A Method for Sensing and Representing Location in Context-Aware Applications

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Abstract: Location context plays a valuable role in ubiquitous computing, and is still a central area of interest for many researchers. We present an easy-to-deploy location sensing system using acoustic spread-spectrum techniques and hyperbolic multilateration, and a scheme for representing and processing location information using switching algebra.

1 Introduction

Context-aware applications provide relevant information and services to a user, using information about the user's situation, such as her location, identity, and the state of people, groups and nearby objects [1]. In response to certain situations or changes in situations, such an application may automatically alter its execution, trigger the execution of another service, or prompt the user to act in a certain way. While the notion of "context" that may be relevant to a user may involve a wide range of things, the *location* of users and surrounding objects plays a very important role and consequently has been the subject of much interest.

We thus present a method for sensing location and transforming it into a form that may easily be processed by a context-aware system. This system uses commercially-available off-the-shelf (COTS) devices, and can easily be used by other researchers to construct a positioning system.

2 A Method for Sensing Location

In designing our sensing system, aside from our preference in using off-the-shelf components and built-in interfaces, we also made an assumption that the located object would operate asynchronously with respect to the positioning system. A location estimation technique known as *hyperbolic multilateration* does not require the tracked object to be synchronized with the positioning system. If beacons, or pairs of beacons can be closely time-synchronized with each other, a receiver could detect the arrivals of each beacon's signal and measure the relative delays between them. If signals from beacons i and j arrive at a receiver at t_i and t_j, respectively, referenced to the receiver's clock, then the time-difference-of-arrival (TDOA) is simply $t_i - t_j$. For a receiver located at coordinates (x, y, z), and any two beacons i and j located at (x_i, y_i, z_i) and (x_j, y_j, z_j) respectively, the equation describing the *range difference* r_k corresponding to the TDOA $t_i - t_j$ for this pair is given by:

$$r_k = c(t_i - t_j) = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - \sqrt{(x_j - x)^2 + (y_j - y)^2 + (z_j - z)^2} \quad (1)$$

where c is the propagation speed of the beacon signal used. Equation (1) describes a hyperboloid, and with at least four beacon signals, three independent TDOA values may be obtained, producing three independent equations. The solution to these three simultaneous equations yields the (x, y, z) position estimate of the receiver. Graphically, this corresponds to the intersection between the hyperboloids generated using Equation (1) for any set of three TDOA values.

We applied this technique using acoustic spread-spectrum signals, with standard PC speakers as beacons and a receiving microphone as the located object. The use of spread-spectrum facilitates the detection of the arrivals of beacon signals at the receiver due to their excellent correlation properties, and provides some measure of resilience against noise and environmental scattering [2]. Four PC speakers, each with a single 3.5" driver, were positioned in a room. Three of these were mounted on the ceiling, approximately 2.2m above the floor on average, while one was mounted on a wall, approximately 80.5 cm above the floor level. Acoustic beacon signals, consisting of 127-bit Gold codes with a chip rate of 10 kchips/s and BPSK-modulated with a 10 kHz sine wave, were simultaneously transmitted through the speakers. A microphone (simulating a Personal Digital Assistant or PDA in our test scenario) recorded the received signal every 10 cm on a 130 cm x 110 cm grid. The recorded signal was then successively correlated with each of the transmitted Gold codes. A correlation peak indicated the instant that a beacon signal arrived at the microphone. The speed of sound is approximated to the first order using the formula

$$c \sim 331.5 + 0.610 t_{air} \quad (2)$$

where t_{air} is the air temperature in degrees Celsius and c is in meters/second. In our experiments, the temperature was recorded from a digital thermometer. In an actual implementation, the ambient temperature may be supplied by an online sensor. Alternatively, a fixed approximate value may be used in environments where the temperature is regulated or typically does not vary to a large degree.

Since the equations for each TDOA pair represented by Equation (1) are nonlinear, we linearized them using the first two terms of their Taylor series, and used least squares to solve the resulting equations.

The results of one of the trials of our acoustic position sensing scheme is shown in Figure 2. The positions marked with “x” indicate the actual microphone positions, while positions marked with “o” indicate the position estimates computed through hyperbolic multilateration. A line interconnects the pairs of actual and computed positions. The gaps in the grid where there are no “x” marks represent points where the least-squares algorithm did not converge within the maximum number of iterations, or the resulting computed position was outside the coordinate system. For the data shown in the figure, the computed position deviated from the actual position by 7.0 cm on average, and 80% of all computed positions deviated by less than 9.4 cm from their actual positions. In sensing the location of people and objects, we are normally more interested in their (*x*, *y*) position rather than their elevation above the floor. For the data represented in Figure 2, the deviation from the actual positions along the xy-plane was around 4.6 cm on average, and less than 7.5 cm for 90% of all computed positions.

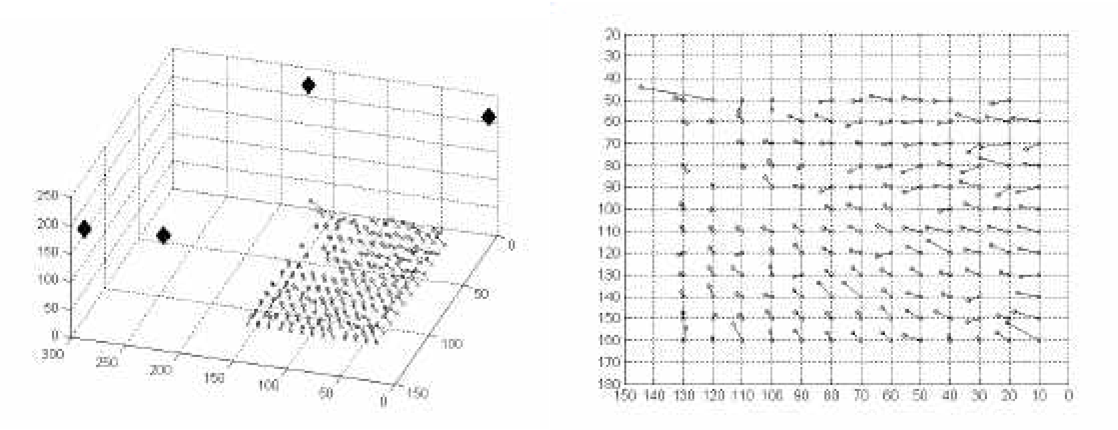

Figure 2. (a) 3D plot showing measurement points, computed positions and beacon locations. (b) Top view.

In an actual implementation the position may be computed on the PDA itself by performing the hyperbolic multilateration computations on the sensed beacon signals and a preloaded database of beacon codes and the corresponding (*x, y, z*) coordinates of the speakers transmitting them. Alternatively, the position information of the speakers may be contained within the beacon signals, although this would require more processing on the part of the PDA and the use of longer code sequences. Either way, the PDA’s location would not be known to the network, so this may be considered a mode of operation that preserves the privacy of the user.

A non-privacy or tracking mode would have the PDA transmit the recorded beacon signals back to the network, using either an 802.11 or Bluetooth interface, for the location computations. This mode sacrifices privacy in favour of hardware simplicity, as it shifts the computational burden from the tracked object to the network.

3 Representing Spaces

For location context to be useful to applications, any information on the location of users, nearby objects and spaces of interest must be represented in a form that can easily be stored, transmitted and processed.

Large 3D spaces, such as rooms, are treated as Karnaugh maps and partitioned into small cubes [3]. Each unit cube is uniquely identified by a set of Gray-coded coordinates. A more precise term used in switching theory for these unit cubes are *0-cubes*. A 0-cube may be contained within one or more spaces of interest, such as “the space in front of workstation *W*,” and such a space of interest is completely defined by the set of cubes that completely enclose it. This is similar to the definition of space containment in [4]. Spaces of interest may thus be represented in terms of switching functions that describe the logical sums of 0-cubes that completely enclose them. With spaces represented by switching functions, various logic operations may then be applied to determine relationships between spaces and the location of objects and users, such as intersection and containment. Operations such as combining spaces may be done through a logical union of switching expressions.

Most of the spaces that we are interested in, e.g. "the space in front of workstation *W*" consist of collections of contiguous groups of unit cubes. We exploit this property to obtain compact space representations by applying logic minimization techniques. This approach is similar to the representation and compression of images in [5]. Although our primary objective is not necessarily to achieve compression, having a compact representation would be desirable from processing, storage and communication viewpoints.

A two-dimensional simplified example of this space representation scheme is shown in Figure 3. A space of interest, S, is shown on this figure. We also indicate two areas, S_1 and S_2, that completely enclose S.

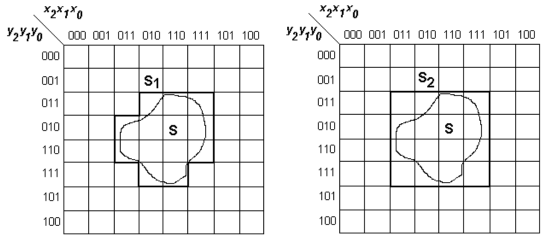

Figure 3. A space of interest S and enclosing spaces S_1 and S_2 are drawn on a Karnaugh map

The switching expressions for S_1 and S_2 in minimal sum-of-products form are

$$f_{S1} = x_1 y_1 y_0' + x_1 x_0' y_1 + x_2 x_1 y_2' y_1 \quad (3)$$

$$f_{S2} = x_1 y_1 \quad (4)$$

It can be seen from this example that the geometry of the enclosing area used to approximate the original space of interest affects the extent to which the switching expression can be minimized. Generally, in building the maps that represent our spaces and the objects contained, we can select geometries that will lead to more compact representations.

One advantage of this space representation scheme is that it implicitly encodes both position and size information. However, there are some potential weaknesses. First, as previously mentioned, space geometries other than those that may be conveniently enclosed in rectangular cubes with dimensions that are integer powers of 2 may tend to have more complex expressions. Second, it tends to view the world in "black and white," that is, if the location of an object is represented by switching expression f_{S*}, then the representation implies that the probability of actually finding the object outside $S*$ is zero. Third, within $S*$, the probability of finding the object is uniformly distributed. These might not be the case if the area being represented by f_{S*} is generated by a sensor that inherently can only provide an *estimate* of location.

One solution to the first problem above, aside from careful geometry selection, is to explore other shapes that lead to simple expressions in other minimal two-level switching representations such as exclusive-OR sum of product (ESOP) forms. Additionally, if the space information is to be shared, the simpler product terms in the minimized expression (corresponding to larger and more regular sub-areas) can be transmitted first for rapid, "short-circuit" logic evaluation. In some cases this may eliminate the need to transmit the other product terms, and thus while the stored representation remains complex, it does not generate too much traffic.

To represent probability distributions that are non-uniform, a space may be built from composite overlapping or non-overlapping sub-areas and a probability assigned to each component. Additionally, if the space information is to be shared, the simpler product terms in the minimized expression (corresponding to larger and more regular sub-areas) or the larger sub-areas can be transmitted first for rapid, "short-circuit" logic evaluation.

4 Related Work

We needed a location sensing scheme that would be compatible with commercially-available off-the-shelf devices such as a PDA. To roughly estimate the position of users within a relatively large area, such as within a 3-4 meter radius, a PDA may be outfitted with an IEEE 802.11 interface, and techniques such RADAR [6] and its variants may be used. For fine-grained positioning, such as within 10-20 cm., while a number of systems such as the Active Bat Location System [4] and Cricket [7] have been discussed in the literature, most of these systems usually use ultrasonic transducers and a channel for transmitter-receiver synchronization such as an RF or infrared channel. We preferred a position sensing scheme that would use available interfaces and require only a bare minimum of hardware interfacing, if any at all.

Girod and Estrin use acoustic spread-spectrum techniques in a ranging system that uses frequencies in the audible range [2]. Although their system only produces range (distance) information rather than location, it may be extended through multilateration in order to estimate location. This has in fact served as a technical basis for our work. In addition, their philosophy of using COTS hardware has served as a guide for us in designing a system that can be rapidly deployed and used in conjunction with commercial devices such as PDAs.

A privacy-oriented location system based on ultrasonic DS/CDMA spread-spectrum and *pseudoranging* has recently been presented by Hazas and Ward [8]. Although the physical sensing base is identical to ours, the difference in approach (hyperbolic multilateration vs. pseudoranging) has some implications in the overall design of the location system, particularly in the need for synchronization within the system. A pseudoranging system typically requires the beacons to be tightly synchronized with each other, and there is likewise some benefit in synchronizing the located object with the beacons as well, as this minimizes the magnitude of the clock bias that needs to be estimated. In a hyperbolic multilateration system similar to ours, tight synchronization is required only among *pairs* of beacons to provide accurate TDOAs, and to a lesser extent, across different pairs. While synchronization between the beacons and the located object may minimize the number of acoustic data samples that need to be processed, the algorithm itself does not require it.

5 Conclusions and Future Work

We have presented a technique for sensing location that may be of interest for experimenters in context-aware computing and in related domains where positioning may be needed, such as in robotics and virtual reality. The system can be rapidly deployed and used, as no additional hardware construction is needed. Our technique does not require any synchronization between the beacons and the located object, and allows very simple commercial devices with little or no computational power, such as an analog wireless microphone, to be tracked. Even an ordinary audio recorder, for example, may continuously record acoustic beacons as it moves within an area, and its traversed path may later be post-processed and reconstructed.

Our ongoing work on the method for space representation we presented includes evaluating its performance in comparison with other schemes. We are also exploring the use of other forms, including Reed-Muller expressions, and binary decision diagrams (BDD).

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