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Original Study

Improving Safety and Operational Efficiency in Residential Care Settings With WiFi-Based Localization

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ABSTRACT

Objectives: To assess the effectiveness of a wireless network (WiFi-based) localization system (devices mounted on resident wheelchairs) in decreasing caretaker time spent searching for residents and providing alerts of residents going outdoors in a skilled nursing facility.
Design: A controlled study over two 2-month periods approved by the institutional review board.
Setting: A long-term skilled nursing facility in Massachusetts specializing in multiple sclerosis previously instrumented with wireless network infrastructure.
Participants: Nineteen residents and 9 staff members at the facility for the first 2-month period; 9 residents and 3 staff members at the facility for the second 2-month period.
Intervention: Software was installed on 4 staff computers to display the locations of residents enrolled in the study. This software was made available to enrolled staff for the second half of the first 2-month period and the entirety of the second 2-month study. In the second 2-month study, the software was modified to provide alerts if any 1 of 9 participating "high-risk"' residents went outdoors, and the accuracy of the alert system was evaluated.
Measurements: In the first 2-month study, 9 staff members recorded the amount of time it took them to locate participating residents (as and when needed during the course of their daily activities). In the second 2-month study, 3 staff members recorded whether outdoor-alerts correctly identified a resident leaving the building or if it was a false alarm.
Results: In both phases, participating staff members made frequent use of the system (44 searches and 215 outdoor alerts). Overall, the localization information decreased the average time needed to find residents by about two-thirds (from 311.1 seconds to 110.9 seconds). For outdoor alerts, the system had a false-alarm rate of 9.1% (under normal facility operations); systematic tests of the outdoor-alert system carried out by the authors had a false-negative, or missed-alarm, rate of 1.7%.
Conclusion: Using timely resident location information can provide significant gains for both operational efficiency (finding residents) and enhanced resident safety (outdoor alerts). This approach may provide an inexpensive alternative for facilities that have sufficient wireless infrastructure; future work should assess its effectiveness in additional settings.

Residential care facilities have an ethical and legal responsibility for the safety of their residents, which includes ensuring that residents (especially those with cognitive impairments) do not wander off the premises without the staff's knowledge. Several studies and systems have been devoted to methods for reliably detecting when patients and residents have wandered[1–4] or may be in distress.[5,6] Moreover, residents living in skilled nursing facilities also typically have highly structured daily routines with many medical appointments and social activities; even high-functioning older adult residents might have trouble remembering all of these commitments. In settings where residents are highly mobile (with or without the use of wheelchairs or other aids), staff may spend significant time searching for residents for appointments, visitors, or other activities.

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These safety and time challenges might be addressed through appropriate technologies that help staff know the whereabouts of residents. To date, most proposed approaches to localizing patients and residents have used radiofrequency identification (RFID) tags, sometimes augmented with other elements, such as motion sensors[7–16]; a few such systems are commercially available.[17,18] Although systems that provide location awareness can improve operational efficiency and safety, existing approaches require a large infrastructure investment. Sensors, tags, and detection equipment required for a single-purpose location-monitoring system within a medium-sized residential facility can cost thousands of dollars. Moreover, tag-based systems determine only whether a resident has passed a certain location, not the resident's current location. Ultrasound-based systems[19] can provide real-time location data but also require the placement of specialized beacons, sensors, and communications infrastructure to relay the results throughout the facility. Finally, the performance of these services and systems under standard operating conditions has not been evaluated in controlled studies; anecdotal reports of utility appear to come largely from industry marketing literature.

In this study, we evaluated an alternative approach to localizing residents that exploits a facility's existing wireless infrastructure.[20] Specifically, facilities use devices called wireless access points to bridge between wired and wireless networks. Each wireless access point is connected to the wired network and contains a WiFi-signal transmitter and receiver. WiFi-enabled devices access the wired network through nearby wireless access points. Our method uses commodity WiFi-enabled devices that scan repeatedly for high-strength wireless access points. As each device moves through the facility, the set of wireless access points that are "visible" (ie, near enough that their signals can be received clearly) changes. The list of which wireless access points are visible at any point in time, as well as their relative signal strengths, can be used to estimate the device's location to room granularity.[21]

Specifically, we note that the presence of wireless access points in facilities (used both by residents and staff for internal IT purposes, Internet access, or wireless reporting of care) is increasing, whereas the cost of wireless-enabled devices is falling. Also, the advent of small, low-power wireless devices makes it often possible to inconspicuously attach such devices to powered wheelchairs without significantly reducing wheelchair battery life. Harnessing these readily available technologies for resident localization may offer significant economic incentives over alternative (eg, tag-based) methods.

This case study assesses the effect of a WiFi-based localization system, implemented by incorporating wireless-enabled devices into resident wheelchairs, on improving safety and operational efficiency in a skilled nursing facility. We perform 2 studies where the effect of the localization system was tested during the daily operations of the facility. In Study One, we evaluated the extent to which WiFi-based localization information could be used to reduce the amount of staff time spent searching for residents. In Study Two, we evaluated the utility of WiFi-based localization information for generating staff alerts when high-risk residents moved outdoors. Closest to our work is that of Denis et al[22] and Liu et al,[23] who describe the software architecture for a WiFi-based localization system; however, to our knowledge, ours is the first quantitative study of the effect of WiFi-based localization systems on standard eldercare functions.

Methods

Technology and Interface

The residential care facility where the studies took place already had a pervasive wireless network (WiFi) system with 53 wireless access points across 3 floors with 4 wings each. Because the system was originally installed for a speech-based care-reporting system called AccuNurse used by staff, the deployed system offers virtually full coverage of the facility. Additional access points were also located in the outdoor patios and loading areas. Our system localizes residents on any of the 3 floors, as well as the outdoor spaces on the facility's 7-acre grounds.

Each floor of the facility contained 4 wings configured as a cross (see Figure 1 for a sample floor). Floors ranged between 22,474 and 28,553 square feet of wheelchair-accessible space. Each wing was between 58 and 168 feet long and took roughly between 30 seconds and 1 minute for a staff member to traverse on foot. Traveling from one end of the facility to the other often required several minutes. Finally, even when a region technically had a line-of-sight (such as along a wing), the corridors were often packed with staff managing food, medicines, and appointments as well as residents socializing. Thus, residents were often difficult to locate from a distance. Residents could exit the building to the front yard from the ground floor and the back patio from the first floor.

We used Nokia N810 Internet tablets (each approximately the size of a smartphone; Nokia, Espoo, Finland) as our WiFi-enabled devices. Each participating resident had a Nokia N810 tablet attached to the back of his or her wheelchair and agreed to let enrolled staff view our resident localization interface (Figure 2). The interface displayed each resident's last recorded location and the time since that recording. Measurements that were more than 5 minutes old were drawn with a gray marker, whereas more recent (and therefore more reliable) measurements were drawn with a green marker. In general, the location estimates were updated every 30 seconds; however, updates could be delayed if the resident was in an area with poor or no connectivity, or if the tablet hardware failed.

Each resident participant provided informed consent, as per the requirements of our institutional review board, and could opt out of the study at any time. Residents could cease participation in the study at any time by simply requesting that the staff push a button that would stop the tablet from reporting wireless signal strengths. More generally, in developing and deploying the system, we took measures to safeguard resident privacy while handling data about their locations. Only certain staff who consented to participate in the study had access to location information. Staff could see only a current location, rather than a location history, for each resident. The data-handling protocols, the opt-out mechanism, and the careful selection of staff with access to real-time location information were designed in close consultation with residents, staff, and management at the facility, and could help inform the design of systems deployed elsewhere.

Before deployment, the localization system was configured by the research team. The configuration process involved taking a tablet to each room in the facility (or sections of a large room, such as a dining area) and using a graphical user interface on the tablet to record which wireless access points were visible along with their signal strengths, over a 5-minute period. These "ground-truth" signal strength measurements were used to train a classifier that, given a new list of visible wireless access points and their associated signal strengths, would compute the most likely room estimate. The localization system was made more robust by using a Hidden Markov Model (HMM) to bias the system toward modeling physically plausible spatial transitions. For example, the patterns of wireless signal strengths are similar in both adjoining rooms and for rooms directly above or below each other; the HMM ensured that the system would not predict that a resident had jumped from one floor to another.

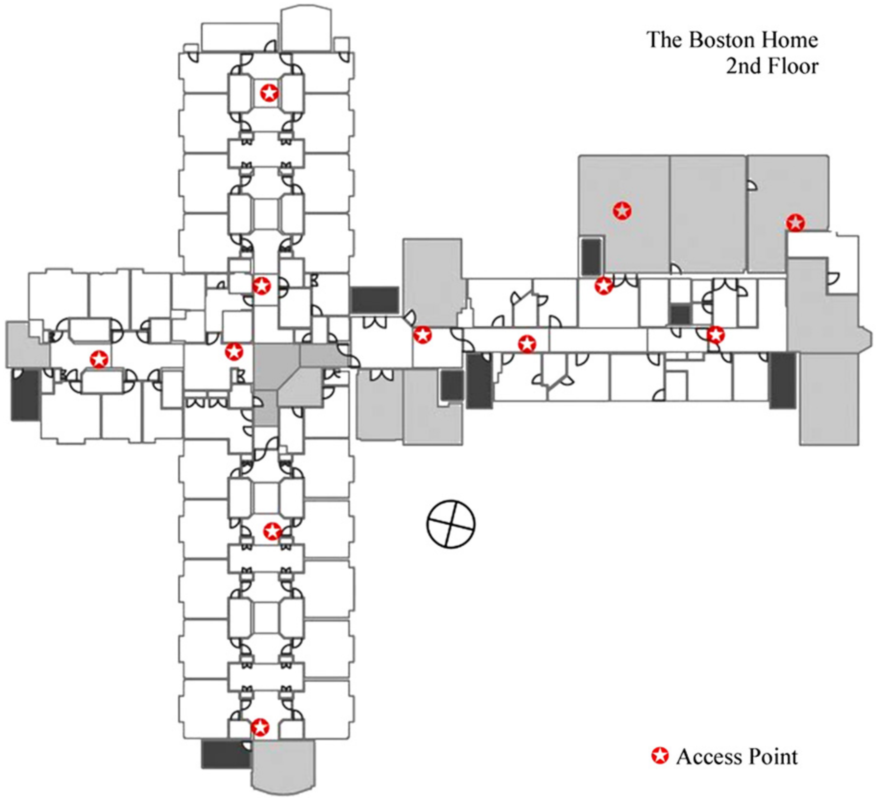

Fig. 1. Access points on the second floor of The Boston Home.

Study One: Effect of Location Information on Time Spent Finding Residents

Nineteen highly mobile residents and 9 staff consented to participate in Study One, which measured the extent to which use of location information could reduce the time required for staff to locate residents. We defined the amount of time required to locate a resident as the time from the start of a search to the time at which the staff member had verified the whereabouts of the resident. Three processes could be used to verify a resident's location: (1) the staff member could initiate a search for the resident, in which case the time to verification was the time until the staff member made visual contact with the resident; (2) the staff member could page the resident and ask the resident to report to a specified location, in which case visual contact at that specified location was the time to verification; and (3) the staff member could call one or more other staff members to ask whether any had instant visual contact with the resident, in which case the time to verification was the time until the staff member originating the search received confirmation from a staff member who was called. These processes were chosen as verification procedures because they captured the approaches already used by the staff to locate residents.

A "people-finder" software interface was provided to the following staff: those who managed activities and physical therapy (both of whom frequently needed to find residents if they did not come for activities or appointments); unit secretaries, who frequently needed to find residents for appointments; and the adaptive technology specialist, who frequently needed to find residents to adjust or repair their wheelchairs. Each staff member was given a stopwatch and a clipboard and asked to log "find events" involving participating residents, by recording the date, time, and amount of time required to locate a resident during the course of the staff member's everyday activities.

Study One had 2 phases lasting 4 weeks each (the intervention phase took place over a period of 5 rather than the planned 4 weeks, because of the need to reconfigure a computer required during the study). In the first phase (control), the staff recorded the time required to find participating residents without using the person-finder. In the second phase (intervention), the person-finder software was installed at 4 computer terminals accessible to participating staff. After this phase of the study was complete, all participating staff were interviewed regarding their impressions of the system's usability and utility of the system.

Results

Figure 3 shows the amount of time required to find residents, with and without use of the interface. There were 24 find events (as defined in the previous section) during the control phase of the study and 18 events during the intervention phase of the study (5 events that were improperly recorded were removed). The interface was used most by the technology specialist (26 total events) and least by the activities staff (4 total events). Using a single-tail, 2-sample *t*-test with unpooled variances to compare times, we found a significant decrease in the time spent by the staff locating residents in the study ($P = .0008$, $t = 3.40$) to a mean of 110.9 seconds from a mean of 311.1 seconds. The mean decrease in time was 200.1 seconds, or a little more than 3 minutes, per find event. This decrease roughly corresponds to the staff locating the resident in 1 attempt instead of 2 (the staff knew the residents well and usually knew the 2 to 3 places a resident was likely to be, but they still needed to search those locations).

All interviewed staff reported that the interface was simple and easy to use; the staff did not state a need for any additional features to increase clarity. Only 1 staff member had experienced a situation in

Fig. 2. MIT people finder interface.

which the interface reported a location for a nonmoving resident that was not within visual range of the resident's true location. Two staff members noted that they had experienced situations in which the resident had moved from the reported location by the time the staff member reached that location. Two staff members also reported a few instances of confusion owing to a "stale" estimated location being displayed, especially because occasionally the interface misreported the age of a location estimate because of latency in the software or network.

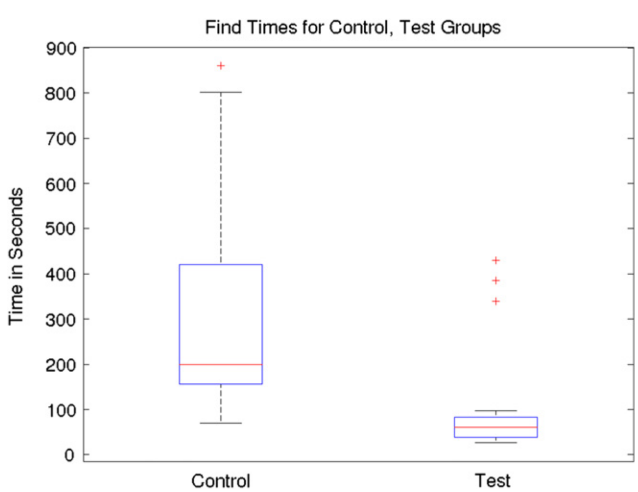

Fig. 3. Find times for control and test groups.

As the staff were already generally familiar with the pattern of resident behavior at the facility, one question was whether they felt qualitatively that having the interface was valuable. The answer to this question was uniformly affirmative. The staff in the study reported that usually they would have to search 2 to 3 of each resident's usual locations to find him or her; with the interface they could go straight to resident's actual location. Alternate uses of the interface were also reported. For example, the physical therapy staff noted that they sometimes used the interface to determine whether a resident was on his or her way to an appointment by monitoring a series of locations for that resident over time. In this way, the staff could differentiate between a resident who seemed to have forgotten an appointment and a resident who was merely moving more slowly on a particular day (a common occurrence in a population of residents living with multiple sclerosis). All of the interviewed staff reported that they would like to continue using the interface. The unit secretaries, physical therapists, and adaptive technology specialist had especially positive appraisals of the system because they frequently needed to locate residents. The activities staff did not report any issues with the interface but noted that it had limited utility for their purposes.

Finally, the staff also reported that, for 2 reasons, the effectiveness of the interface should be greater in practice than the statistics measured in the study might suggest. First, they noted that they occasionally forgot to record the time required to locate a resident because of other distractions (the unit secretaries, in particular, often had to handle 3 to 4 find requests at once). Thus, the number of uses of the interface was definitely underreported. Second, the residents participating in the study were all relatively high-functioning and thus more likely to remember their appointments; thus, application of the system to the full resident population would likely result in more time saved per resident, on average. In general, the staff reported that they usually had to find 2 to 3 people per day; thus, a mean decrease of 200.1 seconds in locating time would correspond to a total savings of approximately 1 hour of staff time per resident per week at this facility with its approximately 100 residents.

Study Two: Effect of Location Information for Wander Management

Nine residents and 3 staff members consented to participate in Study Two. The residents were chosen from a population that was both highly mobile (as in Study One) and had a tendency to wander off the premises without informing the staff as they were supposed to do per facility policy. The person-finder interface was modified to generate a pop-up window and an audible alert on the caregiver's computer whenever a participating resident had been outdoors for more than 3 minutes (as a possible precursor to wandering). Also provided was an indication of whether the resident was in the back patio (less concerning) or front yard (more concerning, as a short path led from there to the public sidewalk adjacent to the facility grounds). Staff were asked to determine independently, in the event of each alert, whether the participating resident was indeed in the reported outdoor space; then click a check box indicating to the software whether the alert was a true or false alarm. The interface required the staff member to perform this "validation step" before it would dismiss the pop-up. Since the interface was meant to be used in the course of everyday operations, we also provided the staff the option of disabling the alerts for a particular resident for a limited period of time if they knew that he or she would be outside or away from the facility for some extended period.

Deploying the interface in this way enabled us to evaluate the false-positive rate in a real setting as part of the facility's normal . However, it did not provide information regarding the false-negative rate, that is, how often the system failed to alert the staff when a resident went outdoors. Thus, we measured the false-negative rate in a test situation in which we took 7 N810 tablets in and out of the facility, 3 times in the front yard area and 3 times in the back patio for a total of 42 trials. We defined the false-negative rate to be the fraction of times that the system failed to report that a tablet was outdoors within 10 minutes of the tablet's actually moving outside. The 10-minute threshold was chosen because (1) after this time, a wandering resident could have left the grounds and (2) after this time, during normal operation, the system should have stabilized and reported its updated location estimate. Specifically, the system was designed to report after 3 continuous minutes of being outside; often there would be 2 to 3 minutes of initial "bounce" in the location estimates between the outdoor space and some adjoining indoor space.

Table 1
Wander Events Detected by System Over the 2-Month Period

True positives	215
False positives	21
False positive rate	8.9%

Table 2
System Characterization Test of False-Negatives

Outdoor devices correctly detected	59
Outdoor devices undetected	1
False-positive rate	1.7%

Results

Table 1 shows the total number of alerts and false alarms for the back patio and the front loading area. Overall, during the 2-month period of Study Two, our interface reported 236 alerts, of which 21 were false-positives for an in-operations false-positive rate of 0.089 (95% confidence interval [CI] = 0.058–0.137). As expected, many of the false-positives occurred when the resident was near the exit of the facility but still indoors (for example, in a nearby lobby or atrium).

Table 2 shows the total number of trials and missed alerts for the back patio and the front loading area from our controlled experiments. The overall false-negative rate was 0.017% (95% CI = 0–0.049). The single false-negative occurred in the back patio, which is closer to adjacent indoor spaces. False-negatives in this space were arguably of less concern than false-negatives in the front loading area, because leaving the premises from this more secluded outdoor location requires navigating around a large part of the facility.

Discussion

The results presented above suggest that the WiFi-based location discovery system was an effective tool for enhancing staff effectiveness and resident safety in this skilled nursing facility setting. Specifically, the system significantly reduced the staff time required to find residents for appointments and activities, and helped staff monitor the locations of residents at risk of wandering. These quantitative findings were corroborated by interviews with staff, who suggested that the system was effective for both of these purposes.

The system presented here differs from many wander-management systems discussed in the literature in that it uses WiFi-based localization. The most common systems, which use RFID tags, typically require installation of RFID detectors in doorways and other parts of the built environment. As a result, our system has the potential to be much more cost-effective than an RFID-based system. Specifically, the cost of deploying a system such as ours can be broken down into the following parts:

- Installing WiFi-enabled devices on resident wheelchairs. The Nokia N810 tablets that we used cost $250 each and required 1 hour from the adaptive technology specialist (or a member of our team) to install. The remaining attachment peripherals cost about $20. We note that the price of WiFi-enabled mobile computing devices has and continues to fall, and future residents of such facilities are likely to own their own personal devices that could run our localization scripts in the background.
- Providing a computer acting as a central server to collect location information from the WiFi-enabled devices and disseminate it to staff members. A standard laptop or desktop machine is more than sufficient.
- Creating the software. Our software had approximately 40,000 lines of code, and we estimate that a production-quality application could be completed by a team of 3 BS/MS-level software engineers in 3 to 4 months. The software is general and can be used across multiple facilities.

- Calibrating and testing the software for the particular facility. Approximately 15 to 20 minutes of recording WiFi signal strengths were required to characterize the signal strengths for each location. Most of the calibration and testing is a 1-time task that does not require skilled staff. We estimate approximately a week of skilled developer time might be needed to trouble-shoot any facility-specific issues.
- Annotating the architectural drawings of the facility with doorways and hallways for the HMM required a few hours from someone familiar with architectural drawing formats. This process could potentially be automated. If the facility does not have floor plans in an electronic format, additional costs will be incurred to generate electronic floor plans.

We assume that the facility already has the necessary wireless infrastructure to deploy the system as part of the network connectivity that it provides to the staff and residents. Any staff member using the system will also require ready access to a computer or a mobile computing device on which to run the software application.

Another advantage of our WiFi-based system is its specificity. RFID-based systems work by causing an alert to be issued once a resident has passed a certain checkpoint, such as a doorway leading outdoors. In contrast, our WiFi-based localization system uses existing wireless network infrastructure and provides estimates of each resident's location at regular (roughly 30-second) intervals. In the resident-finding part of this study, the immediacy of the location information was an attractive feature because it allowed staff to know the room or hallway where the resident could be found; an RFID-based system would require a prohibitive number of detectors to provide comparable information. In addition, the WiFi-based system can provide more precise location information if a resident were outside, instead of a binary indoor/outdoor reading from a checkpoint-based system based on RFID or other similar technologies.

The staff participants who used the software responded positively to its simple user interface, which consisted of a list of participating residents and the location of each, along with pop-up alerts when a participating resident was considered by the system to have moved outside. Although this study did not seek to compare the effectiveness of different kinds of user interfaces and alerts, the high level of usage of the system suggests that a simple user interface was sufficient.

Conclusions

This study demonstrated the potentially transformative effect that existing, standard wireless infrastructure can have on both safety and operational efficiency in clinical environments. We provide one of the few quantitative, end-to-end evaluations of a system deployed during the normal day-to-day operations of a facility. We showed that a simple interface to WiFi-based location information can both reduce the amount of time needed to find residents, and provide accurate, timely alerts when residents go outdoors. Using WiFi-based localization, which requires 2 steps (measuring the wireless signal-strength map of the facility, and mounting a WiFi-enabled device on resident wheelchairs) may provide an inexpensive alternative for facilities desiring a resident localization and wandering alert capability, especially as it becomes more common for facilities to have many wireless access points and residents may increasingly carry WiFi-enabled devices. Besides the uses investigated in this study, such software could also be used to alert staff about residents who are in unexpected parts of the facility for unexpected periods of time (which may suggest, for example, a wheelchair problem or an issue with well-being).

Our 2 pilot studies demonstrate that, beyond being technically feasible, our system was effective both in promoting resident safety and increasing staff efficiency under real-world operating conditions. These results were made possible by the number and layout of the existing wireless access points at this particular facility. Similar studies at other facilities are needed to understand to what extent this technique can be applied in more general residential care settings.

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