Cost-Precision Tradeoffs in Unencumbered Floor-based Indoor Location Tracking

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Abstract. Unencumbered location tracking is becoming increasingly important, especially in indoor pervasive environments. In this paper, we describe an unencumbered indoor location tracking system with a high hit rate that uses a network of embedded floor sensors to determine user location.

1. Introduction

Locating people indoors is becoming of significant importance for many pervasive applications. An effective pervasive space requires a system that is aware of its surroundings. Knowing where the users are in a pervasive space boosts the performance level of any application running in that environment.

Several problems need to be overcome before indoor location tracking systems go mainstream. These include unit and installation cost, precision, privacy, identification, and the required level of user attention. For instance, the acoustic-based system developed at the University of Florida [1] requires that the user wear transceiver tags on a vest, making sure the tags are placed on the correct shoulder sides and that the batteries are charged. Such a system encumbers the user and requires high maintenance and attention. It does, however, allow for preserving privacy, as the user may choose not to wear the vest when privacy is sought. The Smart Floor project at Georgia Institute of Technology [3] provides location and identification (with 93% accuracy) without encumbering the users, but its highest precision will not be reached until the user steps on the exact centers of the floor tiles, which for reliable measurement would require conscious attention. The ORL Active Floor at The Olivetti and Oracle Research Laboratory [4] uses similar technology, and has achieved recognition accuracies of 91%.

The advantages of our system are described by comparing it with other floor-based location tracking systems, showing the tradeoffs among deployment cost, hit rate, and advanced functionality such as identification. Furthermore, we provide an overview of the Smart Floor model and corresponding simulator we created to test sensor technology and deployment strategies before implementing our system in the Gator Tech Smart House.

Part of developing a cost-effective indoor location tracking system involved creating a simulator to help test how various changes to our smart floor implementation would affect the overall accuracy and cost of the system. We tested various topologies, sensors, and applicators. This paper will discuss the implementation details of the simulator and a method we discovered to increase the effective range of a sensor.

Finally, we discuss how smart floor technology can be integrated with other systems to produce full-featured location, orientation, and identification services.

2. Deployment

The Gator Tech Smart House includes a residential-grade raised floor. It allows us to run data and power wiring throughout the house without creating eyesores for the resident. Each square foot block of the floor (Figure 2) is an independent platform atop a 5x5 grid of plastic feet. Applying pressure to any part of the platform distributes some force to the center feet. Therefore we were able to deploy a system with a density of one sensor per square foot, and still achieve almost 100% coverage.

This paper will cover the problems we encountered deploying the floor, especially with mapping sensors to physical locations. We will discuss how a spatially aware sensor platform could solve the later problem.

3. Pressure Sensor Technology

Pressure sensor technologies have been used widely for the acquisition and evaluation of weight distribution in beds, chairs, and even shoes. For example, [5] uses pressure distribution sensors in a “sensing chair” to classify and correct sitting posture. Other studies use these sensors in beds as part of an investigation of support surface pressure and reactive hyperemia in older populations [6].

Most pressure measurement systems consist of thousands of densely packed sensors. For example, the Gait Mat [7] provides enough data to detect which way the feet are pointing, and this determines the orientation of the user. Awareness of user orientation can enable a wide range of services in a Smart House. For example, if we want to relay video instructions to a senior resident with moderate Alzheimer’s, we do not want to activate every monitor in the room. This would likely confuse the user. Instead, we want the message to play only on the monitor closest to where the user is looking. Orientation would also be necessary for directing blind residents through the building.

These densely packed mats, however, are extremely expensive. At more than $1000 per square foot, they are obviously not practical for a commercially viable Smart House. We decided to investigate lower-resolution solutions for the floor, and find auxiliary systems to provide additional functionality.

We wanted to have a floor that is aware of presence (position and general direction of motion) of any object that steps on it, and could be constructed for a similar price as traditional flooring. After exploring many different sensors, we chose the Phidgets 1.5 inch pressure sensor (Figure 1) as the basis for our system.

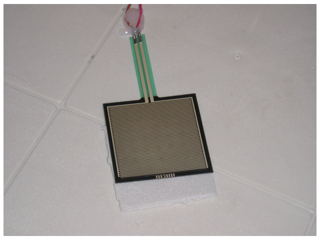


Figure 1. Phidgets 1.5-inch Pressure Sensor

The 1.5 inch sensors fit well under the central feet of each floor block (**Figure 1**), are relatively inexpensive, and, because we were already using other Phidgets devices for various automation tasks, integrated into our existing network.

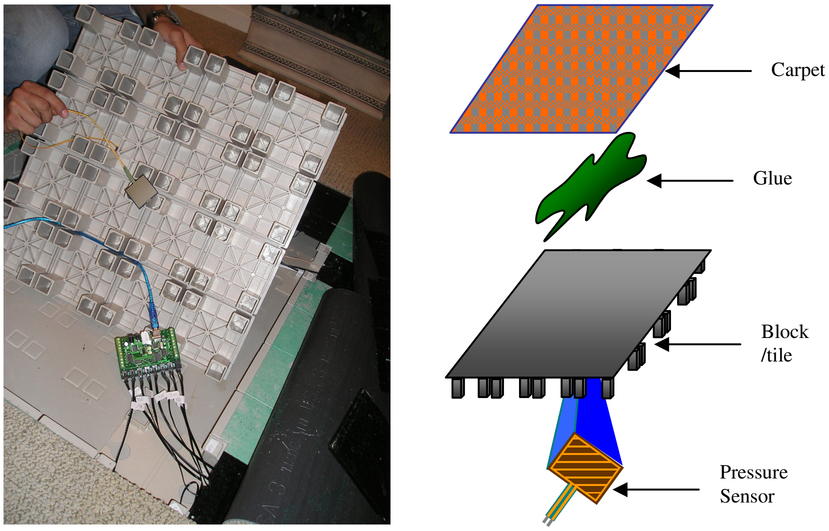


Figure 2. Real picture of attaching a sensor to a block (right), representation of the attachment (left)

The total cost for the smart floor, as deployed in the 350-sqft kitchen, breakfast, and family area of the Gator Tech Smart House, was approximately $4000, which includes the material and installation costs of the raised floor). Our floor includes a full location system, and it provides a space for running power, data wires, and controllers for other applications. Due to the slight “springiness” of the tiles, walking on our floor puts less stress on the knees and lower back, which is an important ergonomic benefit, especially in Smart Houses designed for senior residents. Yet the cost of our system is equal to the price of some traditional flooring, such as hardwood.

4. Cost analysis of related floor-based location tracking systems

We will discuss the example of building a 4x4 tiles space following two different structures.

The Active Floor technology requires a load cell at each tile corner (neighboring corners share cells). Building a 4x4 space therefore requires 25 load cells. Each cell costs $290, so the system will cost $7500 plus the cost of the steel plating and wood pieces that make up the physical floor.

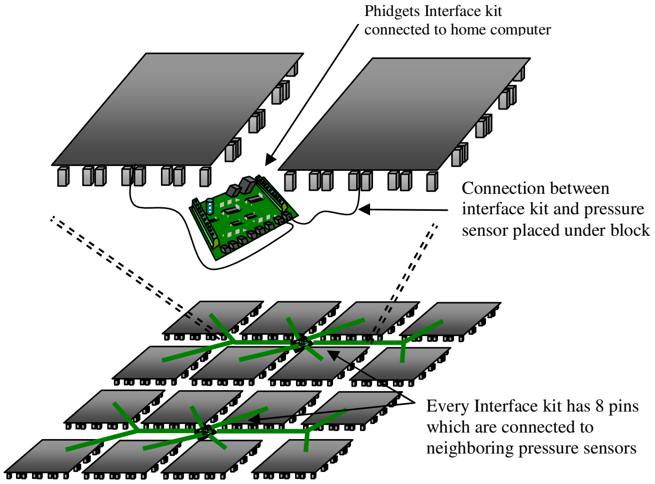


Figure 3. Sample 4x4 tiles using our floor-based indoor location tracking structure

With our Smart Floor system, construction requires 16 pressure sensors (see Figure 3) at $7 each. Connecting 16 sensors requires 2 Phidgets 8/8/8 Interface Kits ($80 each), for a total system cost of $272. The commercial-grade raised floor used in the Gator Tech Smart House is no more expensive than the flooring material used in the Active Floor, so we saved more than $7000 by sacrificing identification detection. Our system does have some dead zones in the 9.5-cm channel between tiles, whereas the tiles in the Active Floor are juxtaposed for complete coverage. However, this dead zone does not significantly affect the hit rate for most applicators (adult-sized feet), as the feet are large enough to span the gap in most orientations.

Infineon Technologies has developed a smart carpet using intelligent textile. They have woven conductive fibers into a carpet and attached it to tiny sensor modules inlaid into the fabric to build a mesh network [8].

A significant feature of this system is that the carpet can be cut without affecting the behavior, and that the tiny sensors will be able to determine its positions within the network after power up. However, this system requires direct contract with the sensors. Not only would it require a higher sensor density for a reliable hit rate but the sensors are exposed to damage from furniture or high heels.

5. Simulation

As part of the study, we created a simulator to help generate the formal relationships among variables in our model. It also provides a visual aid to development of Smart Floor areas, and as a test bed for sensor technologies and distribution methods.

We abstracted our Smart Floor model into three core objects. These are described in Figure 4.

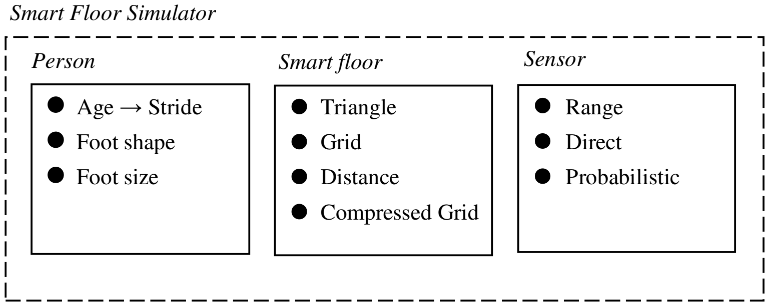


Figure 4. Key Smart Floor Simulator Variables

We designed the simulator to be as modular and multilayered as possible. For example, since our Smart House targets an elderly population, we wanted to be able to test various applicators and walking patterns (two feet, two feet and a cane, wheelchair, etc.). The sample simulator output presented in this section of the paper come from using the applicator shape shown in figure 5-d.

Before working in the actual Gator Tech Smart House, we used the simulator to experiment with different sensor deployment topologies, to see if a particular topology would yield a higher hit rate given the irregular applicator shape. We decided to use a grid topology because it is easy to deploy in general, and the residential-grade raised floor installed in the house was itself a grid of platforms. The data here represents a simulation of the floor as deployed in our smart house. The distance between sensors is 60.5 cm. The sensor type is "fixed square," meaning the sensor has a square activation area, a step anywhere inside the area will always be detected, and a step immediately outside the range (the length of one side of the square) will never be detected (as opposed to a probabilistic sensor, which involves a function defining the probability of detecting a step based on the distance from the sensor). The range is set to 51 cm, which is the length of a side of the platforms used in our raised floor.

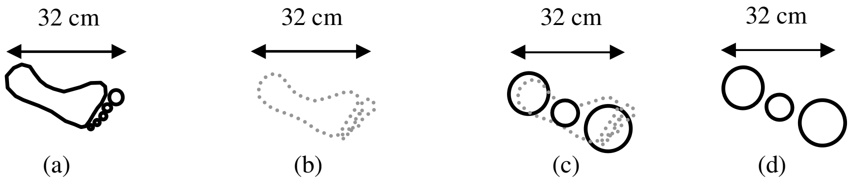
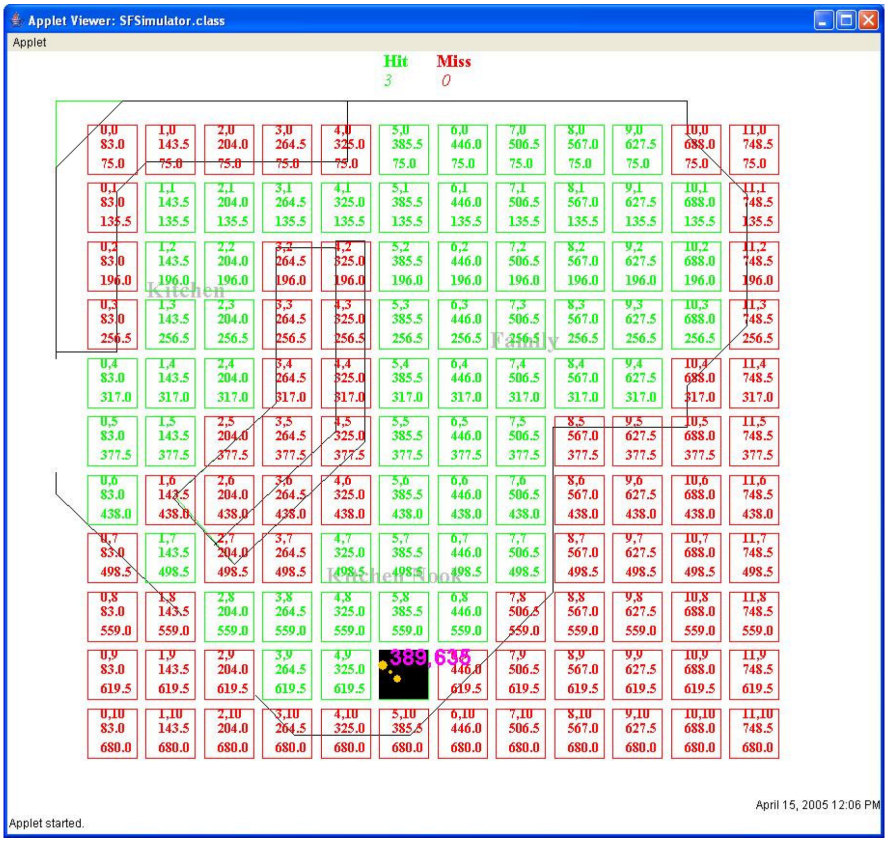


Figure 5. Foot shape

The simulator consists of a base layer (defining the floor plan of the house), at least one sensor layer, and at least one obstacle layer. The obstacle layers define features or objects in the house (such as tables, chairs, or couches) that block someone walking through it.

The final module of the simulator is the walking model, which defines how the virtual resident moves through the house. We implemented a “drunken walk” (a random direction is chosen at each step, and the resident moves in that direction unless an obstacle would be hit). Another option is a bouncing path, where the resident walks in a straight line until an obstacle is hit, then a new random direction is chosen. We also support a more advanced, task-oriented walking model. With this model, the simulator takes a list of daily activities (including their frequencies and locations in the house associated with the activity) and moves the virtual resident through the house based on these tasks (choosing the shortest path between the current location and the location associated with the next activity).



Hit 3
Miss 0

0,0 83.0 75.0	1,0 143.5 75.0	2,0 204.0 75.0	3,0 264.5 75.0	4,0 325.0 75.0	5,0 385.5 75.0	6,0 446.0 75.0	7,0 506.5 75.0	8,0 567.0 75.0	9,0 627.5 75.0	10,0 688.0 75.0	11,0 748.5 75.0
0,1 83.0 135.5	1,1 143.5 135.5	2,1 204.0 135.5	3,1 264.5 135.5	4,1 325.0 135.5	5,1 385.5 135.5	6,1 446.0 135.5	7,1 506.5 135.5	8,1 567.0 135.5	9,1 627.5 135.5	10,1 688.0 135.5	11,1 748.5 135.5
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April 15, 2005 12:06 PM

Applet started.

Figure 7. Screenshot of the simulator

As a test of our software, we simulated the floor as deployed in the Gator Tech Smart House, and compared the results to a test in the physical house. Both reflected an average hit rage between 87% and 81%.

6. Hybrid Systems

While the Smart Floor provides a cost-effective location system, it only provides position data. Orientation of the user is unavailable, except for a crude estimate based on the direction traveled. Similarly, the floor does potentially offer a weight-based identification service, but this system would be confused by ordinary events that alter the residents' apparent weight, such as when they are carrying groceries or other goods. However, these services could be enabled and made reliable by using the smart floor as a component in a hybrid location system. We are investigating two additional layers, one using an optical location system and one using RFID technology.

We are considering using cameras inside the Gator Tech Smart House for security and other applications. These cameras could also be used to locate precisely residents in the house and determine their orientation and possibly identification. While full scene image analysis is certainly possible, including this as a layer on top of the smart floor allows us to use the floor's data to target the cameras and simplify the image recognition process. Having the smart floor as the fundamental location service is also important because there may be times when the resident wants to turn off all the cameras. Indeed, there are some places (such as the bathroom) where cameras would be completely inappropriate, and the smart floor will be the only location system available.

We are also investigating using RFID technology to provide an identification service on top of the smart floor. We have RFID readers in many places throughout the smart house. We have RFID tags on residents' keychains for entry into the house, and washable tags in the clothes to assist with laundry sorting. Since these tags are already associated with a particular resident, the RFID readers in the house could notify the smart floor process when a user tag is identified. The floor would maintain this association while the resident is away from readers, and could use recent weight history to resolve ambiguities (such as when two residents cross paths).

7. Future Work

Although the Smart Floor is already an inexpensive and reliable system, we are investigating methods to reduce the cost further. First, total sensor coverage of the floor is unnecessary if the system can accurately predict the resident's location based on factors such as their stride, walking velocity, and previous movement. We intend to add this predictive element to the floor.

Additionally, sections of the floor do not require sensor coverage if they are rarely traversed. Traffic analysis of a house's floorplan (using the task-oriented capability of our simulator) could be used to prioritize the deployment of sensors.

Deploying the floor over a 350 square foot section of the house required 72 man-hours, mainly due to the tedious process of mapping sensors to physical locations. Now that the cost of the system is reasonable, this installation effort is the largest roadblock to a commercially viable smart floor. We hope to solve this issue by making use of another project being developed at UF's Pervasive Computing Lab -- an inexpensive, modular sensor platform. By including a spatially aware component to the sensor platform, only one sensor will have to be mapped by hand. After that, the system will be able to map all the other sensors automatically, much like the Infineon Smart Carpet mentioned in section 4.

8. Conclusion

The floor-based indoor location tracking system proved to be outstandingly robust in the Gator Tech Smart House. We deployed the floor in the middle of January, 2005. Despite the constant traffic from students and guests, moving heavy furniture and equipment, and floor tiles being moved to route other wires and cables, none of the pressure sensors or connectors have been damaged. However, since the floor is deployed in areas such as the kitchen and bathrooms, we will eventually need to coat the Phidgets Interface Kit to avoid possible water damage.

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