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# Integration of global positioning system and inertial navigation for ubiquitous context-aware engineering applications

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## Abstract

Evolving technologies such as context aware computing offer significant potential of improving decision making tasks in several engineering applications by providing support for tedious and time consuming activities associated with timely and accurate access to needed information. Bi-directional flow of information relevant to the spatial context of a mobile user requires continuous and accurate tracking of the user's position and orientation. The tracking technology used cannot be dependent on installed infrastructure because it is not possible to install such infrastructure in every building. Additionally, a disaster may cause partial or complete damage to the installed infrastructure itself. The Global Positioning System (GPS) is a convenient option because it is independent on pre-installed infrastructure; however it fails when the line of sight to the satellites is obstructed. To overcome this problem, this paper presents research that investigated the development and effectiveness of a ubiquitous location tracking system based on the integration of Real Time Kinematic Global Positioning System (RTK-GPS) and Personal Dead Reckoning (PDR) technologies for dynamic user position tracking. The designed GPS-PDR switching algorithms, along with initial results documenting system effectiveness based on path complexity, length and duration are described.

*Keywords*: context awareness, position tracking, GPS, PDR, mobile user

## 1 Importance of the research

Context aware computing is defined as the use of environmental characteristics such as a user's location, time, identity, profile and activity that is relevant to the current context (Burrell and Gay, 2001). Context aware computing can thus potentially enable mobile users (e.g. construction inspectors, firefighters) to leverage knowledge about various context parameters to ensure that they get highly specific information, pertinent to the decisions at hand. The relevance for context awareness for mobile users has been demonstrated in several applications (Aziz et al., 2005). The concept of context-aware information delivery (Aziz et al.2005) centers around the creation of a user centered mobile dynamic indoor and outdoor work environment, which has the ability to deliver relevant information to on-site mobile users by intelligent interpretation of their characteristics in space and time so that they can take more informed decisions (Schilit et al., 1994). Context awareness is of great value for civil engineering inspectors, emergency responders, security and military personnel. For example, tracking civil engineers during post disaster assessments, or while conducting bridge inspection reports, can allow bi-directional flow of streamlined information and thereby improve the efficiency of the decision making processes.

RTK-GPS is a convenient option to track a mobile user continuously in an outdoor environment. It is highly accurate and is free of accumulated errors. GPS, being a satellite-based navigation system, works very well outdoors but lacks support indoors and is unreliable in dense foliage, in so called "urban canyons" and generally in any environment where a clear line of sight to the satellites is unavailable.

In recent years, the need for indoor localization has been rapidly expanding in many fields and currently offers significant potential on construction sites in particular. However, unlike outdoor areas, the indoor environment imposes different challenges on location discovery due to the dense multipath effect and building material dependent propagation effect (Khoury and Kamat, 2008b). There are many potential technologies and techniques that have been suggested to offer the same functionality as a GPS indoors, such as Wireless Local Area Networks (WLAN), Ultra-Wide Band (UWB) and Indoor GPS. By tagging users with appropriate receivers/tags and deploying a number of nodes (access points, receivers, transmitters, etc.) at fixed positions indoors, the location of tagged users can conceptually be determined and continuously tracked by fingerprinting and triangulation. A detailed comparison of the WLAN, UWB and Indoor GPS systems has also been done in a recent study (Kamat and Khoury, 2009).

The main drawback of the aforementioned indoor tracking technologies is their dependency on pre-installed infrastructure making them unsustainable in a dynamic environment. To overcome this shortcoming, the authors have developed a Personal Dead Reckoning (PDR) system that does not require pre-installed infrastructure. The Inertial Measurement Unit based PDR system is very accurate in measuring linear displacements (i.e., distance travelled, a measure similar to that provided by the odometer of a car) with errors being consistently less than 2% of the distance travelled. The accuracy of the PDR system, however, degrades gracefully with extreme modes of legged locomotion, such as running, jumping, and climbing (Ojeda and Borenstein, 2007). The main drawback of the PDR system is the accumulated error that grows with the distance travelled by the mobile user.

A dynamic user-viewpoint tracking scheme has been designed and implemented in which mobile users' spatial context is defined not only by their position (i.e. location), but also by their three-dimensional head orientation (i.e. line of sight), thereby significantly increasing accuracy in the identification of a user's spatial context than is possible by tracking position alone. Based on this framework, a prototype application was developed using GPS and magnetic orientation tracking devices to track a user's dynamic viewpoint in outdoor environments (Khoury and Kamat 2008a).

Construction sites, and other civil engineering structures cannot be classified as purely outdoors or indoors and the mobile user navigating in these areas dynamically shifts between indoor, outdoor and "urban canyon" environments. The Integrated Tracking System (ITS) implemented in this research combines features of RTK-GPS and PDR, to continuously and effectively track the momentary location, orientation and trajectory of a user in *both* indoor and outdoor environments. Relevant information can be delivered to any decision maker in real time by monitoring the physical and environmental context and then reconciling the identified context parameters with the available pool of digital information.

## 2 Integrated tracking system

The ITS combines RTK-GPS and PDR systems and minimizes the shortcomings of both technologies by complementing them with each other through integration. The ITS is developed to continuously track a mobile user and to retrieve the user's location to the best possible degree of accuracy. A standardized format of Geographic Co-ordinates (Latitude, Longitude, Altitude) along with Time Stamp markings are employed to denote the user's location. The ITS performs two major functions:

- Provides a PDR system service when RTK-GPS is blocked
- Corrects the accumulated error (drift) in the PDR whenever RTK-GPS is available

### 2.1 *Integrated tracking system hardware*

The ITS hardware used consists of the RTK-GPS hardware and the PDR hardware. Our RTK-GPS uses a Trimble AgGPS RTK 900 base station and the recover receiver is Trimble AgGPS 332. A snapshot of the documentation describing the accuracy of the RTK-GPS used is shown in Figure 1. Our PDR system currently uses a small nano Inertial Measurement Unit (nIMU) strapped to the side of the subject's foot as shown in Figure 2. The IMU is connected to a small computer that can be strapped onto the user. The system is powered by a battery making the whole system portable. The RTK-GPS and the PDR are connected to the serial ports of a small portable laptop carried by the mobile user.

**Table 2.1 Absolute accuracy of GPS positioning method**

| GPS positioning method | Corrections used | Approximate absolute accuracy |
|---|---|---|
| Real-Time Kinematic (RTK) GPS | Trimble CMR corrections broadcast by a local base station | 2.5 cm (0.98 in) + 2 ppm horizontal accuracy, 3.7 cm (1.46 in) + 2 ppm vertical accuracy |

Figure 1. RTK accuracy (Trimble, 2005: AgGPS 332).


Figure 2. Small sized nIMU used for this research.

### 2.2 *Integrated tracking system algorithm*

The accuracy of RTK-GPS (1 to 2 inches) is much higher than the accuracy of the PDR. The principle behind determining the ITS co-ordinates is that RTK-GPS co-ordinates, if available, always take precedence over the PDR co-ordinates. The PDR drift is corrected by applying a correction equal to the difference in the user's GPS and the PDR co-ordinates. When the user is disconnected from the GPS (i.e., user no longer has clear line of sight to the satellites), the PDR correction is the same as the PDR correction at the last instant the GPS was available. This correction is applied to the PDR until the GPS signal is regained. When the GPS is unavailable, the ITS co-ordinates are determined by the corrected PDR co-ordinates. Once the GPS signal is regained the PDR correction is updated and the GPS co-ordinates determine the ITS co-ordinates. This updated correction manifests as a "jump" in the ITS co-ordinates. The algorithm is shown as a flowchart in Figure 3.

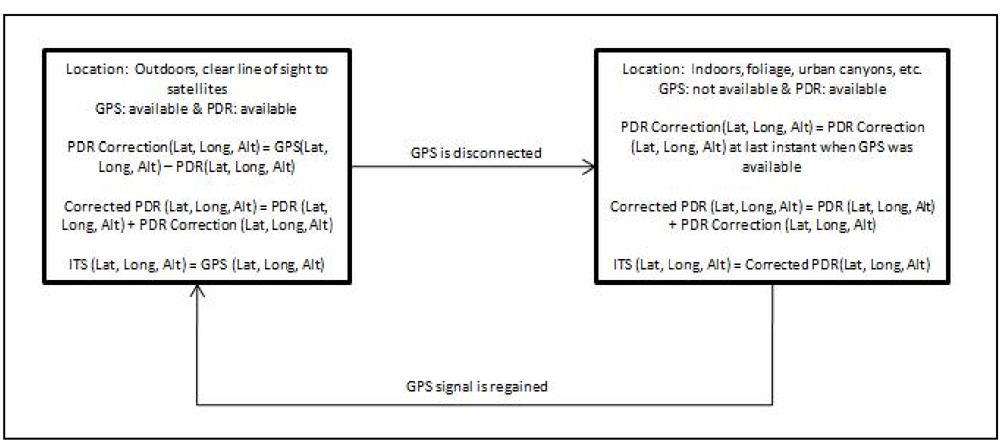


Figure 3. Flowchart of the Integrated Tracking System's algorithm.

### 2.3 *Widely integrated simulation environment*

Widely Integrated Simulation Environment (WISE) is a JavaScript enabled website developed by the authors to help visualize the ITS. It is based on the emerging technology of Google Earth API and ASP.NET 2.0. The hybrid trajectory of the field staff tracked by the ITS is documented as Keyhole

Markup Language (KML) and stored at the web server side. The user can query the location tracking state either online or offline through the web browser enabled with Google Earth Plug-In. On the request, the web server retrieves the relevant location, orientation, and timestamp, and posts it back to the browser side. The received data package is further parsed and rendered in the Google Earth virtual environment as seen in Figure 4. By doing so, the user can have a visualized sense about the current tracking status and also further numerically analyzes the drifting between RTK GPS and PDR.

# 3 Validation experiments

In this paper we present the experimental results obtained with the ITS described in the foregoing section. These results focus on three different types of experiments (1) short and simple walks, (2) short and complex walks and (3) longer walks. The plan of a typical walk is shown in Figure 5.

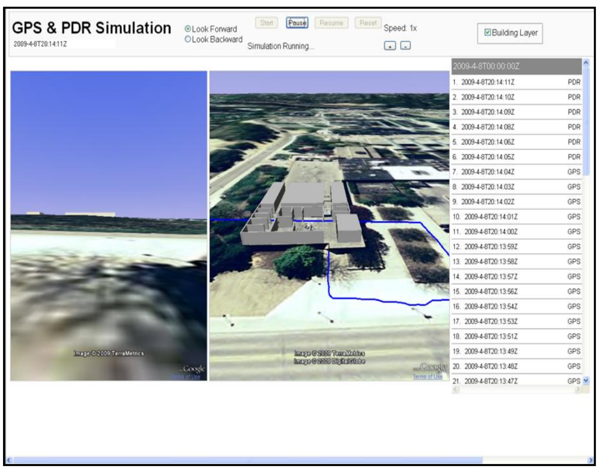

Figure 4. Widely integrated simulation environment.

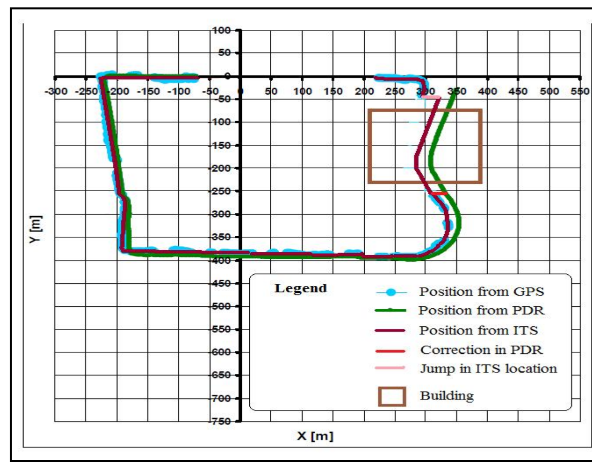

Figure 5. Plan of a typical walk experiment.

## 3.1 *Short and simple walks*

Relatively simple walks having duration between 3 to 5 minutes (indoors) are classified as short walks. These walks involved few turns and almost no abrupt disturbances in motion. Table 1 summaries the “jumps” in the user’s position (ITS co-ordinates) when the user steps out of the building as GPS is recovered. The “jump” is the difference in the last dominant corrected PDR co-ordinates and the first recovered GPS co-ordinates. This is equal to the accumulated error of the PDR during the time spent by the user inside the building (i.e. when) PDR corrections were not being updated instantaneously using the RTK-GPS).

Table 1. Jumps in ITS co-ordinates for short and simple walks.

| | Walk 1 | Walk 2 | Walk 3 | Walk 4 |
|---|---|---|---|---|
| Last dominant PDR(Lat) | 42.29406754 | 42.29469283 | 42.293688 | 42.29369639 |
| Last dominant PDR(Long) | -83.71153664 | -83.71147129 | -83.71345745 | -83.71349191 |
| Recovered GPS (Lat) | 42.29407585 | 42.29469192 | 42.29368167 | 42.29368364 |
| Recovered GPS (Long) | -83.71152177 | -83.711455 | -83.71345969 | -83.71347379 |
| Jump (meter) | 1.536 | 1.347 | 0.727 | 2.058 |

## 3.2 *Short and complex walks*

Relatively complex walks having duration between 3 to 5 minutes (indoors) are classified as short and complex walks. These walks involved relatively more turns, abrupt disturbances in motion, climbing and sideward motion. Table 2 summarizes the “jumps” in the user’s ITS position co-ordinates when the GPS is recovered.

Table 2. Jumps in ITS co-ordinates for short and complex walks.

| | Walk 1 | Walk 2 | Walk 3 | Walk 4 |
|---|---|---|---|---|
| Last dominant PDR(Lat) | 42.29369813 | 42.29369732 | 42.29370127 | 42.29369917 |
| Last dominant PDR(Long) | -83.7134819 | -83.71344807 | -83.71345722 | -83.7134601 |
| Recovered GPS (Lat) | 42.29368493 | 42.29367664 | 42.29367843 | 42.29367342 |
| Recovered GPS (Long) | -83.71345852 | -83.71346203 | -83.71345254 | -83.7134486 |
| Jump (meter) | 2.423 | 2.571 | 2.566 | 3.013 |

### *3.3 Longer walks*

Relatively complex walks having duration over 5 minutes (indoors) are classified as longer walks. These involved relatively more turns, abrupt disturbances in motion, climbing and sideward motion. Table 3 summarizes the “jumps” in the user’s ITS position co-ordinates when GPS is recovered.

Table 3. Jumps in ITS co-ordinates for longer walks.

| | Walk 1 | Walk 2 | Walk 3 | Walk 4 |
|---|---|---|---|---|
| Last dominant PDR(Lat) | 42.2936999 | 42.2936882 | 42.29393721 | 42.29484218 |
| Last dominant PDR(Long) | -83.71349888 | -83.7134695 | -83.71318452 | -83.71107857 |
| Recovered GPS (Lat) | 42.2936725 | 42.29367521 | 42.29390902 | 42.29483705 |
| Recovered GPS (Long) | -83.71349173 | -83.71345096 | -83.71318044 | -83.71103446 |
| Jump (meter) | 3.101 | 2.102 | 3.15 | 3.682 |

### *3.4 Sustainability test*

To test the sustainability of the ITS we conducted a very long walk (over 30 minutes). The walk involved a lot of turns, abrupt disturbances in motion, climbing and sideward motion in order to simulate a mobile user’s natural motion in a complex environment. The walk was divided into 6 parts; 3 parts were of a short duration, less than 5 minutes indoors, and rest were longer. At the end of each part, the user walked out of the building, recovered the RTK-GPS correcting the error in the ITS and continued his walk into the building. Table 4 summarizes the walk used for testing ITS sustainability.

Table 4. Jumps in ITS co-ordinates for the six parts of the sustainability test walk.

| | Duration (Min:sec) | Last dominant PDR (Lat) | Last dominant PDR (Long) | Last dominant GPS (Lat) | Last dominant GPS (Long) | Jump (meters) |
|---|---|---|---|---|---|---|
| Part 1 | 4:30 | 42.29388927 | -83.71325826 | 42.29388571 | -83.71327255 | 1.24 |
| Part 2 | 4:44 | 42.29389793 | -83.71319148 | 42.2938827 | -83.71321428 | 2.53 |
| Part 3 | 4:52 | 42.29389745 | -83.71328397 | 42.29389404 | -83.7133059 | 1.85 |
| Part 4 | 7:23 | 42.29390512 | -83.71336043 | 42.29389401 | -83.71340656 | 3.99 |
| Part 5 | 8:18 | 42.29377712 | -83.71348004 | 42.29374614 | -83.71348369 | 3.45 |
| Part 6 | 8:49 | 42.29378699 | -83.71348071 | 42.29374324 | -83.71347634 | 4.87 |

## 4 Conclusions and further work

As tested to date, the ITS is very accurate for tracking smooth walks. The accuracy of the ITS, reflects that of the PDR and degrades gracefully with both path complexity and time spent indoors. Once the accumulated drift in the ITS starts to overshoot the satisfactory level the user needs to step outdoors and recover the GPS signal to reset the corrections. Depending on the degree of accuracy required by the context-aware application, the required frequency of corrections can be determined.

The average "jump" in the ITS co-ordinates when the GPS is recovered increases with the time spent indoors. This is expected because the corrections to the PDR are not being updated instantaneously due to RTK-GPS being unavailable. Table 5 summarizes the experimental results.

Table 5. Jumps in ITS co-ordinates for longer walks.

| Type of walk | Average Duration Indoors | Average jump |
|---|---|---|
| Short and simple walks | 3 minutes 45 seconds | 1.4 meters |
| Short and complex walks | 3 minutes 45 seconds | 2.6 meters |
| Longer walks | 6 minutes 15 seconds | 3 meters |

The ITS jumps in the sustainability test walk are reflective of the average jump of several complex walks with similar duration, indicating that the ITS is sustainable. The PDR accumulates heuristic drift due to non-straight motions like swaying, curving and turning. Although not implemented in these experiments, Heuristic Drift Reduction (HRD) algorithms have been developed for unstructured environment (Borenstein et al., 2009). The PDR requires that the first eight steps are taken in a straight line. Significant deviation from the dominant directions while using the PDR software that does not account for heuristic drift will cause significantly larger errors.

We are currently working on using a PDR system with HRD software in our ITS to compare its performance with that of the current ITS version. We are also planning to develop streamlined methods that will use context aware location systems for several applications. One such alternative context aware location system is being developed to help facilitate information retrieval for decision support in bridge inspection processes. The design and implementation of the presented ITS is the first logical step in pursuing research in these promising directions.

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