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Combining Cricket System and Inertial Navigation for Indoor Human Tracking

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***Abstract*—We present a system-level approach to localizing and tracking users on a basis of different sources of location information. We have applied a combination of the Cricket system and inertial navigation sensors to improve the coverage and accuracy of our framework when used indoors. The system can be applied outdoors as well using, for example, GPS as the source of location data. The overall system architecture is modular and extendible, allowing for creation of location and context aware services and inclusion of additional sources of localization data. Extensive performance evaluation presented shows that the system is both accurate as well as scalable.**

I. Introduction

The visions of context-sensitive services, ubiquitous computing and ambient intelligence have driven several aspects of wireless sensor networks research, but perhaps none more so than localization and tracking. Location of a user is one of the most fundamental types of context, and can be applied in a vast number of environments from smart homes to improved security solutions. However, accurate localization of users is not trivial, and most of the individual systems presented (see, for example, [1]) suffer from coverage problems, high cost or reduced accuracy. Besides user tracking general asset tracking is, of course, also of importance. Automatic localization of goods has a number of applications in the business domain, especially in the context of inventory management. Even though we focus on the problem of tracking users in this paper, much of our framework is also applicable in the general case.

In this paper we present a system-level approach to the problem of localizing and tracking a human user who assumed to be carrying a portable terminal. The terminal estimates its location by using any number of different sources of localization information available to it. In outdoors this could mean, for example, GPS or information obtained from cellular systems whereas when indoors ultrasonic and RF beacons are an option. We have further combined these approaches with additional sensors enabling inertial navigation to be used to improve localization accuracy and coverage of the system. Combining readings from different types of sensors to improve localization and tracking performance is, of course, a well-known technique in, for example, robotics [2]. However, the combination of inertial navigation and the Cricket system reported on here appears to be new. The terminal communicates its estimates to a backend server located in the network, which in turn gives users back information about their surroundings (including the locations of other consenting users). The system also supports the creation of location-based services such as service discovery based on physical proximity.

The rest of the paper is structured as follows. In Section II we give an overview of the related work available in the literature. In Section III we present the architecture and implementation details of our system, focusing on the inertial navigation solution design and on the services offered by the backend server. Results from a detailed performance evaluation of the different elements of the system are given in Section IV before conclusions are drawn in Section V.

II. Related Work

A broad class of localization systems rely on the received signal strength. However, due to the complicated indoor propagation and mobility patterns, these systems either require accurate indoor models, pre-configuration and/or extensive calibration, which in many cases is impractical [3]. Furthermore, the location estimates obtained are not very accurate and reliable.

Microsoft's RADAR [4] is an indoor RF based localization and tracking system, which measures the RSSI of several access points in a WLAN infrastructure, with overlapping regions of access point coverage. Experimental results show that RADAR is able to provide location accuracy within several meters, which is also similar to another RF based localization system SpotON [5]. Motetrack [6] is also an RF based localization system, which uses the RSSI from different decentralized sensor nodes to calculate the position. All these methods require building up a location map database of the signal signatures after several measuring points.

The Active Badge [7] and the Active Bat [8] are examples of non-RF-based localization systems. The former uses infrared signals, whereas the latter is based on ultrasonic pulses. Both have issues with scalability and the Active Bat additionally relies on Time-of-flight principle requiring very accurate clock synchronization in the system.

Cricket system [9] uses beacon nodes, mounted at known positions which periodically transmit beacon signal consisting of an RF signal and an ultrasonic signal. A mobile user with a listener node performs time-difference-of-arrival based distance ranging between an RF signal and an ultrasonic signal transmitted at the same time from the beacon nodes. Trilateration is applied to result in location estimates. With passive listener nodes carried by the people, the Cricket system scales very well with the number of users.

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UWB based systems are an emerging indoor localization technology and can provide an accuracy of the order of a few centimeters. However, they are very expensive. Image processing based tracking systems suffer from limited coverage, camera distortions (rotations, scaling, perspective etc.), lighting conditions etc and are expensive to realize. Current, RFID based systems for human tracking are not so attractive since they suffer from range limitations and scalability can be a problem because of the absence of any organized medium access mechanism.

Inertial Navigation Systems (INS) have been very well-known in both military and civil applications [10]. Based on simple Newtonian principles, calibrated gyroscopes and accelerometers can be used for localization. However, over a period of time INS accumulates error, which needs to be compensated for.

Many of the above mentioned systems suffer from requirements of having full coverage, which is less practical in many applications. Furthermore, various kinds of interferences result in faulty location estimates or in some cases the location estimates are not computed at all. In our system, we have addressed the problem of blind spots and the missing instants especially in the context of human motion tracking system.

III. System Design and Implementation

We have developed an indoor localization system for human localization and tracking services by combining Cricket nodes and inertial sensors. In order to be able to locate users on general outdoor maps from our localization system, we added a module that transforms the local coordinates of the users into GPS coordinates using the algorithm proposed by Vincenty in [11]. In addition to the localization features, we have enhanced the system with Geocasting and Service Discovery capabilities. The basic working principle of the system is illustrated in Fig. 1.

Both the localization and the tracking systems are connected to a terminal, where the localization is performed. Furthermore, the terminal runs a GUI application, where the indoor map is provided. The map does not only show the users but also some additional services. The application has also capabilities of discovering and using services provided by sensor nodes. The service discovery and service use communication is done over TelosB [12] motes.

The terminal, which has WLAN capability, communicates over an AP with a server. The server hosts the database where all location information of the users and the indoor map data is stored. The server runs a small service application. It is a bootstrapping application allowing the GUI application to discover and to connect the localization system. As soon as the user obtains a connection to the LAN, the GUI application searches for the localization service. The service application provides the terminal with the needed information about the connection to the database and also provides the ID of the map to be used. With this information the client is able to connect to the database and get the description of the indoor map. The map is then generated on the client and

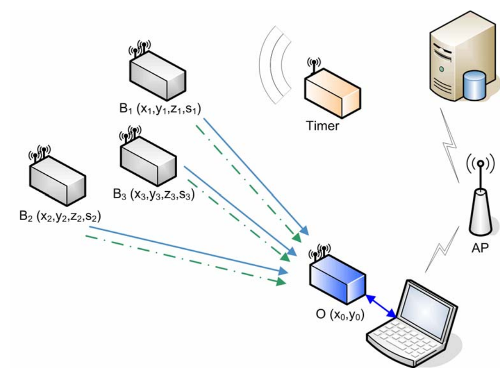

Fig. 1. In an assigned time slot from the Timer node, each of the Beacon node, located at different coordinate position, transmits the beacon signal to the listener node O, which performs the distance ranging and later trilateration based localization.

the localization application is activated. The client periodically stores its computed location in the database and fetches the location information of the other users from the database.

A. Localization with Cricket Motes

This section describes the main principle of the localization process based on Cricket [13] motes. As described in Section II the Cricket motes have RF and ultrasonic transceivers and they use the TDoA technique for distance estimation. We use a TDMA based scheme for the beaconing nodes in our system to limit the interference in the system and for increased stability. In order to be able to reuse the time slots one can adjust the transmission power of the RF and the US signals at each of the beacon node. For US signals, the transmission power is not so crucial because walls act as natural boundaries. However, this is not so for RF signals. By reducing the transmission power especially of RF signals, small cells may be created and time slots may be reused. The *Timer* mote is the synchronizing and controlling unit for motes within one cell and acts as a kind of trigger for the localization process.

The position of the user is computed by the client application. After receiving enough distance samples for localization via trilateration, an outlier detection follows in order to filter out erroneous distance samples, which may occur because of reflection and other effects. After localizing the user, one more step is required for validation of the obtained coordinates. The validation process for the localized user is described in Section III-C.

B. Tracking with Inertial Sensors

The localization with Cricket motes is not possible if there are not sufficiently many Cricket nodes providing line-of-sight (LOS) between the listener and beaconing mote. As we want to have a constant and continuous localization, we add a tracking technique into our system. It is used whenever the main localization system cannot operate due to the absence of LOS.

This system is built using STM LIS3L02AQ accelerometer and an Analog Devices' ADIS16100 gyroscope connected to a TelosB [12] mote. The INS box is shown in Fig. 2. The accelerometer is used for the motion detection and velocity estimation of the user, as described in Section IV-3 and the gyroscope is used for tracking the orientation. The system requires an initial orientation information, which is assumed to be known beforehand. In the future, a digital compass can be used for this purpose. Each location update is dependent on the previous location and on the current sensor readings. By applying a motion model to the sensor readings and the previous location, the new location is calculated. Every state update contains a certain error. Therefore the error accumulates over time and the estimated location diverges more and more from the real position. It is very important not only to minimize the location error generated each step, but also to have a mechanism that can correct the accumulated error. Therefore, we use the Cricket system to correct the error of the INS system. The localization of the Cricket system has a higher priority and keeps the error within the predefined boundaries. By combining these two different methods we can guarantee a continuous localization. After the new location is calculated, its validity is again checked as described in the next section.

C. The Indoor Map

In our system, an indoor map shows not only the localized users, but also plays an important role for the localization process. The main idea is that all the components of the indoor map are stored as polygons defined in a string as a set of points. This way, we are able to check if the localizations are inside the allowed boundaries and to have a mechanism for validating computed localizations. The indoor map has a defined reference point to which all other entities refer to. The reference point of the indoor map has also a known GPS point and a known orientation. Furthermore, the whole indoor map description is stored in a database. That means that the client is completely map independent. The map information is automatically downloaded from the server and dynamically created on the client, depending on the area where the user is currently present.

D. Location Discovery - The Application

The client application which is shown is Fig. 3, runs on the user's computer. It creates and illustrates the actual indoor map and is responsible for the localization of the user and also allows the position of other users. Furthermore it provides some service discovery capabilities for motes and shows the location of the service in the map. One has the possibility to search for services only in certain areas of the map by using the geocasting feature.

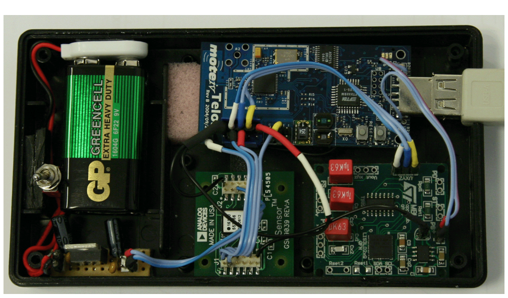

Fig. 2. The Inertial Navigation System connected to a Tmote Sky mote.

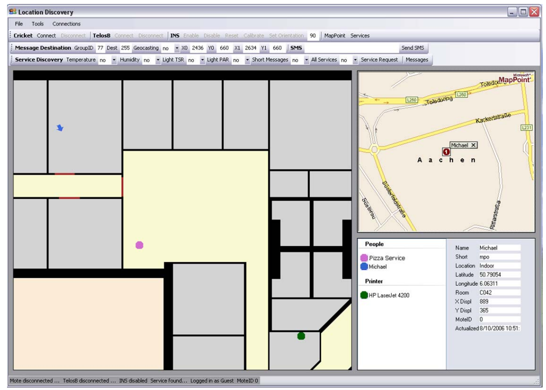

Fig. 3. Management and graphical user interface of the system.

E. Geocasting and Service Discovery

Geocasting is a technique for delivering packets from one source node to several destination nodes within a certain geographic area. In order to be able to communicate with motes in certain areas, we added support for basic geocasting features, such as for message delivery into rectangular regions specified by the coordinates of the corner points.

Service Discovery systems implement a set of different protocols that enable the application to dynamically discover services provided by the network and also help services to advertise themselves. We use a reduced version of the *Minimal SLPv2 Features* set described in [14]. It is a SLP-based based protocol [15] that aims to operate on sensor nodes, that have very limited computing resources and a small communication bandwidth. As a solution, we want to avoid using the ASCII representation of the requests and replies as far as possible, but use predefined binary values as their representatives instead.

IV. Performance Evaluation

The system described above is designed to provide a reliable human tracking capability. In order to evaluate the performance of various sub-components of the system, we conducted a series of experiments, which are described in the following subsections.

1) Cricket System Localization: In order to evaluate the performance of the localization system with Cricket nodes for static objects, we took 500 localization samples for a fixed measuring point. Fig. 4 shows the distribution of the obtained location estimates and the corresponding Euclidean error. We observed that 186 location samples possess Euclidean error of less than 1 cm while 310 samples showed Euclidean error of 5 cm. This means that about 99 % of the location estimates lied within the accuracy of 5 cm. This experiment also showed

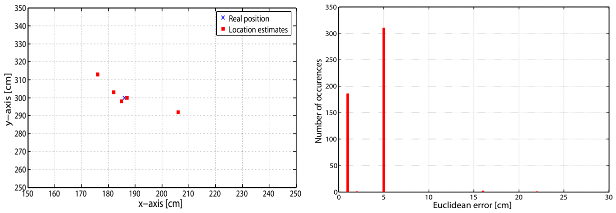

Fig. 4. Accuracy of static localization with Cricket nodes.

that the Cricket system is able to give high enough accuracy for human localization applications.

In order to observe the localization accuracy of the Cricket system in an office environment when a person walks, we repeated the experiment 40 times on the same path. The results are shown in Fig. 5. The real path is indicated by the blue line and the positions of the beaconing nodes are shown as the green triangles. One may easily observe that due to the absence of LOS, the Cricket system was unable to compute the localization estimates in certain areas. Starting from the lower termination point on the path, "blind" spots can easily be observed in regions where the two groups of Cricket nodes were not deployed. It can also be observed that the positioning accuracy degrades a bit for this experiment compared to the static case. This is so because each distance estimate was performed with a delay of 90 ms at the listener from the three beacon nodes and the person had shifted her position during this interval.

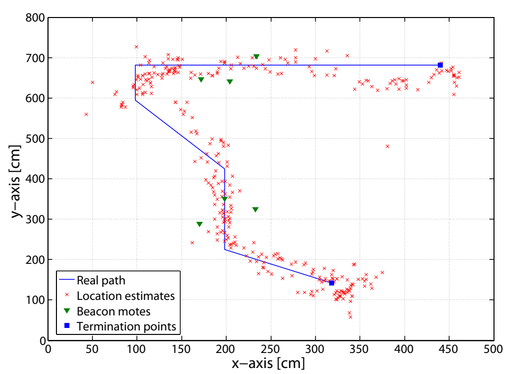

Fig. 5. Localization of a moving object with Cricket nodes.

2) Limitations of the Cricket System: We have shown in our experiments, that the localization with Cricket nodes is very accurate but gives position updates only in the regions where LOS is available and all the three distance estimates, necessary for trilateration, are computed. This requirement cannot be fulfilled in some situations. It is possible to improve the situation by deploying more Cricket nodes into the system in order to have a better coverage, but this would escalate the cost of the system.

The ultrasonic transmitter and receiver on the Cricket nodes have conical reflectors. This allows to have the highest gain at zero degree to the normal and the gain decreases monotonically at higher angles. The ultrasonic detection circuitry in Cricket nodes work on the threshold basis. Because incoming signals at higher angles have a weaker signal strength, the detection circuitry needs more time to detect the signal, thereby causing a positive error in the distance estimation. This behavior is also seen as the real distance between the transmitting and receiving node increases.

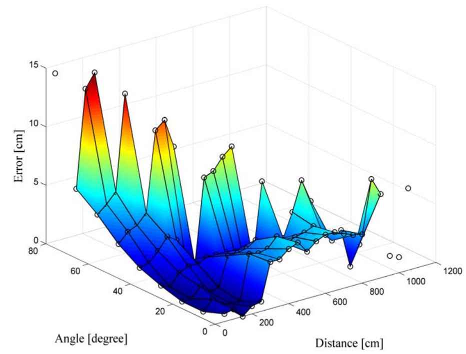

Fig. 6. 3D plot of the distance ranging error for distances between 50 cm and 1050 cm and angles between 0 degree and 80 degrees.

The range depends upon the sensitivity of the ultrasonic receiver module, the detection threshold and most importantly on the power level of the transmitted ultrasonic pulse. We observed a maximum working range of Cricket nodes to be approx. 11 m. We also observed in our experiments that the error remains quite stable within 2 cm boundaries for a range of 0...40 degrees. From 40 degrees on up to 75 degrees, the error rises to 9 cm. From 75 degrees onwards, we were unable to detect the ultrasonic signal anymore. This behavior was even more profound for higher distances, since the signal strength gets weaker. Fig. 6 shows the relationship of the Euclidean error in the distance estimation with respect to the real distance and angle between an ultrasonic transmitter and receiver on the Cricket system.

Since trilateration based localization scheme entirely relies on the distance estimates, any inaccuracies or spurious estimates can result in erroneous position. In the Cricket system, the signals take some time for propagation and to avoid phenomena like hidden terminal problems and RF and US interferences, the design includes various delays and backoffs [9], which limits the number of beacon signals transmitted per second. This limits the number of position updates possible per second. The constraints on the maximum number of beacon signals that can be transmitted per second are mostly imposed by the initial delay that has been put to let any stray US pulse die down before the transmission of the beacon signal. On the other hand, the noise added from sensor miscalibration, digitization, quantization, numerical computations, variable interrupt handling durations and US-speed variations (due to refraction and depending on the composition of air) cannot be eliminated.

3) Human Tracking Signature: In order to track a person, we need to know the speed and direction of the motion. In theory, integrating the acceleration twice over time leads to the displacement. In practice human motion is very complex and is characterized with several accelerations all the time. Fig. 7 shows the accelerometer readings for human motion. One can directly observe that the human motion is quite complex compared to wheeled objects and it is nearly impossible to get the accurate velocity or the displacement by integrating the acceleration over time.

When closely looking at the z-axis in the Fig. 7, one can observe a regular pattern. The existence of such a signature had also been established earlier by Brannstrom in his M.Sc. thesis [16], which we became aware of during the writing of this manuscript. Every spike in the pattern exactly corresponds to a single step. Comparing the two figures, one can see that in the faster motion, the spikes are nearer to each other. For slower and smoother steps, the x-axis and y-axis accelerometer values are less indicative to the true motion. But the pattern of the z-axis is always clear for normal human motion and it can always be realized.

Owing to this peculiarity, we use the z-axis pattern in our system as the indicator of motion. We set the zero point of the z-axis to zero and introduce a threshold value to filter out the noise. All the sensor readings which are below an empirically computed threshold are set to zero and indicate no motion. The above settings easily and reliably allow to estimate if a person is moving or not. Several consecutive samples are needed to be analyzed for this purpose.

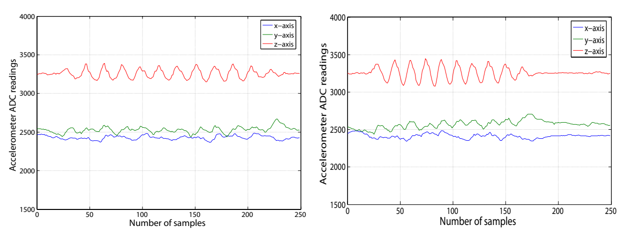

Fig. 7. Human motion profiles. Slow and fast motion are shown on left and right, respectively.

After recognizing the motion, the displacement is needed to be calculated. For this purpose, we devised a step model after extensive experimentation. We can say that in most of the cases, the step size of the same person remains constant. This is valid for normal motion and not for extreme cases like running or jogging. In our system, we consider a normal everyday human motion. We assign a mean motion velocity to each user based on the step size. As explained before, when someone moves slower, the inter-peak distance along the z-axis accelerometer readings is larger and when someone moves faster the peaks lie close to each other. Since we know the sampling rate, we can also know the duration of a sample and by counting the number of samples between two peaks during a motion period, we can estimate the velocity of the user.

4) Inertial Navigation Performance: Owing to the limitations of the Cricket system, we use an INS based tracking system complementary to the Cricket system in order to address the blind spots problem. We evaluated the distance estimate errors by the INS system using laser ranging as the reference. It is more difficult to obtain accuracy bounds for the distance estimates from the INS as compared to the Cricket system. Since we only rely on the human motion, it is difficult to obtain exactly the same motion signature over multiple times. However, in order to be close to the realistic case, we focussed more on the natural motion of a person and therefore the results bear some degree of error margin.

In one experiment, we performed measurements for two different distances: first for a distance of $D = 5$ m and second for a distance of $D = 8$ m. For both the cases, we collected 50 samples. The results are shown in Fig. 8. It can be seen that in general, the error for shorter distances is smaller than for larger distances. This is also indicated by the average error values of the measurements for both the distances. The mean error for the distance estimates, $D = 5$ m and for $D = 8$ m was found to be 0.19 m and 0.37 m, respectively. This fact can easily be explained, because the distance estimates are computed by integrating the estimated velocity over time. Each velocity estimate introduces a certain error and the error accumulates in time. In general, the longer a person walks the higher is the accumulated error. In summary, we found that INS-based distance estimation is accurate enough to track the position of a person for short distances of a few meters.

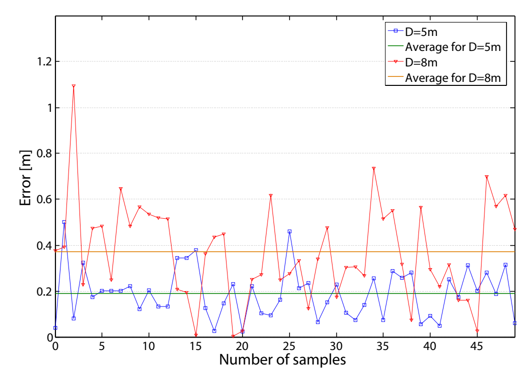

Fig. 8. Error of the INS based distance estimates for $D = 5m$ and $D = 8m$.

5) Combination of Cricket System and INS: In the following, we examine and compare the localization accuracy of the hybrid combination of Cricket localization and INS tracking. We again repeated walking on the same track 40 times. In this experiment, the Cricket system was the main localization system and the inertial sensors tracked the position between any two localization updates. As soon as a new location estimate was obtained by the Cricket system, the position was corrected and the accumulated error of the tracking system was reset. Fig. 9 shows the results for both the systems working together. One can clearly see that the areas which suffer from absence of LOS with the beaconing nodes are bridged by the tracking system. We therefore get much smoother and regular location

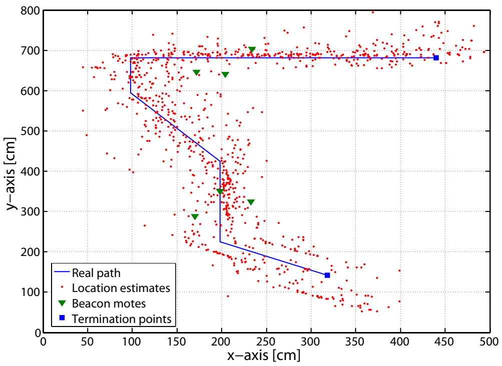

Fig. 9. Combined localization of a moving object with Cricket nodes and inertial sensors.

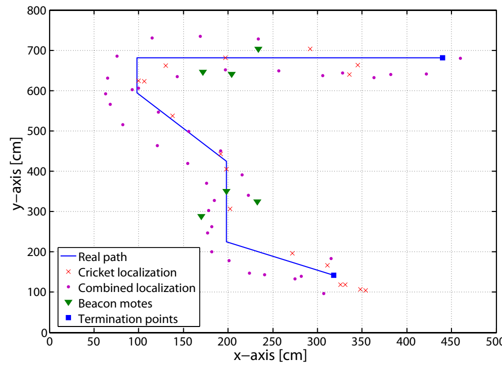

Fig. 10. Comparison of localization methods for a single track.

estimates, which makes the localization process continuous. The location estimates obtained are distributed more uniformly over the whole path. It may be noted that in this experiment, the accuracy of the system is compromised due to the lack of the orientation, which is not usually the case.

In order to compare the accuracy of both the localization methods, we calculated the RMS error along the path for the measurement samples. Since it is not possible to map each measurement sample to its real position, we used the following method: We represented the whole path as an array of reference points placed at a distance of 10 cm from each other. We assigned a reference point to each measurement sample. This was done by calculating the Euclidean distance to each of the 99 reference points in our path for each measurement sample. Then, we assigned the measurement point to the reference point with the smallest Euclidean distance.

Fig. 10 compares the localization results of the Cricket system alone to the Cricket and inertial navigation systems combined together. We show the location estimates for each of the systems when walking the path only a single time. It is clearly evident that there are no blind spots and the combined system gives continuous and accurate tracking. Combining the INS based tracking with Cricket system is able to avoid the sporadic and missing position updates resulting from NLOS and highly acute angles between ultrasonic transmitter and receiver. It may be noted that further smoothening and error minimization can be achieved by using Bayesian filtering framework [2], [17].

V. Conclusions and Future Work

We have presented a system-level solution for localizing and tracking users. In addition to the overall architecture design and implementation, we have developed specific inertial navigation based solutions for improving the coverage of other sources of localization information used in the system. The experiments carried out have convincingly demonstrated that the addition of inertial navigation significantly improved both the coverage and accuracy of especially Cricket-based localization. The system developed is also highly extendible and modular, allowing for new services to be integrated and new sources of localization information added. We intend to pursue these aspects in our future work.

Acknowledgment

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