Equipment Location in Hospitals using RFID-Based Positioning System

Ali Asghar Nazari Shirehjini[12], Abdulsalam Yassine[2], Shervin Shirmohammadi[2]
[1]Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[2]Distributed and Collaborative Virtual Environments Research Laboratory
School of Information Technology and Engineering, University of Ottawa, Ottawa, Canada

ali.nazari@kit.edu, ayassine@site.uottawa.ca , shervin@site.uottawa.ca

***Abstract*—Throughout various complex processes within hospitals, context-aware services and applications can help to improve the quality of care and reduce costs. For example, sensors and RFID technologies for e-health have been deployed to improve the flow of material, equipment, personal, and patient. Bed tracking, patient monitoring, real-time logistic analysis, and critical equipment tracking are famous applications of real-time location systems (RTLS) in hospitals. In fact, existing case studies show that RTLS can improve service quality and safety, optimize emergency management and time critical processes. In this paper, we propose a robust system for position and orientation determination of equipment. Our system utilizes passive Radio Frequency Identification (RFID) technology mounted on flooring plates and several peripherals for sensor data interpretation. The system is implemented and tested through extensive experiments. The results show that our system's average positioning and orientation measurement outperforms existing systems in terms of accuracy. The details of the system as well as the experimental results are presented in this paper.**

Keywords- Sensors and RFID technologies for e-health, context-aware services and applications, Real time location system, equipment tracking, bed tracking;

I. Introduction

Economic reasons enforce hospitals to implement cost-cutting strategies. As a consequence, efforts have been put to reduce costs by improving patient throughput, resource allocation, workflow optimization, and operational performance [1]. Throughout various complex processes within hospitals, context-aware services and applications can help to improve the quality of care and reduce costs [1]. For example, sensors and RFID technologies for e-health have been deployed to improve the flow of material, equipment, personal, and patient [2]. Bed tracking, patient monitoring, real-time logistic analysis, and critical equipment tracking are famous applications of real-time location systems (RTLS) in hospitals. In fact, existing case studies show that RTLS can improve service quality and safety, optimize emergency management and time critical processes [3]. It helps to monitor wandering patients, which is one of the hot topics in developing assisted systems for elderly safety. In terms of hospital operation management, RTLS increase efficiency in the utilization of processes and staff productivity and brings transparency within the logistics and reduces inventory and over buying, decreases search times, and ensures that the right patient is available for the right procedures. The specific environment and operation conditions in hospitals dictate higher requirements on the development of such RTLS. This is because hospitals are very sensitive work place**s** and as such decision makers must ensure the deployed RTLS for example does not introduce interference with critical medical equipments or designated areas for special treatments. Also, robustness, scalability, easy installation, acquisition and maintenance costs are important factors for hospital managers when they decide to deploy such systems. Furthermore, the intended applications for the system determine the requirements of its development. For example, some equipment need only to be tracked with certain acceptable approximation such as the case of distinguishing beds before and after being in the washing area. Other applications need higher accuracy to locate and track objects and persons [4].

Today, some hospitals have adopted RTLS and deploy products such as Sovereign Tracking Systems, VeriChip, Radiance, AeroScout, Ekkahau, WhereNet, Sonitor Technologies, or Ubisense. Most of these systems are based on WiFi, Ultra Wide Band (UWB) or RFID technology. However, they lack to provide high accuracy at low cost. Most of them, as explained later in the related work section, are hard to calibrate and not robust against signal propagation issues such as reflection, absorption, or diffraction (e.g. areas with heavy metal doors). This leads to uncertainty in indoor object localization and the measurement error could be up to 3m. Moreover, some of the existing systems suffer from low precision measurement and uncertainty. This may lead to false actions based on the seen results. For example, a high risk patient that is not allowed to leave a certain area or his room could be falsely located to be outside the critical area, which would raise a false alarm. Or a patient on a bed waiting to enter the x-ray room could be mistakenly tracked by hospital managers to have been moved through the rest of process because his position is shown to be in a neighboring room. Such positioning errors would falsely let care givers conclude that the x-ray process has been completed. It is obvious that such uncertainty and lack of robustness, even if it only happens few times a day, will have consequences in terms of technology acceptance and adoption.

In this paper, we take upon the challenge of determining, with acceptable accuracy, the location and orientation of mobile objects in indoor environment by proposing a robust and novel system based on RFID technology. RFID tags come mainly in two forms; passive RFID tags and active RFID tags. Active RFID tags have on-board power supply and the capability for long range communication, thus making them several times more expensive [13]. Despite that, active RFID might cause interference with critical medical equipment or designated areas for special treatments. While each type is appropriate for specific applications, passive RFID tags are widely recognized for their distinctive advantages with respect to their low cost and identification capability [7]. In addition, they do not face the signal interference problems as we have described above. Furthermore, passive RFID tags are evolving as stable technology with increasingly available open architecture. One of the main advantages of RFID tags is that they do not require a line of sight and can stand harsh environments [5] [8]. This is in addition to the fact that they are robust, cheap, and widely-used in numerous applications (e.g. [6] [9], [10], [11]). For such reasons, we adopt the use of passive RFID tags in our system.

Currently, there are many existing techniques for indoor localization for mobile objects. An extensive analysis of these systems as well as their shortcomings is detailed in section 3. In our system, described in details in section 4, RFID tags are mounted on floor pads where the mobile objects are placed. Up to four RFID readers can be mounted to mobile objects at a distance from 2cm to 8cm from the floor pads. Each RFID reader is supposed to read one tag, which will determine the position of the corresponding reader. Having up to 4 positions for a mobile object, its center position and orientation can be calculated. The system is designed to work for objects that are connected, directly or indirectly, to a point which is at a short distance from the ground. The RFID tags are placed on fixed, predefined positions within a specific floor pad. The tags do not store any position information except their row and column coordinates within the floor on which they are mounted. The system is validated by a proof-of-concept implementation and tested through extensive experiments.

The main contribution of this paper is therefore the design, development, and testing of a passive RFID-based positioning system for hospitals. What makes this approach elegant is its simplicity, allowing the implementation, deployment, and maintenance of our indoor positioning system inexpensive while still being very robust and delivering highly accurate measurements. To summarize, the main benefits of our approach are as follows: First, our system outperforms many existing systems in minimizing the average positioning and orientation errors. In our experiments, the average position error of our system ranged from 5 cm (stddev 2cm) to 13 cm (stddev 11 cm), and the average orientation error is about 12 degrees (stddev 10 degrees.) Second, accuracy in our approach is independent of region geometry or target distribution, and remains constant over the entire region. This is in contrast to other positioning approaches that rely on measuring RF propagation attributes and the accuracy is subject to region geometry, target distribution, ranging-error distribution, and landmark layout [29]. Third, since our approach does not depend on RF propagation measurements, the precision is not affected by propagation issues such as absorption, diffraction, or reflection, while these are major sources of uncertainty in traditional RFID positioning approaches [28]. Fourth, the system design is scalable while the cost remains controllable without affecting the error margin. Finally, our system does not require sensor calibration and accurate sensor placement (reference points), and there is also no need for time synchronization.

As it will be explained later in the paper, our system can be extended to cover arbitrary large spaces by simply adding more plates at low cost (few cents per RFID). Furthermore, the average error for any given area is controllable simply by increasing or decreasing the density of the tags of the corresponding floor pad(s) in order to meet specific application needs. For example, for tracking equipment in the bed cleaning area of the hospital, because only a rough positioning accuracy is required, we could reduce the number of deployed tags to reduce costs. However, in other clinical areas where higher accuracy is required, we can increase the number of tags per each square meter to decrease measurement error down to less than 13cm.

And because each object calculates its own position and orientation based on 1 to 4 RFID tag positions, the computational complexity does not increase. Thus, the system's complexity is neither affected by the covered area nor by the number of available objects in a specific floor area that autonomously calculate their own position.

The general feasibility of our approach has been shown in [10, 30], where a chess-boarded tag distribution layout was used. However, this configuration is not supported by commercially available RFID floors such as [24]. Therefore, RFID tags needed to be attached to the floor manually. Depending on the number of tags per square meter, this job can become very time consuming and expensive in a hospital setting. Although the cost structure of the system in [30] is still lower than many other high-precision systems, we attempt in this work to lower the installation effort and the number of deployed tags in order to make the approach more suitable to cover very large areas such as hospitals. Therefore, the current work uses a different tag distribution pattern that is similar to the commercial RFID floor presented in [24]. Off-the-shelf products can be used to eliminate the manual preparation of the RFID pads, reducing installation costs and making the proposed system more suitable for large scale deployments.

The rest of the paper is organized as follows: In the next section we describe an example problem scenario to better familiarize the readers with the application domain and to describe their requirements. In section III, we discuss the related work. Section IV describes the approach and the system proposed in this paper, followed by the experiments in section V, and analysis in Section VI. Finally, in section VII we conclude the paper and present plans for future work.

II. Health Care Scenarios and Requirements

In this section, we present a few scenarios where multiple physical objects can be tracked using RTLS that lead to improve service quality and save on cost. The scenario describes a typical problem related to objects localization in

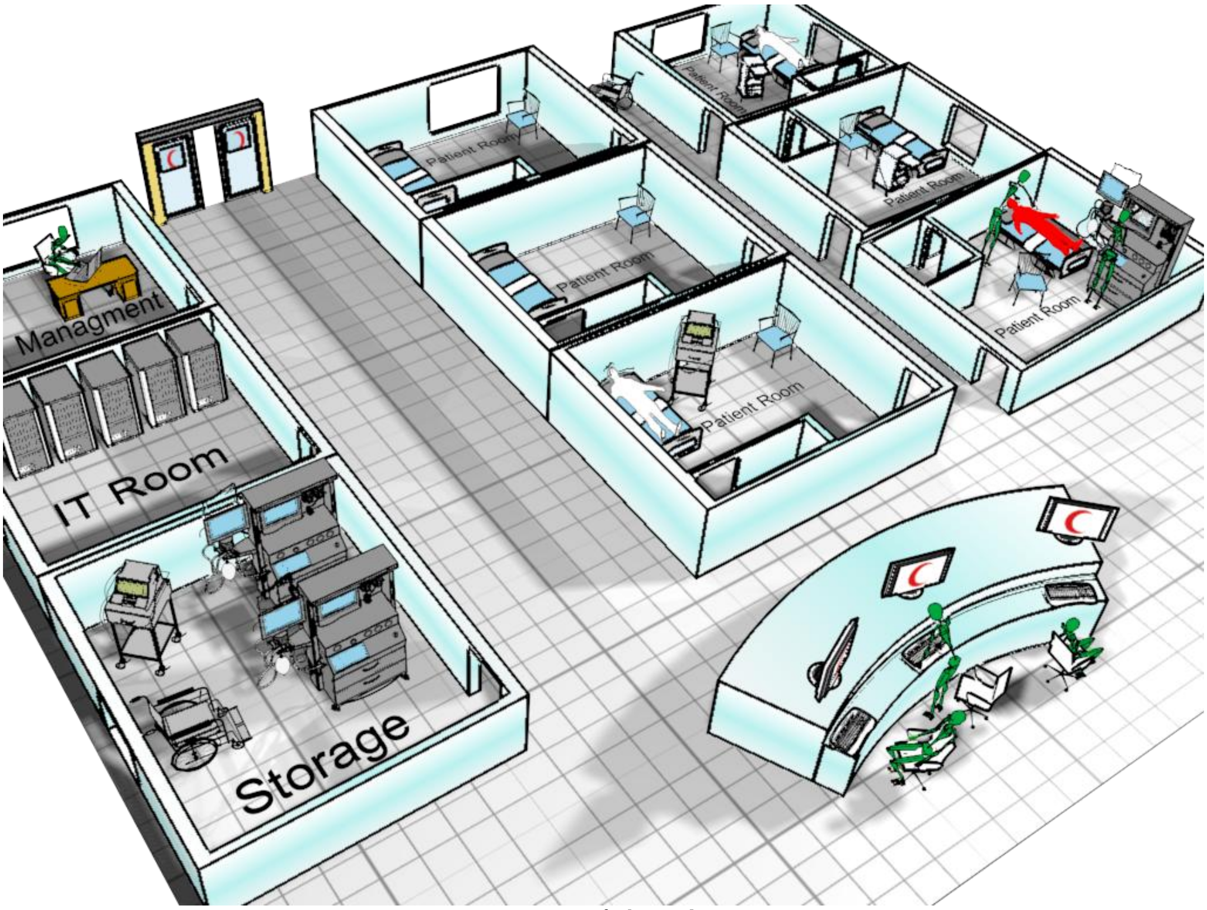

Fig. 1. Scenario of a hospital setting

hospital settings and the solution to such problems as addressed by the proposed system in this paper.

shows a typical hospital setting. In such an environment, we have patient rooms, storage for medical equipment, IT room, and managers who control the work flow of personal, patients, and equipments.

Consider for example 4 patients delivered to the hospital due to a car accident. Two of them need wheelchair for quick treatment while the other two are more seriously injured and require specialized equipment such as oxygen mask and heart pumps and of course the availability of two beds. The workflow manager needs to quickly check for the location and availability of the needed equipments. The storage equipment room in figure 1 includes two heart pumps and one monitoring device. The other required monitoring equipment is available in a patient's room, but not currently used there. Typically, hospitals would over stack such goods in the storage room; however, several monitoring equipments are available somewhere in the hospital and not in use. Finding such equipment quickly at peak time is a matter of life and death for patients. With RTLS, the material manager can query this through the system and get the position and state of this monitoring in a split second. The same also applies for the wheelchairs and two beds that are in bed cleaning station. It should be noted that for this scenario, the RTLS only needs to provide a positioning accuracy at room level, and it is enough to scale the RTLS to provide only this needed accuracy to save costs.

Another scenario is that some high risk patients, such as senior patients with Alzheimer, need to be continuously tracked, so they do not leave a pre-defined area, because they might get lost or be exposed to danger. It is obvious that in emergency situations most of the personnel are focused on the admitted cases and might not have time to track and take care hof senior stationary patients. However, with a location and tracking system that can create yellow and red alarm as shown in figure 2, high risk patients can be easily tracked if they leave a designated area or even the clinic and inform care givers about the patient's position. It is important to note, that in this case a positioning error of few centimeters could leave to a false alarm. For example, if the senior patient is still in the clinic and is using a public phone at the entrance, there should be no red alarm raised, while after passing the door such an alarm is strongly needed.

The open literature has also described several location and positioning systems. Many of the current RTLS, especially those that are WiFi-based, provide a measurement with an error of about 3 meters. This adversely affects the reliability of the system if it is used to track wandering patients for example. This is because managers are forced to shorten the area where seniors can move freely before the alarm is raised and thus causing unnecessary restrictions on the patients. Other systems suffer from signal interferences where the measurements fluctuate and lead to false alarms. It is obvious that such false alarms will not be accepted in hospital settings, even if they happen few times during the day.

Therefore, as a requirement for RTLS, the reliability of positioning should be high enough that such false alarms are completely excluded. Based on the existing surveys and the scenario explained above, we can list the requirements of such systems as follows:

Fig.2. An alarm raised after a high risk patient leaves a designated area

A. Measurement error and uncertainty

As discussed in the previous section, effective realization of equipment tracking in a hospital setting requires false alarms to be reduced. This means the average error in measuring the location is minimized. In the related work section, we have listed in Table I the differences with respect to the measurement provided by related systems and our system.

B. Affordability and Standard Compliancy

It is important that the positioning technology be based on well developed standards so that off-the-shelf components are used. Furthermore, the cost of RFID tags is only a few cents, that is, even an RFID infrastructure consisting of thousands of tags would only incur a small cost. Such characteristics guarantee wider acceptance and adoption of our system.

C. Object Scalability and Mobility

The system should support rooms of different sizes. Furthermore, the number of objects to be positioned should be scalable. In addition, the calibration effort should be minimal as new objects are added or existing objects are moved or removed. This is rather important for hospitals especially when they extend their operation to new departments or acquire new equipments and devices.

In the next section, we cover some of the existing systems and demonstrate that they do not meet at least one of the above requirements.

III. RELATED WORK

Most of the existing approaches for objects' localization and orientation are centered around four different approaches. These approaches, as described in details in the following subsections, face several issues with respect to the average localization and orientation errors as well as scalability.

A. Beacon-based Systems

Many beacon-based systems for object positioning have been proposed in the literature. An example is in [17] where use an "Active Badge" location system which utilizes a network of beacons communicating with pulse-width modulated IR signals in order to locate users in intelligent office environments. Other approaches have also been proposed that utilize radio frequency or Ultra-Wide-Band technology [16] to determine the user's position. Some other special types of beacon-based systems use Wi-Fi technology [22]. An extensive survey of these studies can be found in [14]. However, a common issue in beacon-based systems is that using radio frequencies makes the reliability of the whole positioning system very dependent on different variables related to shapes of objects, materials, etc., that are found in the environment. This is because RF signal propagation is influenced by phenomenon such as reflection, diffraction, diffusion, and absorption. Therefore, extensive calibration is required for such systems. Furthermore, this approach does not scale well since the computational complexity increases as the number of objects increases in the environment. Another limitation of beacons-based systems is that beacon or tags cannot be embedded inside metallic objects. Also, for some critical applications in special environments, such as tracking medical surgery equipments in hospitals, the use of radio frequency may interfere with equipments and therefore it is not permitted.

B. Camera-based approaches

The use of camera and computer vision such as the work presented in [12] and [23], is another approach. Yamada et al. [21] present systems for measuring 3D position of users in indoor environments using multiple calibrated cameras and adaptive background models. A common problem with camera-based positioning is that environment models or object information is required to detect and recognize objects before their position can be determined. Furthermore, vision based systems require line of sight in order to establish a connection with the objects and locate them. Hidden objects are invisible to the system. Furthermore, they only allow a limited number of objects to be positioned in parallel, and thus are not arbitrarily scalable. Such limitations make it very hard to apply this technology to detect arbitrary mobile objects in complex hospital settings.

C. RFID-based approaches

Recently there are many approaches that take advantage of the emerging mass production of very small, cheap RFID tags [24], [19]. The work presented in [19] is somehow close to our work in utilizing passive RFID tags for object positioning and localization. In such system, the position of each tag, the relative position of the surrounding objects, and other supplementary information in the room are stored in each tag. The system also tracks the moving person using RFID-mounted shoes.

While the system in [19] requires equivalent amount of tag writing as the system proposed in this paper, in our case it is done only once, unlike [19] which stores in the RFID tags the absolute position information and the semantic information about surrounding objects to help visually impaired people navigate freely. The drawback of their design is in the massive rewrite to the stored data in the RFID tags in case certain objects are removed or the surrounding environment changes. In our system, however, we made sure that if the whole floor pad is moved within the room or if the global coordinates of the room change (e.g. re-arranging the walls in a mobile hospitals) we do not need to update the stored information in the RFID tags. Instead we only change the reference vector pointing to the origin point of the floors' local coordinate system. This vector is not stored in the RFID tags but (currently) managed by each mobile object as global context information. The vector is used to perform coordinate transformation.

Similar to the work presented in [19], Yeh et al. [25] have developed a system based on infra-red sensors that adapt smart signal processing to provide users with information about the position of objects hindering their path. Multi-sensor strategy for locating and tracking objects is also used in [7].

Contrary to these works, the RFID tags in our system do not store data that refer to their position. Instead the data in the tags correspond to the row and column numbers within a floor plate which integrates those RFID tags like a grid. By so doing, we can move the floor plate to any place in the room without the need to change the stored data. This makes our system unique and more practical compared to the above mentioned approaches.

Alternative positioning approaches using RFID tags would be to attach the tags to the mobile objects and place readers in the environment. Generally, the position can then be estimated using lateration or triangulation methods. For a good overview of such RFID localization techniques, readers may refer to [28]. Most of these approaches rely on radio propagation measurements such as measuring Time of Arrival (TOA) or Angle of Arrival (AOA). However, these approaches suffer from several signal propagation issues such as absorption, diffraction, or reflection [28]. Also, while the accuracy in such approaches is subject to region geometry, target distribution, ranging-error distribution, and landmark layout [29], our approach provides a constant accuracy over arbitrary large spaces of any geometry. Furthermore, it is independent of target distribution.

D. Other approaches

Ashokaraj et al. [20] have developed a multi-sensor system to measure the position and orientation of a four wheeled robot based on ultrasonic signals using interval analysis. Ultrasonic sensors are integrated around the robot giving low level information affected by noise, bias, outliers, etc. to detect obstacles. However, these approaches are also unsuitable for our type of applications, due to requiring an a priori 2D map describing the surrounding environment with its landmarks and obstacles, as well as the unsuitability of velocity-based estimation for such cases, as we've argued in [30].

In summary and as shown in Table I, no system works optimally for all indoor cases and each has its own shortcomings. In this paper, we are proposing that our system works better than other existing systems for a hospital scenario. In the next section, we provide the details of our proposed system.

IV. SYSTEM DESCRIPTION AND DESIGN

The system consists, as shown in Figure 3, of passive RFID technology mounted on floor plates, several peripherals for sensor data interpretation, and positioning information.

A. Syetm Setup

In our approach, we require the RFID tags to be integrated into the floor in a grid where the mobile objects are placed. The floor, as illustrated in Figure 3, is composed of N by M plates which are equal in dimensions, such that N; M ≥ 1. On each floor plate, RFID tags are attached at location (X; Y) such that X; Y $\geq$ 1. Each tag is placed on a fixed, pre-defined position within a specific floor plate. In Figure 3, the coordinates X and Y correspond to the row and column of the floor plates. The tag stores the integer values x and y that are referring to the horizontal rows and the vertical columns in the plate respectively. The tag also stores the horizontal row variable *m* and the vertical column variable *n* that correspond to the plate's location within the room dimensions. It must be mentioned that the distribution of the RFID tags on each floor plate does not need to be the same. However, it is important that the position information stored in each tag refers to variables x and y in relation to the grid design as shown in Figure 3. In our design we made sure that if a change is required in the distribution (for example, fewer RFID tags in the floor plate) then it is done by skipping rows or columns as required, but not changing the position of the RFID tags in the plate. By so doing, we avoid having to change the stored data in each RFID. Furthermore, we can manipulate the density of RFID tags on different partitions of the floor to achieve the desired resolution and to separately control specific floor areas in order to meet specific application needs. We can also extend the RFID floor for covering arbitrary large spaces. The cost of setting up the system is as follows: hardware cost of one reader is $75 CAD and the tags are at 50 cents each. In our system we use 4 readers which cost $300CAD and 20 tags/$m^2$. The software is very light and simple to implement compared to other RF based or vision based systems. Therefore, the software cost can be neglected. The initial installation cost requires 2 hours for a student (paid $10CAD/hour) to setup one mobile object, also we need wires and glue etc at $5CAD cost, 25hours at 10CAD/hour = 250 CAD to prepare RFID tags for a surface of 10 m^2 and to attach the RFID-tags to the floor plates.

TABLE I
ANALYSIS AND COMPARISON OF EXISTING SYSTEMS

Reference	Application Domain	Approach	Average Error	Scalability	Issues
Hile and Borinelloe [15]	Indoor Navigation	Image-based	10cm-150cm depending on runtime and availability landmarks; average is 30 cm after 6 seconds runtime	Scalable	Very low speed: 9 seconds from the time of taking the image to image to calculate the camera position; privacy issues; depends on lighting conditions
Ando and Graziani [8]	Navigation for visually impaired	Infra-red sensors	NA	NA	Issues with hidden objects, signal reflection
Roy Want et al. [17]	Generic	Beacon-based	NA	NA	RF signal propagation is influenced by phenomenon such as reflection, diffraction, diffusion, and absorption
Krumm et al. [12]	Generic	Camera-based	NA	Not scalable for parallel objects positioning	Computational complexity, sensor calibration
Zhou and Shi [18]	Robot tracking	Passive RFID	NA	Scalable	Fixed objects are excluded as they do not provide velocity data
Lorincz and Welsh [7]	Person and object tracking	Beacon-based (sensor nodes)	0.8 m – 1.6 m ; can go up to 3.3 m depending on the variance of obstructions. Beacon node failure, radio signature perturbations, and beacon node density	Not arbitrarily scalable	Sensitive to radio interferences and signature perturbations; precision highly depends on surroundings objects' material
Proposed system in this paper	Object positioning and orientation	Scanning labels, passive RFID	Between 5 cm to 13 cm for positioning error and 12.17 degrees orientation error	Arbitrarily Scalable	Designed for objects with small distance to the floor; provides only 2D position (no height)

B. Mobile object setup

In our setup, we have mounted RFID readers on all mobile objects. The RFID reader components are connected to an embedded computer via the serial interface through which the position and orientation information are calculated based on the stored tag information. Since the distance between the reader and the transponder must be small, we have installed the readers under the mobile object.

C. The distribution of the tags

The arrangement of the tags is in a manner that only one tag can be covered from a reader. The main reason is the expected resolution and reliability of the position results. While theoretically it is enough to have one reader per object that can read one RFID tag to calculate its position, at least two readers need to detect two RFID tags to calculate its orientation. For more accurate orientation measurement, two readers are not always enough since they would not necessarily match with the tags. For example, if the tags' distribution is very sparse, then the probability of getting a reader in an untagged zone is high and thus it receives no positioning data. Therefore, using more readers per object increases the systems' robustness and measurement accuracy.

D. Measurement methods

The overall measurement steps are as follows:

SCANNING: the transponders read out the tags in a synchronized manner. The tag's ID, the value for the coordinates M, N, X, and Y are time stamped and forwarded as a data tuple <M, N, X, Y> to the software module.

MEASUREMENT: the software module calculates the position of the object based on the data tuple <M, N, X, Y>, the RFID tag's ID, and the time stamp. This information is scanned from the RFID tag which is close to the specific reader.

SYSTEM'S COMPONENTS AND COMMUNICATION: The system's component modules are shown in Figure 4. The intercommunication among them is as follows: When the data is scanned, the embedded computer translates the measured information into high-level "context events" and sends it to the software modules. The software modules consist of a context management agent and a database which stores the mobile objects' movement history. In this setup, the embedded computer is part of an agent communication module using the Knowledge Query Markup Language (KQML) which offers a plain-text based TCP/IP agent communication mechanism to interact with the entities in the system.

An alternative approach would have been to send the RFID reader output using a wireless serial adapter such as Bluetooth,

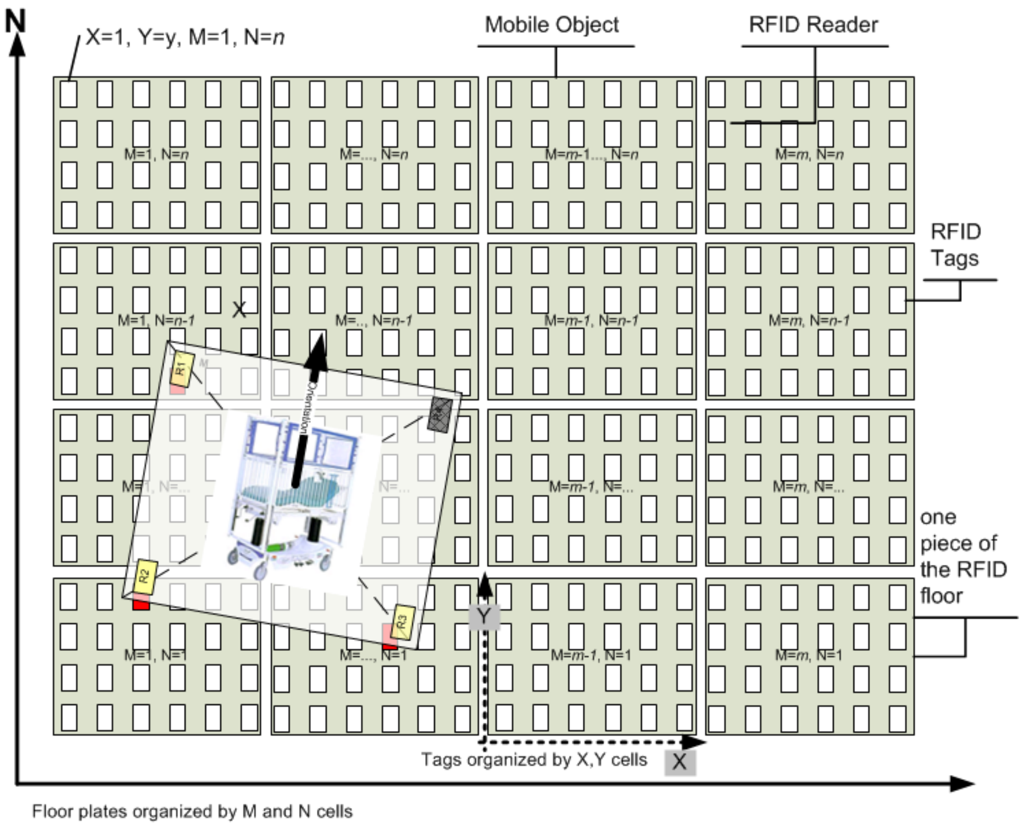

Fig. 3. An extensible RFID floor composed of n*m components with a hospital be on it

ZigBee, or WiFi to a remote computer. Each RFID reader would need to be connected to a wireless serial adapter that is paired with a remote computer in the room. While such approach could save on energy consumption of the mobile device by just operating the wireless serial devices, it produces signal interferences, especially if there are more than 2 or 3 mobile objects in the room. That is, 12 wireless serial adapters will operate in the same room using the same remote computer.

E. *Measurement of position and orientation*

In order to calculate the position of a tag which is scanned by a particular reader, we use the following formulas:

$$P_x = (m-1) * SecW + (x-1) * (TraW + DisTraX) + \frac{TraW}{2} \quad (1)$$

$$P_y = (n-1) * SecH + (y-1) * (TraH + DisTraY) + \frac{TraH}{2} \quad (2)$$

Note that m, n, x, and y are all digits greater than 0. The symbols in equations (1) and (2) are described in Table II.

TABLE II

GLOBAL CONSTANTS RELATED TO THE TAGS

Variable	Description	value
TraW	The width of the tag	8.5cm
TraH	The height of the tag	5.5cm
SecW	The width of the plate's section	60cm
SecH	The height of the plate's section	60cm
DisTraY	Distance between two transponders in y axis	6.5cm
DisTraX	Distance between two transponders in x axis	6.5cm

For cases where we can scan a tag, the values *x* and *y* components of *P* are not determined. The above equations show that with two location points we can determine the position and the orientation of an object. However, to increase the robustness of the system we have used four readers. If one or two readers fail, the system can still effectively calculate the position and orientation of the mobile object.

The position of the mobile object is determined by the center point P_0 as shown in Figure 5. The z-component of the 3D position can easily be calculated from the height of the mobile object. The orientation of the mobile object changes only around the z-axis (yaw). The center point P_0 is calculated by building the vectorial average of the n identified reader positions:

$$\vec{P}_0 = \frac{\sum \vec{R}_i}{n} \quad (3)$$

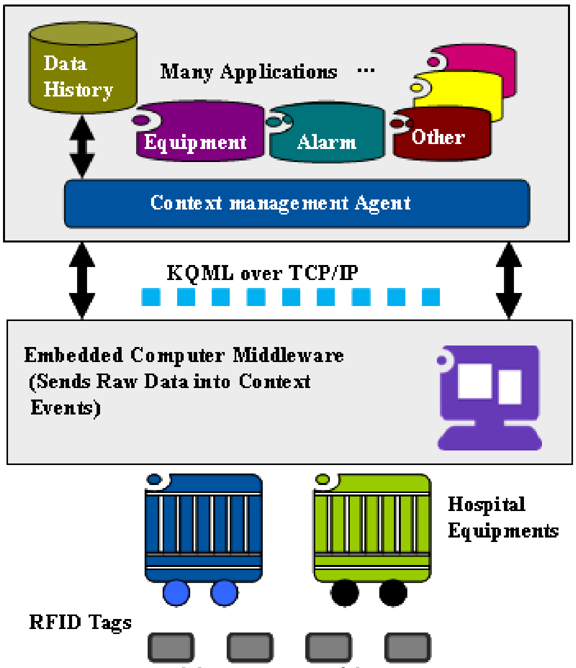

Fig. 4. Module components of the RFID system

where $i=1..n$ such that $1 \le n \le 4$, $\vec{P}_0$ is the middle point of the mobile object, and $\vec{R}_i$ represents the vectors (points) received from the readers.

However, if the size and dimensions of the mobile object are known, the position can be calculated by using only two points using the length of the object or its diagonal as it is shown in Figure 5. To illustrate that, consider the following cases: If $\vec{R}_1$ and $\vec{R}_3$ are known, then the position of the mobile object can be calculated using the following equation:

$$\vec{P}_0 = \frac{\vec{R}_1 + \vec{R}_3}{2} \qquad (4)$$

If $\vec{R}_2$ and $\vec{R}_4$ are known then the position is the centre point of the line $\vec{R}_2\vec{R}_4$ which is calculated by using the following simple formula:

$$\vec{P}_0 = \frac{\vec{R}_4 - \vec{R}_2}{2} \qquad (5)$$

If we get the position from two readers, i.e. $\vec{R}_1$ and $\vec{R}_3$ or $\vec{R}_2$ and $\vec{R}_4$ as shown in Figure 5, then to obtain the middle point of the object, we need the unit vector $\hat{u}$ between the points as well as the middle point $\vec{P}_x = \hat{u} * A/2$ of the line connecting the two points. Then we need to rotate the unit vector $\hat{u}$ using the rotation matrix R_Φ and the formula $\hat{v} = \hat{u} * R_\Phi$.

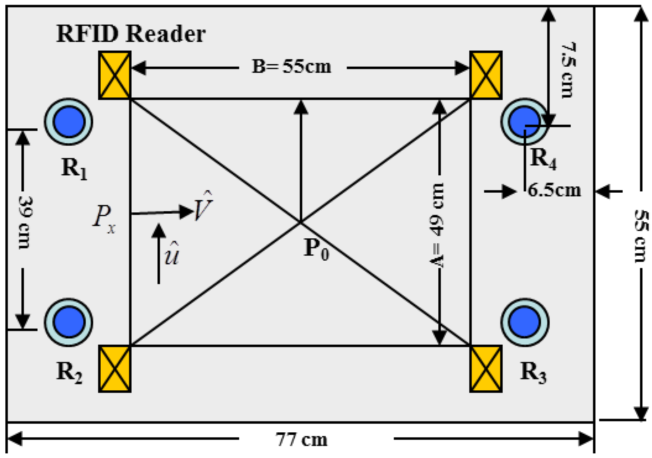

Fig. 5. Illustrated map for the size and dimensions of a mobile object with mounted RFID readers

With this new unit vector we can obtain the position of the object through multiplying it by half of the side of the object and adding it to P_x. Using $\vec{R}_1$ and $\vec{R}_3$ we can calculate P_0 as follows:

$$\vec{P}_0 = \vec{P}_x + B/2$$

$$= \frac{\vec{R}_1 - \vec{R}_2}{\left\|\vec{R}_1 - \vec{R}_2\right\|} * A/2 + \frac{\vec{R}_1 - \vec{R}_2}{\left\|\vec{R}_1 - \vec{R}_2\right\|} * R_\Phi * B/2 \qquad (6)$$

whereby $\Phi = \pi/2$ or 90 degrees. Using $\vec{R}_1$ and $\vec{R}_3$ we have to use A instead of B and the rotation angle Φ will be $-\pi/2$ or -90 degrees. For the example shown in Figure 5, the length of B is 55 cm and A is 49 cm. The orientation is seen as a normalized, orthogonal vector from the mobile object towards the center of a user-defined side of the object's bounding box (see Figure 5). The unit vector between $(\vec{R}_1 - \vec{R}_2)$ or $(\vec{R}_3 - \vec{R}_4)$ is the orientation $\vec{o}$ of the mobile object:

$$\vec{o} = \frac{\vec{R}_1 - \vec{R}_2}{\left\|\vec{R}_1 - \vec{R}_2\right\|} \qquad (7)$$

For the case when we only have the positions of ($\vec{R}_2, \vec{R}_4$), the unit vector must be rotated in the right direction with an amount $\Phi = \arctan \frac{A}{B}$. If ($\vec{R}_1$ and $\vec{R}_3$) are known instead of ($\vec{R}_2$, $\vec{R}_4$), then the rotation angle will be $\Phi = Arc\tan\frac{A}{B} + \pi/2$. The following numerical example illustrates the above analysis:

Example: Consider the layout shown in Figure 3 and assume that the readers R1, R2, and R3 (marked in red) are detected and the data collected from these readers are as follows:

R1 readings are (m, n, x, y) = (1, 3, 4, 1)
R2 readings are (m, n, x, y) = (1, 1, 3, 4)
R3 readings are (m, n, x, y) = (2, 1, 4, 3)

Applying equations (1) and (2), we get for R1

$$P_{x_1} = (1-1)*60\ cm + (4-1)*(8.5\ cm + 6.5\ cm) + \frac{8.5\ cm}{2}$$
$$= 0 + 3*15\ cm + 4.25\ cm$$
$$= 49.25\ cm$$

Then, for R1 $P_1 = (49.25\ cm; 122.75\ cm)$. Similarly, the positions for readers R2 and R3 are calculated and shown below.
For R2, $P_2 = (34.25\ cm; 38.75\ cm)$ and for R3, $P_3 = (109.25\ cm; 26.75\ cm)$

Applying equation (3) we get:

$$\vec{P}_0 = \frac{\sum \vec{R}_i}{n} = \frac{\begin{pmatrix} 49.25+34.25+109.25 \\ 122.75+38.75+26.75 \end{pmatrix}}{3} = \frac{\begin{pmatrix} 192.75 \\ 188.25 \end{pmatrix}}{3}$$
$$= \begin{pmatrix} 64.25 \\ 62.75 \end{pmatrix}$$

The orientation of the object in Figure 3 is calculated based on the readings from R_1 and R_2 per equation (7) as follows:

$$\vec{o} = \frac{\vec{R}_1 - \vec{R}_2}{\left\| \vec{R}_1 - \vec{R}_2 \right\|} = \frac{\begin{pmatrix} 49.25 - 34.25 \\ 122.75 - 38.75 \end{pmatrix}}{\left\| \begin{pmatrix} 49.25 - 34.25 \\ 122.75 - 38.75 \end{pmatrix} \right\|}$$
$$= \frac{\begin{pmatrix} 15 \\ 84 \end{pmatrix}}{\sqrt{15^2 + 84^2}} = \frac{\begin{pmatrix} 15 \\ 84 \end{pmatrix}}{85.33} = \begin{pmatrix} 0.175 \\ 0.984 \end{pmatrix}$$

$$\Phi = Arc\tan \frac{0.98}{0.175} = 1.395 \text{ Radians or } 79.92 \text{ Degrees}$$

The above example shows how the position and orientation of mobile objects are calculated according to the coordinates of the floor itself. However, if the layout of the floor is done in a way that it does not share the same coordinates with the room in which it is integrated, then we have to transform the position vector to line up with the room's coordinates in order to get the final location and orientation. For this case, two additional vectors need to be taken into consideration to map to the room's coordinate system. One vector will be pointing to the origin of the local coordinate system while the other vector is going to be a unit orientation vector of the *N* axis as shown in Figure 3. An alternative way is to arrange the RFID floor tiles so that they line up with the exact dimensions of the room. In such configuration, we can directly read out the absolute position according to the room's coordinates and not the local coordinates of the plate.

In the next section, we provide implementation evaluation and analysis of our system

V. IMPLEMENTATION AND TEST RESULTS

We validated our proposed approach based on a proof-of-concept implementation and an experiment that analyzes the average error for the mobile object's position and orientation measurements. The next subsection provides a brief description of the proof-of-concept implementation, to show that the system is feasible and has the capability to read the position and orientation data of the mobile objects on-the-fly. Furthermore, we will analyze the measurement errors while the mobile object is moving from one point to another.

A. Test setup

. As shown in the Figure 6 right, we used a metal stand to simulate a hospital bed, since getting a real hospital bed was neither possible nor needed, and we equipped it with RFID readers. The dimensions of the stand are the same as in Figure 5. For flooring, we used commercial carpet plates. The square type plates span over a 2.88m^2 surface and are organized in 2 rows and 4 columns. The size of each plate is 60cm ×60cm. On the back of each plate, we attached 20 RFID tags (Tag-it HF-I transponders, Texas Instruments). The tags are organized in 5 rows and 4 columns. The sizes of the tags are 8.5 cm × 5.5 cm and are installed in the floor plates as shown in Figure 6. The range between the tags is 2cm to 10cm depending on the type of the TAGs (Philips or Texas Instrument) and the used antenna. However, the best suitable distance was about 4-6 cm, where we had less tag collision and best positive scan rates, i.e. detecting a tag. It should be noted that the material of the surface or floor that covers the RFID tags has an influence on the RFID scanning range. The radiation power for RFID is approximately 14 dBm. However, through basic testing we could not determine significant difference between the specific plates that we used and the PVC flooring material that is widely used in hospitals. The RFID readers are made by MEGATRON Elektronik AG & Co and they are in compliance with the ISO 15693 standard. The readers were installed at a distance of 4.5 cm from the edge of the lower part of the mobile object to read the tags that are installed in the floor plates. Through several trials, we were able to optimize the vertical distance of the readers from the ground, which turned out to be 5 cm in order to detect the tags even if they are not located directly under the readers. The readers were mounted on plastic rails so that they do not have physical contact with the bottom of the stand (see Figure 6).

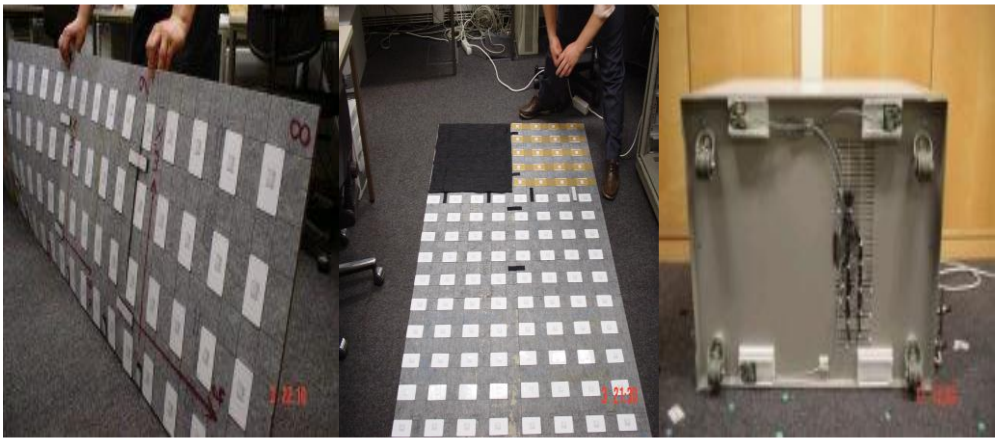

Fig. 6. The floor with RFID tags (left, middle) and mobile object with RFID readers simulating a hospital bed (right)

Our experiment consists of two routes: The first trial is based on a route that consists of nine test positions (i.e. different locations and angles), as shown in Table III, where the mobile object will pass through four times. Each test position is tested by four runs. The frequency of reading is every other tag and only when movement is detected. In each run we select three readers to analyze the data. The total readings will be 9*4*3 = 108. We intentionally simulated a failure in the fourth reader by making it inactive. By so doing, we can show that our system exhibits redundancy while maintaining a low average error. The average of the four runs for each position calculates the position of the mobile object on the route. The second trial is based on a different route that consists of ten test positions. The mobile object will pass through this route one time only. For both routes in the two trials we have used the same methodology of calculation. The results of the experiments are discussed next in subsections B and C.

B. Results and analysis of the first route

Table III shows the test results of the first route. Among 108 scans performed, only in 18 cases we could not identify the tags. The reason is that the wheel of the hospital bed passes through a non-tagged area or in an interference region (i.e. when two tags are read at the same time). In the first route, the hospital bed passes through 9 positions. The reading result of the 9 positions is as follows: Six positions provided location information for the three wheels (the fourth is intentionally disabled), two test positions provided location information for two wheels (positions 3 and 4), and at position 1 we identified only one wheel. The average error is 12.8 cm with a standard deviation of 11.3 cm. In Table III, the results show that at test positions 5, 6, 7, 8, and 9 the range of measurement errors (Euclidean localization error) was between 1.92 cm - 7.54 cm. This means that if three readers can obtain RFID tag data, the position of the mobile object can be calculated with an average error of about 5cm and standard deviation of 2 cm. This represents a significant improvement to existing positioning systems.

TABLE III

Positioning Results of the First Route (average error 12.8cm, stddev 11.3cm)

Test Position	Measured Position	Reference position	Euclidean localization error
1	64.25,218.75	27.67,200.33	40.96
2	26.75,170.75	32.67,187.17	17.45
3	64.25,152.75	49.50,155.00	14.92
4	71.75,128.75	55.50,125.67	16.54
5	64.25,90.75	65.83,89.67	1.92
6	54.25,26.75	52.17,34.00	7.54
7	49.25,30.75	43.83,30.83	5.42
8	64.25,26.75	58.33,23.83	6.60
9	64.25,18.75	62.33,22.17	3.92

C. Results and analysis of the second route

In the second route the mobile object passed through ten positions. The result of this experiment is shown in Figure 7. In eight of the ten positions we could locate the three wheels. In the other two positions we could locate two wheels. The average error with respect to the reference points is 6.38 cm with a standard deviation of 4.39 cm. The Euclidean localization error – the absolute value of the difference vector between measured and reference points - in the ten positions are 9.02 cm, 5.75 cm, 6.54 cm, 7.02 cm, 8.51 cm, 4.44 cm, 16.24 cm, 0.60 cm, 3.83 cm, and 1.84 cm. The overall results show that when using three readers,_the error range of the measurements was between 0.60 cm to 16.24 cm with an average error of 6.37 cm. Obviously, if the fourth reader was not intentionally malfunctioning, the average error would be less.

In Figure 9, we show the measurement of the orientation angle. The average error of orientation is 0.21 radians (12.17 degrees) with a standard deviation of 0.18 radians (9.52 degrees). The difference between the measured angle and the reference angle for the 10 test positions were 0.18, 0.01, 0.19, 0.14, 0.35, 0.19, 0.57, 0.12, 0.001, and 0.38 radians. The results show that the precision in the orientation measurement is very high.

Throughout the experiment, we noticed that due to the parallel arrangement of the tags and the low transmission range of the tags (about 8 cm), sometimes we had difficulties to detect and read out the tags. This is especially so when the wheels moved in a non-tagged area, that is, between two rows. In order to avoid such case, we can re-arrange the tag positions and use a chess board arrangement followed by extensive benchmark testing. This is something to consider for future work.

It should be noted that, a chess board style pattern of tag distribution as used in [30] outperformed the system proposed in this paper in terms of minimizing the average error, and reached an average error of 5cm. For the experiments in [30] we used 39 tags per 60cm^2 while in the experiments in this work we only used 20 tags per 60cm^2. From a pragmatic point of view, it should be questioned if an average error as low as 5cm is really required for hospital scenarios described in Section II. In most cases where indoor positioning is required in hospitals, an average positioning error of 13 cm should be more than sufficient, which we are achieving with the approach proposed in this paper. So for hospitals, a higher density of tags and a chess-boarded style of distribution are not required, in particular because such a tag distribution is not supported by commercially available RFID floors and would need to be installed manually. As a side note, the prototype described in this paper used hardware from different vendors and is completely different from [30], although it follows the same general approach.

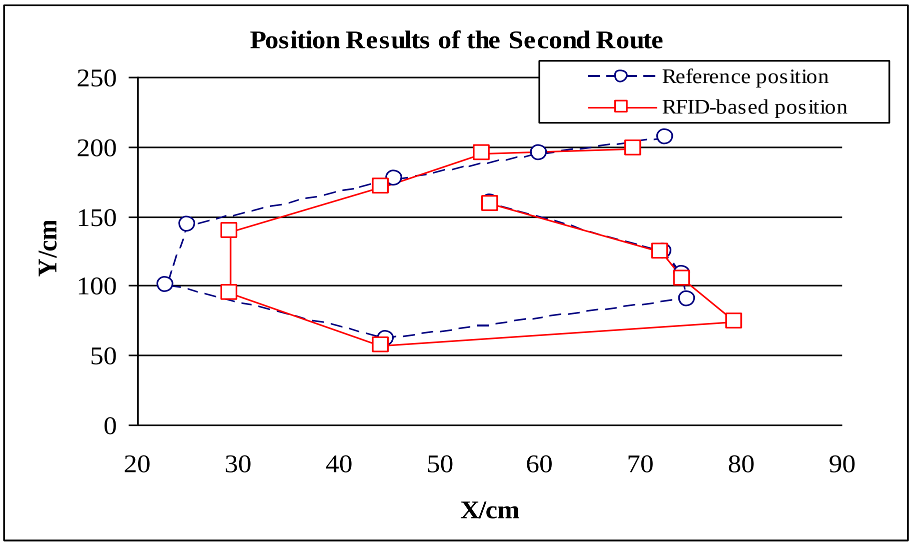

Fig. 7. Results of the second route experiment

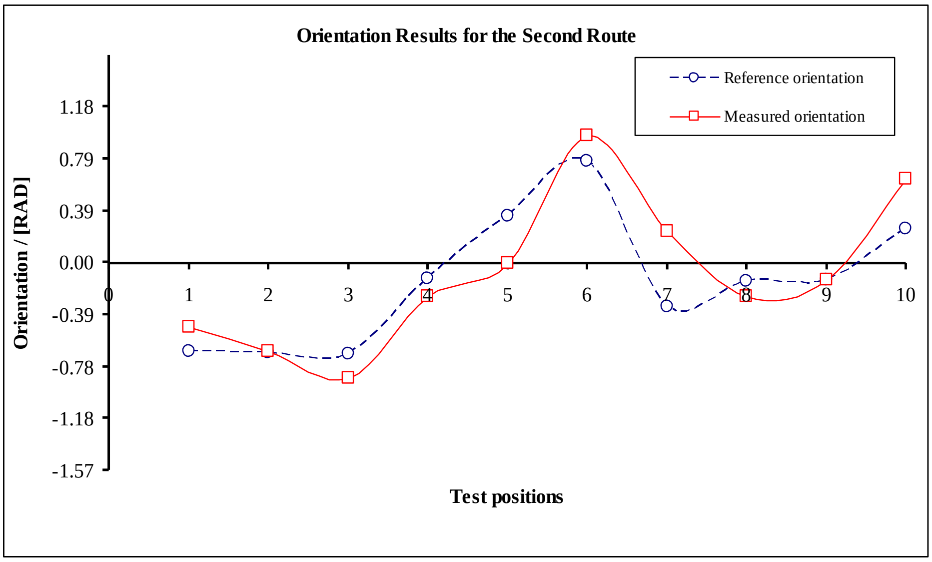

Fig. 8. Second route: Comparison of the real orientation angle with the measured angles in radian

VI. Analysis

There are few factors that affect the accuracy and precision in our system such as the range of RFID readers, form factor and type of the tags, distance of readers from the floor, and form and size of antennas. Another factor is the number and layout of RFID placement on mobile objects. However, beyond the presented experiments, we do not have yet any results to report on how exactly the layout of reader placement affects the accuracy and precision of our system. Our system further depends on tag density and distribution layout on the floor. Another minor dependency is on the distance between the readers and the floor. However, an appropriate distance can be determined through a few preliminary trials, which for our implementation and experimental setup came out to be between 2cm – 8cm. There were no changes in accuracy when the distance was changed from 4cm to 6cm.

Based on our preliminary experience, for a given combination of RFID technology once a distance has been decided, the system works with a nearly constant accuracy. Of course the optimal distance depends on the type of the specific hardware that is used (range, frequency, antenna, vendor-specific attributes of readers and tags, form factor of tags). But this dependency is controllable. Moreover, the hardware has no correlation to the other factors that affect the accuracy in our approach.

It should be noted here that our approach has similar or lower installation complexity compared to RFID positioning approaches that rely on signal propagation measurements and use triangulation or lateration to estimate the position. In particular, when off-the-shelf RFID floor pads [24] are used, our approach does not require a high installation effort. In this case, the effort is restricted to mounting RFID readers on mobile objects. The required effort is linear proportional to the number of mobile objects. And if the floor needs to be manually prepared, i.e. RFID tags need to be attached to the floor, the effort is still comparable to or lower than other approaches. This effort should be compared to the effort of sensor installation, calibration, and time synchronization in other approaches such as [27]. Approaches that measure TOA to estimate target position require very accurate time synchronization and rely on on-site calibration of reference points (readers). This makes the installation and maintenance of readers a very time consuming task. Extensive experimentation is required to find an appropriate position to place the RFID readers to obtain high localization performance [29]. An example, in the localization system presented in [27], for a region of 3m×3m, five sensors need to be placed in the environment, interconnected, and calibrated, and still the achieved measurement accuracy is around 10cm only. If the region to be covered is larger, a new cell of 5 sensors needs to be installed, making the system expensive.

VII. Conclusion and Future Work

In this paper, we presented an RFID-based system for mobile object positioning in hospitals. Our approach is based on passive RFID tags to meet the requirements for compatibility and scalability. A number of contributions were made in this paper. First is the simplicity of our calculation and lack of complex calculations. This is a major benefit of this approach that makes is easy to implement and highly accurate at the same time. Second, due to the way we have used the RFID technology, the average error, accuracy and precision in our approach are not affected by parameters such as environment geometry and size, number and distribution of mobile objects, or signal propagation issues such as reflection or absorption. Finally, we showed through a proof of concept implementation and a series of experiments that the system is feasible and can achieve a low average error, for indoor object positioning and orientation, which is superior to previous work as described in section 3.

For future work, we are planning to study the effect of using different types of floors. This is because the absorption rate of RF energy varies from one type of floor to another (e.g. wood floor, concrete floors etc.) and thus affects the measurement quality. Furthermore, we plan to study the effect of continuous pressure on the floor and the impact that might have on the tags which affects the resiliency of the system. Finally, we are planning to study the power performance of the system.

References

[1] L. Revere, K. Black, F. Zalila. " RFIDs can Improve the patient Care Supply Chain." Journal of Hospital Topics, Taylor and Francis, Vol. 88, Iss.1,pp. 26-31, 2010.

[2] W. Yao, C. H. Chu, Z. Li. " The adoption and Implementation of RFID Technologies in Healthcare: A literature Review." Journal of Medical Systems, Springer, 2011. DOI=10.1007/s10916-9789-8

[3] Frost & Sullivan. "World RFID real time locating systems market." Tech. Rep., 2005, Market Engineering Research F549-11,Palo Alto, US.

[4] Wan Mohd. Yaakob Wan Bejuri, Mohd. Murtadha Mohamad, and Maimunah Sapri. "Ubiquitous positioning: A taxonomy for location determination on mobile navigation system." Signal and Image Procesing Journal, Volume 2, Issues 1, pp. 24-34, 2011.

[5] Vince Stanford. "Pervasive computing goes the last 100 feet with RFID systems." IEEE Pervasive Computing, vol. 2, pp. 9-14,2003.

[6] L.W. Yeh, M.H Hsu, H.Y Huang, Y.C Tseng. " Design and Implementation of a self-guided indoor robot based on a two tier localization architecture." Pervasive and Mobile Computing, Elsevier Volume 8, Issue 2, pp. 271-281, 2012.

[7] Konrad Lorincz and Matt Welsh. "Motetrack: a robust, decentralized approach to rf-based location tracking." Personal Ubiquitous Comput., vol. 11, pp. 489-503, 2007.

[8] B. Ando, S. Grazianiand C. Orazio Lombardo, and N. Pitrone."Development of a smart clear path indicator." Proceedings of the 21st IEEE Instrumentation and Measurement Technology Conference (IMTC04), .pp. 492-497, 2004..

[9] Massimo Bertolini. "Performance measurement and analysis for an RFID technology application to commercial products." International Journal of RF Technologies: Research and Applications, vol. 1, no. 4, pp. 279-305, 2009.

[10] Ali Asghar Nazari Shirehjini and S. Shirmohammadi. "A High Precision Sensor System for Indoor Object Positioning and Monitoring." Proc. IEEE Workshop on Robotic and Sensors Environments (IEEE ROSE09), Lecco, Italy, November 6 - 7, 2009.

[11] A. Solanas and J. Castellà-Roca. "RFID Technology for the Health Care Sector." Bentham Science Publishers Ltd. Recent Patents on Electrical Engineering, Vol. 1, No. 1. 2008.

[12] John Krumm, Steve Harris, Brian Meyers, Barry Brumitt, Michael Hale, and Steve Shafer. "Multi-camera multi-person tracking for easyliving." Proceedings of the Third IEEE International Workshop on Visual Surveillance (VS'2000), Washington, DC, USA, 2000.

[13] B. Glover and H. Bhatt. "RFID essentilas.", O'Reilly Media Inc., First edition, ISBN 978-0596009441, 2006.

[14] Hui Liu, H. Darabi, P. Banerjee, and Jing Liu. "Survey of wireless indoor positioning techniques and systems." IEEE Transactions on Systems,

Man, and Cybernetics, Part C: Applications and Reviews, , vol. 37, no. 6, pp. 1067-1080, 2007.

[15] H. Hile and G. Borriello. "Positioning and orientation in indoor environments using camera phones." Computer Graphics and Applications, IEEE, vol. 28, no. 4, pp. 32-39, July-Aug. 2008.

[16] Ubisense Products Website, How It Works, Cambridge, UK, February 2005, http://www.ubisense.net/Product /howitworks.html.

[17] Roy Want, Andy Hopper, Falc ao Veronica, and Jonathan Gibbons. "The active badge location system." ACM Trans. Inf. Syst., vol. 10, pp. 91-102, January 1992.

[18] Junyi Zhou and Jing Shi. "Localisation of stationary objects using passive RFID technology." International Journal of Computer Integrated Manufacturing, vol. 22, no. 7, pp. 717-726, 2009.

[19] Scooter Willis and Sumi Helal. "A Passive RFID Information Grid for Location and Proximity Sensing for the Blind User." Technical Report Number: TR04-009, University of Florida, Florida, US, May 2003

[20] I.A.R. Ashokaraj, P.M.G. Silson, A. Tsourdos, and B.A. White. "Robust sensor-based navigation for mobile robots." IEEE Transactions on Instrumentation and Measurement, vol. 58, no. 3, pp. 551-556, march 2009.

[21] T. Yamada, S. Nakamura, and K. Shikano. "Robust speech recognition with speaker localization by a microphone array." Proceedings of Fourth International Conference on Spoken Language, ICSLP 96, vol. 3, pp. 1317-1320 vol.3, oct 1996.

[22] Ekkahau Inc., Company Website, 2004, http : / / www . ekahau.com.

[23] Wenjie Yan, Cornelius Weber, and Stefan Wermter. "A hybrid probabilistic neural model for person tracking based on a ceiling mounted camera." J. Ambient Intell. Smart Environ., vol. 3, pp. 237-252, 2011.

[24] Vorwerk AG, "Smart plate" Web, 2003, Website retrieved on 07.01. http://www.vorwerkteppich. de/sc/vorwerk/template/r_d.html.

[25] Shun-Yuan Yeh, Keng-Hao Chang, Chon-In Wu, Hao-Hua Chu, and Jane Yung-Jen Hsu. "Geta sandals: a footstep location tracking system" Personal Ubiquitous Comput., vol. 11, pp. 451-463, August 2007.

[26] Sonitor Technologies, www.sonitor.com

[27] Salah Azzouzi, Uwe Dettmar, Rainer Kronberger, Marcus Cremer, and Thomas Knie."Design and measurement results of an UHF RFID localization system." In *Proceedings of the 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies* (ISABEL '11). ACM, 2011. DOI=10.1145/2093698.2093855

[28] Mathieu Bouet and Aldri L. Santos. "RFID Tags: Positioning Principles and Localization Techniques". Retrieved on 07th june 2012 from http://www.nr2.ufpr.br/papers/RFIDTags08.pdf

[29] Junyi Zhou and Jing Shi. "A comprehensive multi-factor analysis on RFID localization capability." Advanced Engineering Informatics, vol 25, no 1, pp. 32-40, January 2011. DOI= 10.1016/j.aei.2010.05.006

[30] Ali Asghar Nazari Shirehjini, Abdulsalam Yassin, and Shervin Shirmohammadi. "An RFID-Based Position and Orientation Measurement System for Mobile Objects in Intelligent Environments." IEEE Transaction on Instrumentation and Measurement, vol 61, no 6, pp. 1664-1675, 2012. DOI= 10.1109/TIM.2011.2181912