commercially available Bluetooth access point (BTAP) and Bluetooth beacon (BTID) base stations with Takebishi corp., a subsidy of Mitsubishi Electric, as shown in Fig. 3. The base stations transfer obtained vital signs or signal strength via Ethernet or WIFI. To simplify the prototype sensor network, the base stations are used as the beacons and the Bluetooth module of a host computer is used as the access point.



Figure 3. BTAP / BTID base station

Figure 4 shows the prototype vital sign sensors. The left photo shows a clinical thermometer of OMRON corp. connected with a B-pack Bluetooth wearable sensor device developed by ATR [43]. The prototype thermometer transmits the obtained body temperature via a serial port profile (SPP) through B-pack. B-pack also works as a transponder during idle time. The right image shows a Continua-ready blood pressure meter of OMRON corp. coupled with a B-pack. The device transmits the obtained data via a health device profile (HDP) by its originally equipped Bluetooth module, whereas B-pack works as transponder.



Figure 4. The prototype sensors

Figure 5 shows the servers and their functions. The servers collect the obtained data via WIFI and Ethernet. Once a new vital sign is sent to the vital sign manager, the position data

manager queries its own database for the position of the source device using the MAC address of the device and the time of the measurement. Finally, the combined data is stored into the integrator. Figure 6 shows the user interface for checking the stored data. Each line shows a vital sign and its supplemental data; the position, the time, and the name of the target patient. If all data is correct, a nurse clicks the ok button to confirm them. If not, a nurse can edit the data with the keyboard and confirm them. Under a real HIS setup, the confirmed data will be sent to the EPR.

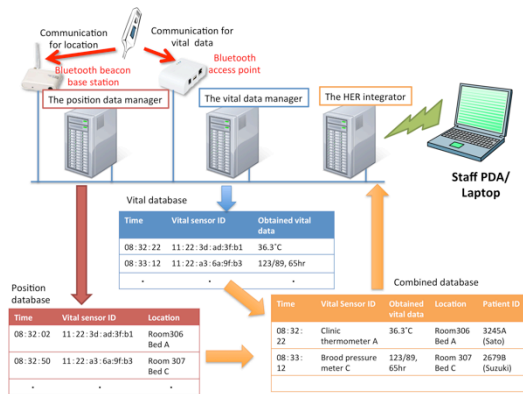


Figure 5. Server configurations

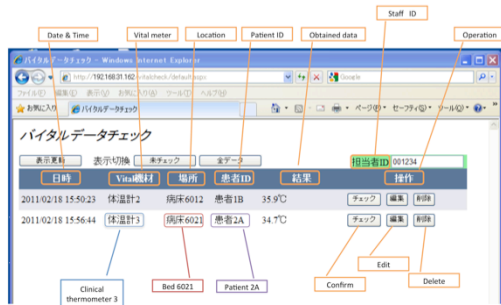


Figure 6. Interface for checkup

3. Evaluation method

The prototype was evaluated in a pseudo-clinical setup by nurses of Kyoto University Hospital.

The prototype is implemented in six out of 22 beds in the dialysis room of Kyoto University Hospital as shown in Fig. 7. The beacons are mounted on a 100 cm tall separator, and a HIS terminal and a terminal connected to the prototype are placed at the foot of patient A as shown in Fig. 8. As beds in the dialysis room are more concentrated than in the ward, the setting is rather challenging for the positioning system.

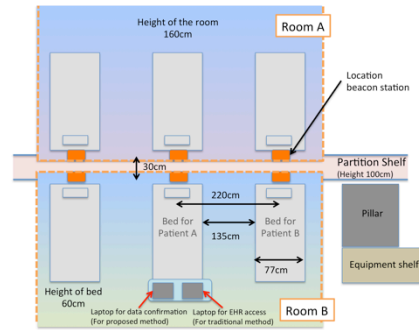


Figure 7. Setup for the evaluation



Figure 8. Terminals

The evaluation is performed with the cyclic paired comparison [44-45]. The paired comparison is the standard method for the affective testing to analyze subjective data in ergonomics (human factors) researches. The purpose of paired comparison test is to rank provided entities through pairwise comparison based on Thurston's theory [46]. Scheffe's method [47], one of the most conventional and common process, asks the subjects to provide preferences of given pair of entities $\{i, j\}$ on the five-graded semantic differential (SD) scale, that is +2) i is preferable, +1) i is comparably better, 0) same, -1) j is comparably better, -2) j is preferable. When we denote subject k 's i - j comparison score as X_{ijk} , and K subjects comparing N entities, the average preferable score A_i becomes as $A_i = (X_{i.} - X_{.i})/2NK$. Here we need to be careful that X_{ijk} is not always equal to X_{jik} , especially if the target entities provided in turn. As interactions of various parameters, such as personality or test order, affect the obtained result, the obtained result is first evaluated by ANOVA. When the result appears significant, finally yardstick Y using studentized range. When $|A_i - A_j|$

> Y , the preference of i and j is evaluated as significantly different.

As conventional Scheffe's paired comparison method requires $2_N C_2$ comparisons for each subject. The cyclic paired comparison is the method to minimize the number of comparisons. For example, to rank 4 entities $\{A, B, C, D\}$, the Scheffe's method requires 12 comparisons, whereas the cyclic paired comparison requires just 4 comparisons, $\{A-B, B-C, C-D, D-A\}$.

Figure 9 shows the test process. Three to four subjects formed a group. Each subject plays a pseudo patient and a pseudo nurse in turn, and performs vital signs collection under following two processes.

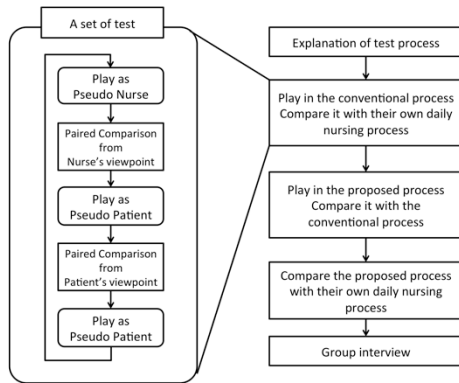


Figure 9. Test process

With “the conventional process”, the nurse writes down the obtained vital sign on a given paper sheet after each measurement. After the nurse finishes the vital signs collection for two patients, the nurse inputs the obtained data into the sample patients’ EPR of Kyoto University Hospital. Here the nurse has logged in to HIS before starting the data collection process to exclude time for the login procedure.

With “the proposed process”, the nurse transmits the obtained vital signs after each measurement by pressing the transmit button of the prototype device. After the nurse finished the data collection for two patients, the nurse checked the collected data using the interface shown in Fig. 6.

The target entities of comparison are three processes; the conventional process, the proposed process and their own daily process at their daily workplaces, namely “the daily process.” The subjects compared the efficiency and safety of the three processes from the viewpoint of the nurse, and the reliability and psychological resistance of the three processes from the

viewpoint of the patient, and scored on the five-graded SD scale. Additionally, the subjects were asked to provide comments and reasons of their scoring in free text of each comparison in free text.

The result of the questionnaire is first filtered to remove irrelevant answers to the test objectives. After the screening, the variance of the result was analyzed by Nagasawa’s formula [44-45].

The subjects were 24 nurses of Kyoto University Hospital. The subjects widely varied in their age, sex and career. Most of the groups consist of one head or sub-head nurse and two or three younger nurses.

The inpatient wards of Kyoto University Hospital are dispersed in four buildings. Mainly because of available space in each building, the daily nursing process differs. Some nurses bring a laptop to the bedside to input vital signs there just as POCS (the bedside group), and others write the data down on paper sheets and input them into the EPR at staff stations afterwards just as the conventional process (the station group). As the daily process is one of the compared processes, the subjects are divided into two groups during the analysis. Table I shows the properties of the two groups.

Table I. Properties of the subjects

	number	age		carrer	
		average	stdev	average	stdev
bedside group	7	25.7	9.8	7.9	8.0
station group	17	23.5	7.9	6.4	6.1

For objective evaluation, the time consumption of each process is analyzed using the statistical hypothesis test.

The process is videotaped and divided along with the event tags defined, as shown in Table II. To make the analysis easier, the subjects were asked to utter each event, such as “start measurement,” “start transmission,” and “transmission complete”.

Table II. Definitions of the event tags

Preparation	Thermometer	From start movement to pass the thermometer to a patient
	Blood Pressure	From whole process for thermometer finished to start putting the blood pressure meter to a patient
Measurement	Thermometer	From pressing start button till a beep that tells finishing the measurement
	Blood Pressure	From putting the blood pressure meter to a patient till a beep that tells finishing the measurement
Memo		During the nurse holding a pen
Transmission		From utterance of "start transmission" till the utterance of "transmission complete"
Terminal Task		During the nurse facing to the terminal

Results

1. Subjective evaluation

At a five per cent level of significance, the proposed process is evaluated as more effective and safer than both the conventional process and their own daily clinical process.

Figure 10 and 11 show the distribution of the average efficiency score of each process and the yardstick. The figures clearly tell that the subjects of the bedside group as well as the ones of the station group evaluated the prototype as been significantly efficient.

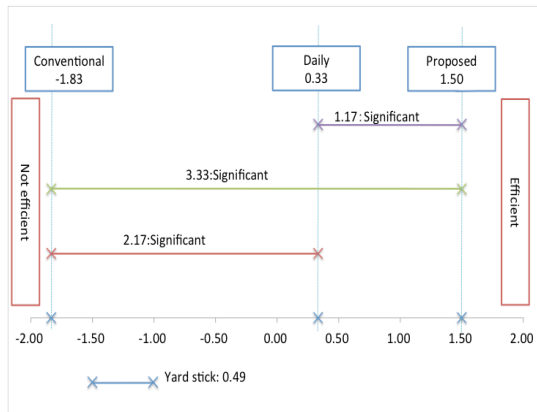


Figure 10. The evaluation of efficiency (bedside group)

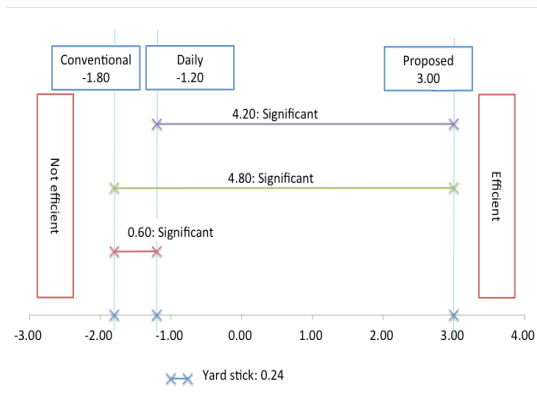


Figure 11. The evaluation of efficiency (station group)

The interviews and reasons given in the questionnaire in free text tell that the subjects welcome any system that might reduce clinical tasks and eliminate the risk of posing failure, although some saw a possible risk of the system to make nurses ignorant of patients' status and neglect the confirmation process.

On the other hand, there is no significant difference between the three processes in the reliability and sense of resistance.

The interviews and reasons given in

the questionnaire in free text tell that the subjects found no clear difference from the patients' viewpoint, although some pointed out that the process change might affect the nursing care to cause a change of patients' acceptance of the system.

2. Objective evaluation

Figure 12 shows the average processing time for each task. The statistical hypothesis test at a five per cent level of significance found no significant differences except for the transmission and terminal task. As equality of variances is dropped in the case of blood pressure meter, the authors used Welch's t-test in this case.

The prototype demands 3.3 seconds for transmission in the case of the thermometer, and 7.87 seconds in the case of the blood pressure meter.

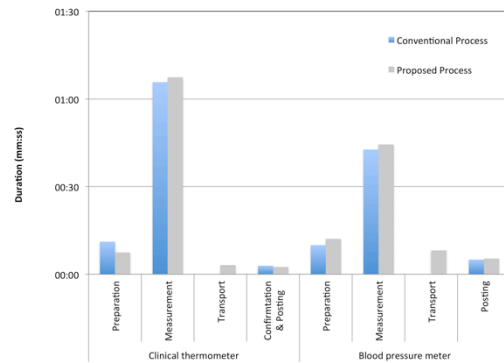


Figure 12. Average processing time for each task

Figure 13 shows the time for the terminal task, which is denoted as "terminal" in Fig. 12, of all the subjects. Subject 7c required a rather long time due to system malfunction. Except for this case, just two subjects (1a and 5d) spent the same duration, and the others spent in average 50% less time with the prototype.

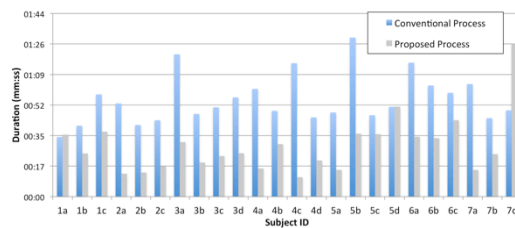


Figure 13. Time spent for terminal task

Talking about safety measure, the authors measured posting failure of data and recognition failure of positions.

Table III shows the numbers of mismatches between written note and output of sensor devices. The prototype always stored correct data into the servers.

Table IV shows the results of device position estimation recognition. The recognition rate was 88.4%.

Table III. The number of memo errors

Num of measurement		Error on memo	
Conventional	Proposed	Conventional	Proposed
192	184	1	4

Table IV. The results of position estimation

Attempts	Valid Attempts	Correct estimation	Wrong estimation
95	91	84	12
Rate		88.4%	12.6%

The prototype estimates the device positions by statistical analysis from multiple signal strength measurement data. Detailed analysis of the erroneous results showed that there was no significant difference between the likelihood of the first candidate and that of the second candidate when the prototype misestimated and that the second candidate was correct.

Finally, the authors checked whether the nurses could successfully correct the miss-estimations. In three out of the twelve miss-estimations, the nurses could not correct the data in the system due to system malfunction. Among the remaining nine miss-estimations, four out of nine were corrected. In the interview, some subjects complained about the small illegible fonts of the interface, and some said, "I have never imagined that the system makes any mistake."

Discussions

The objective evaluation result shows that the prototype halves the time spent in front of a HIS terminal. As Takemura et al [1] assumes that a nurse needs two minutes to input a set of vital signs into EPR, the reduction time of the proposed system is one minute per measurement. According to the annual report of Kyoto University Hospital [48] and the standard of acute period nursing system charge defined by the

Ministry of Health, Labour and Welfare (MHLW) [49], we can assume that 62,000 out of 365,000 patients per year are in need of intensive care. Nurses need to take vital signs every hour for these patients, and twice a day for the other patients. The total projected reduction of time for the whole hospital is 34,900 hours per year. The wage structure survey of MHLW [50] says that the average overtime work of a nurse is twelve hours per month. As Kyoto University Hospital employs about 1,000 nurses, the total projected overtime work is 144,000 hours per year. Therefore, the proposed system is expected to decrease overtime work by 25%.

The subjective evaluation result tells that the proposed system has enough perceivable effectiveness to make nurses welcome the system. Some subjects, especially nurses of the surgery division claimed, "a system which cuts even one second of indirect care and enables us to put more time for direct care, is more than welcome, especially when we need to receive several patients after operation although we have a smaller number of nurses such as during the night shift." The nurses of the psychiatry division also had a strong desire to shorten the time for data collection in order to reduce external stimuli for their patient.

The key feature for reducing time seems to be the direct transmission of the obtained vital signs, realized by the sensor network. Although most of the sensor networking research is dedicated to remote sensing and ubiquitous health support in the home environment as summarized in [17], some [18-20] have attempted at introducing such wireless-ready devices into hospitals and some [21-24] have tried connecting them to EPR. Once sensor networks are connected to EPR, the obtained vital signs are directly transmitted to patient records.

The direct transmission decreases the chance of error. During the evaluation 1.3% of vital signs was not recorded properly on the paper sheet as shown in Tab II. Even in the conventional procedure where the subjects are more careful to record vital signs on the paper sheet than the proposed procedure where the vital signs are sent directly, 0.5% of vital signs are not properly recorded. This means that six errors per ward per month may happen at Kyoto University Hospital. On the other hand, the interview shows that the nurses found at least three missing vital signs, and one clearly wrong vital sign in EPR in a month in their daily procedure. As common knowledge of clinical safety tells that there are five to ten times undiscovered errors, we may assume one to three errors a month may happens

in a ward. The proposed system always stores the correct data given by sensors. Therefore, the introduction of the proposed system may decrease 500 to 1000 errors per year per hospital.

Although the direct transmission is effective for the error reduction, the function cannot relieve the nurses from the terminal task. In order to store the obtained vital signs, the data must be mapped with the data source, that is, the patient. Another key feature of the prototype, which is the most significant feature of the proposed system, is the patient identification using the referential RTLS [42].

The patient identification rate (the position recognition rate) of the prototype was 87.4%. Considering that the beds are more concentrated in the evaluation setting than the standard ward setting, additional tuning within the ward may halve the estimation error. On the other hand, the position resolution of the conventional WLAN-based RTLS is a few meters, according to its catalogue specification. It means the resolution of the conventional RTLS is about two beds in the settings shown in Fig. 7. Therefore, the prototype has a better position estimation performance or at least not a worse performance in comparison with the conventional RTLS [25-26].

Even the position identification rate is better than conventional RTLS, 12.6% of the 6.3% of the measured record is mapped to wrong patients. Even if the further tuning would halve the identification error, 3% of erroneous record is not acceptable for clinical use. How can we eliminate the error without increasing task of nurses?

Using RFIDs or barcodes as the patient identification is another possible approach. However, as discussed in the introduction, to equip them on conventional vital sign sensors is not cost effective. Although a sensor equipped CCD, such as a digital camera, can utilize the barcode as the patient identification without any hardware modification [51], no conventional sensors can read them without hardware modification. For small vital sign sensors, such as thermometers and pulse oxymeters, to equip readers is not plausible. Moreover, barcode or RFID-based systems asks one additional process, to read identification to identify the patient, which the position-based system does not require. The Bluetooth based proximity sensor enables the proposed system to integrate any devices with Bluetooth capability into the system. The current trend of mobile computing and home healthcare under Continua standard may increase the potential of the approach.

As ABMAs request the nurses to read

the identification keys, the accuracy of the patient identification must be higher than the RTLS based systems. However, ABMA cannot eliminate the identification error [52-53]. Therefore, the final checkup is indispensable to keep clinical safety in barcode or RFID-based systems as well as in position-based systems. In the evaluation, half of the miss estimations of the prototype were ignored. Although the unsophisticated input interface shown in Fig. 6 could be counted as a cause of the overlooks, the biggest cause was the discrepancy between the subjective estimates of risk and the objective risk [54]. Previous researches about safety management have pointed out that human beings have a tendency to rely too much on machines as the subjects confessed during the interview after the experiment. However, no machine can eliminate error. This discrepancy may increase the actual risk, just as a subject, a head nurse, stated, "Nurses may neglect the confirmation process as they tend to rely too much on the system." Although the introduction of the mobile terminal to let the nurses check up record immediately after the measurement seems helpful to reduce mapping errors, it cannot be a silver bullet to eliminate the erroneous records due to the tendency of the human beings to rely too much on the information system.

On the other hand, the likelihoods of the first and the second candidate were similar when the prototype missed the estimation. It means the system itself knew the possible risk. Once this possible danger, namely "the system's confidence", can be shared with the nurses, the information increases the nurse's alertness so that they act as a secondary check. Designing a proper interface to make the user to share "the system's confidence" is the key issue to achieve clinical safety under advanced HIS.

Conclusions

This paper proposed a clinical sensor network system that collects vital signs and its supplemental information, and stores this into the EPR in a semi-automatic manner. As the proposed system is based on using BTAP/BTID base stations, it can handle any Continua-ready vital sign sensors that equip a Bluetooth module without hardware modification. Additionally, the proposed system reduces at least one process, to read identification marker to identify target patient, comparing to barcode or RFID-based systems. The evaluation result confirms that the proposed system improves efficiency and safety of nursing tasks both subjectively and objectively

comparing with POCS as well as conventional paper-based process. In order to increase clinical safety further, the system should be equipped with an advanced human interface to improve collaboration between the system and its user by sharing “the system’s confidence”.

The proposed sensor network system is a step toward the next generation of point of nursing care systems, where nurses do not input the data at the data source, but sensors input the data by themselves. The authors believe that the introduction of the proposed system advances a gigantic ubiquitous computing system, namely HIS, by equipping innumerable pluggable sensors and advances clinical fields [51], and, consequently, initiates introduction of pervasive healthcare service in hospital [55].

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