Towards Fully Organic Indoor Positioning

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ABSTRACT

Indoor positioning systems based on fingerprinting techniques generally require costly initialization and maintenance by trained surveyors. Organic positioning systems aim to eliminate these deficiencies by managing their own accuracy and obtaining input from users and other sources. Such systems introduce new challenges, e.g., detection and filtering of erroneous user input, estimation of the positioning accuracy, and means of obtaining user input when necessary.

We envision a fully organic indoor positioning system, where all available sources of information are exploited in order to provide room-level accuracy with no active intervention of users. For example, such systems can exploit pre-installed cameras to associate a user's location with a Wi-Fi fingerprint from the user's phone; and it can use a calendar to determine whether a user is in the room reported by the positioning system. Numerous possibilities for integration exist that may provide better indoor positioning.

Categories and Subject Descriptors

H.2.8 [**Database Applications**]: Spatial databases and GIS

General Terms

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Keywords

Indoor positioning, Organic systems, Wi-Fi Fingerprinting

1. INTRODUCTION

Over the past decade, location-based services have gained in prominence. One report finds that location-based services accounted for a revenue of USD 2.8 billion in 2010 and that the expected revenue in 2015 is USD 10.3 billion [26]. Another report expects a market size of USD 12.9 billion in 2014 [13]. However, today's location-based services target mostly outdoor users [11]. In contrast, studies find that people spend some 87% of their time indoors [7,15,17], and in 2013, 70% of cellular calls and 80% of data connections in the USA originate from indoors [18]. Additionally, one report forecasts a 40% growth of the indoor LBS market over the period 2012–2016 [27]. Thus, time is ripe for enabling also indoor location-based services, where indoor positioning is a key enabler. Specifically, deployments of indoor positioning systems enable a range of indoor location-based services, including simple navigation services as well as more complex shopping assistants and friend finders, to name but a few.

Working on the application side of indoor positioning, we find that two aspects need more attention: the accuracy of the positioning and the maintenance of the positioning system. Many different kinds of positioning systems have been proposed that use different technologies and have different deployment requirements, offer different accuracies, and target different settings. In general, the higher the accuracy, the more expensive or complex the system becomes. We believe that in order to become a de facto standard (as GPS is for outdoors), a technology needs to be sufficiently accurate, cheap to use, and simple and inexpensive to deploy and maintain.

While different technologies possess these characteristics, Wi-Fi is a good candidate for becoming the foundation for a successful indoor positioning; Wi-Fi access points are already deployed in many public and private spaces, and a positioning system based on Wi-Fi can re-use the infrastructure without the need for new deployment expenses; moreover, many mobile devices (e.g., smartphones or tablets) are equipped with Wi-Fi, making the positioning available to many users. Other technologies include cameras (embedded in smartphones or mounted in selected locations) and Bluetooth.

Researchers are studying how to achieve more accurate positioning based on each of these technologies. We believe that indoor spaces have physical characteristics that make this task hard. While a one-meter accuracy is desirable, it may be hard to achieve. Further, it may be insufficient to ensure that users are positioned in the correct room, as walls are relatively narrow. However, we believe that by integrating different technologies available in indoor spaces, it is possible to achieve room-level accuracy, which differs from distance-based accuracies.

As mentioned, the initialization of an indoor positioning system often requires a surveyor to perform measurements in the space. In addition, systems may need new measurements when modifications happen in the space (e.g., new objects are placed in the space or an access point is moved). In the context of Wi-Fi based positioning, a few systems have been proposed that leave the task of performing initial measurements to the users. This kind of system is referred to as an organic system [24]. If the system is totally based on user input, the users are required to keep sending measurements to maintain the system.

We envision a kind of organic system that goes beyond this. We want to avoid any action by any expert, as achieved by a standard

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organic system, but we also want to eliminate the need for explicit actions by users. We envision a fully organic system that is aware of its status (e.g., different accuracies in different parts of the space) and is able to take action as needed to ensure room-level accuracy. We believe that such a system must integrate a range of different technologies and sources of information to be successful.

In this paper, we first characterize the notion of a fully organic system in Sec. 2. Then we give an overview of technologies that can be exploited by such a system in Sec. 3, and we give examples of integration in Sec. 4. We conclude in Sec. 5.

2. ORGANIC POSITIONING SYSTEMS

We envision a fully organic positioning system that needs no user intervention during deployment and operation. As steps towards this ideal, levels of automation can be identified. We first describe basic concepts of standard and organic fingerprinting-based systems that will be useful to better understand our vision.

2.1 Fingerprinting-based Systems

In positioning systems, a fingerprint is an identification feature assigned to a spatial location. In a Wi-Fi based system, a fingerprint is generally generated by aggregating a set of signal strength measurements of Wi-Fi access points that are visible from the location. A fingerprint-based system relies on a database composed by pairs of ⟨*fingerprint, ground truth location*⟩ that are collected by trained surveyors by standing at the specific ground truth location with a Wi-Fi device and recording signal strengths for some prescribed period of time (i.e., *binding process*). Coordinates of ground truth locations together with the set of signal strength measurements are sent to the server that combines the measurements into a fingerprint and stores it in the database together with the ground truth location.

A user, when asking to be positioned, sends the signal strength measurements produced by a Wi-Fi device (e.g, a smartphone) to the positioning system. The position assigned to the user by the system is the ground truth location corresponding to the fingerprint that is the most similar to the set of measurements sent by the user.

One drawback of such a system is the collection phase, since it requires trained surveyors and can be long and expensive. Additionally, a new collection of fingerprints needs to be performed any time a change in the space happens (e.g., an access point is moved).

2.2 Organic Systems

In order to make positioning systems more available and to avoid the cost of trained surveyors, a new kind of fingerprint-based system has been proposed in the past few years that moves the task of collecting fingerprints to users. The notion of an organic indoor positioning system was introduced by Park et al. [24] to denote all such systems that are based on user input.

Different ways of exploiting user input have been explored. One of the most common means, for both initializing and maintaining the system, is to ask the users to perform the same *binding process* that trained surveyors perform. During this process, the user is asked to mark their current location on a map (this is the ground truth location) and then collect a set of signal strength measurements of a Wi-Fi device in that location for some time.

Relying on user input saves the cost of the surveyors, but also introduces new challenges. First, the binding process is more error-prone. Because users are not trained for the task as a surveyor, they are more likely to make mistakes in marking their ground truth location on the map. Second, the quality of the system depends on the willingness of users to contribute during the entire life cycles of the system. Thus, the user input rate can vary with time, making the system "unstable."

2.3 Highly and Fully Organic Systems

A fully organic positioning system is, in our vision, a system that requires no explicit actions on the part of the users while offering room-level accuracy. This can be achieved through a complete automation of the process of collecting fingerprints for initialization and maintenance, and we believe that self-awareness and integration of different sources are essential in achieving this vision.

When characterizing the accuracy of a positioning system, we usually refer to the maximum (or average) positioning error expressed in meters. As a different approach, we can consider room-level accuracy. A system offers room-level accuracy if the reported location is in the same room as is the ground truth location. In fact, for many indoor location-based services (e.g., silence-your-phone-in-a-meeting-room and targeted ads) and for indoor data analysis (e.g., frequent pattern mining or finding sequences of shops visited), the exact position of the user inside the room is not needed, but it is crucial to know in which room the user is. We expect a fully organic positioning system to guarantee room-level accuracy. If this accuracy cannot be guaranteed, users must be informed.

In order for the system to maintain the required level of accuracy, the system needs to be aware of its accuracy throughout the monitored space, and if the accuracy is too low (w.r.t. the required level) in one part of the space, it must take action to improve the accuracy. Thus, we view self-awareness as being essential. Another aspect is that the system knows that different parts of the space have different required accuracies and that it has a way of deciding on the actual accuracy of different parts of space.

As a practical approximation to the vision of a fully organic system, we target a highly organic system that needs as little user interaction as at all possible. The aim of a highly organic system is to reduce explicit actions of users to a minimum. It thus needs to ask users to contribute only when there is no other way of achieving the required accuracy. Therefore, a highly organic system needs to be able to decide when to invoke user actions. Self-awareness is again the property that allows the system to achieve this. In particular, when the accuracy is dropping, the system can notify the users that positioning in a certain region is low and possibly send a request for action to users that are detected in or near the region, asking for specific actions that can increase the accuracy.

3. TECHNOLOGY OVERVIEW

We consider existing techniques for indoor positioning that can be part of the foundation of a fully organic system and investigate different methods for integrating different sources of information that can be employed in order to automate the system. Different technologies have been used in the past few years to provide indoor positioning; most of them rely on wireless sensors (e.g., Wi-Fi, Bluetooth) or on video cameras, but also other types of sources have been explored, e.g., ultrasound.

Wireless technologies are commonly deployed in indoor spaces, and different techniques have been proposed in order to use them for positioning; surveys on different approaches to wireless positioning can be found in the literature [16, 20]. Wi-Fi is one of the most natural solutions to indoor positioning because it is already present in many indoor spaces for supplying network connection; in fact, Wi-Fi based indoor positioning has been studied for longer than a decade, and research is still ongoing to provide better accuracy and maintainability [1, 4]. With respect to accuracy, other technologies have better performance; for example, systems using passive RFID tags [25] or ultrasound emitted by a phone and captured by microphones [8] can provide positioning with an accuracy of 10 cm. The downside of using such technologies is that this necessitates the deployment of equipment in the monitored space.

In the context of video-based systems, many different approaches and algorithms have been investigated for using fixed cameras to track objects moving in a space. Some techniques aim at recognizing the shapes of the objects, and some focus on positioning; a comprehensive survey is given by Yilmaz et al. [29]. The great advantage of using cameras is that all people walking in the monitored space are tracked not only the ones carrying some specific device; therefore, video-based systems can offer a global view on what is happening in the monitored space. On the downside, the use of cameras makes it difficult to identify people because these systems rely only on visual features.

Other systems have been proposed in the literature that make use of inertial sensors to track the movements of a device. Such systems became more interesting because modern smartphones are increasingly being equipped with such inertial sensors and because maps of indoor spaces are becoming available and can be exploited in order to mitigate the problems caused by the cumulative errors that are known to affect dead reckoning methods [10, 19].

More unconventional ways of determining where a person is located in an indoor space also exist. An electronic agenda (or calendar), where a person records appointments related to locations is an example explored by Lovett et al. [21]. Also office assignments can be used for rough positioning since they contain information on the location each person is assigned to in a space during working hours. We can also exploit historical records of users' movements to estimate their current locations, as studied by Furey et al. [9].

An organic positioning system as defined by Park et al. [24] is a fingerprint-based system that has user input as its main resource. Some of these systems are built completely from user input, while others use surveyors for initializing the system and exploit user input for maintenance during operation [3, 5, 6].

As already mentioned, new issues arise in exchange for saving the cost for surveying. Park et al. address two of these issues. First, in a traditional fingerprint system, the surveyor has a precise plan with the locations where fingerprints are to be collected (usually according to a grid). In a user-driven system where fingerprints are collected without such a plan, they provide a method to estimate uncertainty of the positioning and determine when new user input is necessary. Second, users are more prone to making mistakes than is a trained surveyor. Therefore, a method for identifying and filtering erroneous input is provided.

Building on top of such an organic system and in order to make it fully organic, we want to exploit any source of information about the location of a person. Many different technologies are available in indoor spaces that can be sources of positioning information, and few works have considered the integration of them. For example, integration of different wireless sensors (namely Wi-Fi and Bluetooth) has been explored in Baniukevic et al. [2] in order to provide better positioning accuracy. Systems integrating phone cameras with Wi-Fi based systems have been proposed both by Hile et al. [12] and Morimitsu et al. [22]. Their approaches rely on the phone camera as the main positioning system, and they use Wi-Fi positioning to prune the space and improve the efficiency of video matching algorithms. External cameras are considered in connection with Wi-Fi sensors data by Van den Berghe et al. [28] and in connection with RFID localization systems by Nick et al. [14] and Isasi et al. [23] in order to improve intra-room accuracy.

4. INTEGRATION OF SOURCES

Different technologies can provide different views on the same event, and an integration of such different views can yield new information on the event itself. For example, a Wi-Fi positioning system reports some users as being in a room, and a camera monitoring the same room detects a smaller number of people in the room. Therefore, we can learn that one user is mis-positioned. In this section, we consider different ways of integrating sources of information to achieve a highly organic system.

4.1 System Overview

An architecture of a highly organic positioning system is provided in Fig. 1, where different modules are dedicated to different tasks. A *positioning module* computes the position of the user based on the most recent radio map available. A *fingerprinting module* computes new fingerprints when proper input is available from sources, and it updates the radio map. An *interaction module* decides when and how to ask a user for an action. Finally, an *accuracy monitoring module* uses information gathered from different sources in order to compute the level of accuracy of different parts of space. The output of the system can be of two different types: (i) either the estimated position of the user with an alert if the accuracy is below the requirements or (ii) a message asking for an action.

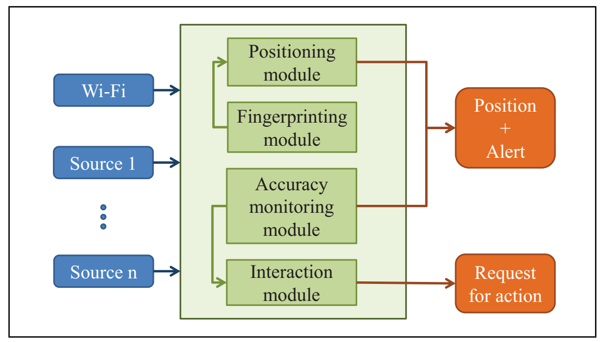

Figure 1: Highly organic system overview.

Comparing information from different sources can be useful in different ways. A first use is to help during the initialization phase when information on the ground truth locations of objects moving in the space need to be collected; later on, the maintenance phase could benefit from this extra information in order to reduce actions required by users, such as deciding which user to ask for help; integration of different sources can also be very useful to provide information on the status of the accuracy of the positioning system. We discuss such ways of exploiting integration next.

4.2 Initialization and Setup

The initialization phase of an indoor positioning system can be very time-consuming and costly. The number and kind of actions in this phase depend on the type of system to be built. Since organic positioning systems have been proposed in the context of fingerprint-based systems, we present examples that work for such a system; different sources of extra information can be useful for fingerprint collection.

Video cameras. Information provided by a camera differs based on the settings. If a camera is monitoring a corridor and a user is positioned in the corridor, the camera can detect which room the user enters, and then we can pair the ground truth location of the room with the set of measurements gathered from the Wi-Fi device of that user during the time spent in the room (i.e., from the moment the camera detects the user entering the room, until it detects the user leaving the room).

Calendars. If we can extract information on which room a user is in during some time from the calendar of the user, we can pair the set of measurements from that user as reported during that period of time with the room.

Office Assignments. If we can determine from the positioning data collected by the system from a user that the user is in the same location for some long and frequent periods (all measurements from these periods are very similar), that location is most likely to be the user's office location. We can use the "office assignment" map to find the location of the room to pair with these measurements.

4.3 Maintenance

When a positioning system is up and running, users can use it for active positioning, and location-based services can be provided, such as navigation or friend finders. During the life of the system, maintenance might be needed due to changes in the physical environment that cause a drop in positioning accuracy. The system might use the same techniques used during its initialization phase in order to update the system. When these techniques fall short, we might need to ask the users to take actions.

Calendar. We may learn from a user's calendar that a user will have a meeting at some time in a specific room. If, when the meeting time is approaching, the user is detected by the positioning system as being far away from the meeting room, we could ask the user whether he is attending the meeting or not. If the user is attending the meeting then the positioning was wrong.

Video camera. If we do not have any alternative way of collecting fingerprints, we need to ask a user to manually collect a fingerprint. As mentioned before, the task of marking the location on the map is error-prone. If a camera is available in the room where the user is performing the collection, the user needs to provide only information on the room (e.g., selecting it from a list). Then we can retrieve information on the precise location of the user from the camera.

4.4 Accuracy Level Detection

An important task for highly and fully organic positioning systems is to be aware of the accuracy in different parts of the monitored space. There are different ways in which we can implement this self-awareness.

Room function. The availability of information about the function of each room can be useful to define different granules of accuracy for different regions. For example, if we know that several adjacent rooms are all storage rooms, we can define the accuracy to consider them as one single room because we do not need information about users being in one room versus another.

Office assignments. If a room is an empty office, but the positioning system reports that somebody is always in the room, there might be something wrong with the system accuracy. In order to find out, it might be needed to contact the user detected there to check whether it is an error or the user is actually using the supposedly empty office.

Historical traces. When a user navigates to a room, we can detect if a user is taking a different path with respect to the one suggested by the navigation service. This can be a case of the user being misled by the navigation service. We can check with the user if the reason for going somewhere else is that the positioning system is positioning him incorrectly, meaning that the navigation is incorrect. Based on the user's answer, we can learn that the accuracy in that part of the space is not good.

Difference in SSM. If users that are reported by the positioning system as being in the same room send very different signal strength measurements, there might be something wrong.

Video camera. A camera monitoring a region of space can detect wrong positioning. An example is shown in Fig. 2, where the real positions of users are marked with blue circles and their positions as reported by the positioning system are marked with red crosses. We can see that a user is reported by the system as in the

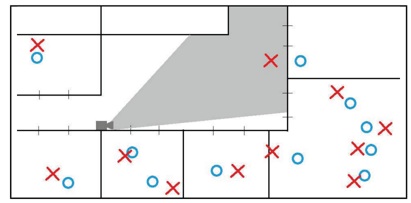

Figure 2: Wrong positioning detected by a camera.

field of view of the camera, but the camera does not detect anybody there (because the user is actually inside the room). Therefore, we can mark that positioning as faulty, and if this happens often, we might need to do something to increase the accuracy in that particular region.

Bluetooth. If a user has a Bluetooth device that detects another user as "in proximity," but the positioning system reports the two users as far apart, there might be something wrong with the system accuracy.

4.5 User Interaction

One of the two types of output of the proposed system is a 'Request for action' by the user. Since it is crucial to ensure that users keep contributing to the system, we need to make each interaction as fruitful and simple as possible.

The preferred means of communication with the user should be the phone, since it is the device that is tracked using a Wi-Fi system. The system can send notifications or issue pop up messages that open a dedicated window on the phone. The specific choice of how to interact with the user depends on the situation; for example, when the system needs an immediate response from the user, we can use a pop up that blocks any other activity the user is doing on the phone, and when it needs optional input from the user, it can use a notification.

The canonical means for a user to help the system is to mark the real location of the device on a map, this way providing the user's ground truth location. To avoid the effort associated with providing a precise and accurate location, the system can show a map and ask the user to click on the room in which the user is located, or it can provide a list of names of rooms from which the user can select one. Other means of making it easier for the user to provide input can be investigated. For example, means of using the phone camera seem promising (e.g., asking the user to take a picture of some peculiar object, such as a door sign stating the number of the room). Another way in which the user can help the system is to give active feedback on the positioning: drawing a line on a map representing the real path the user followed after a navigation session, or moving a pointer located at an estimated location to the real location when the estimated location is wrong.

5. CONCLUSIONS AND FUTURE WORK

We defined the vision of a fully organic indoor positioning system where no user input is required during initialization and operation while offering room-level accuracy. The envisioned system maintains its accuracy automatically. We argued that self-awareness is an essential feature of such a system. The system needs to be aware of its accuracy throughout time and space and must be able to take action automatically in order to maintain its accuracy.

As steps towards a fully organic system, we identified techniques that can play a role in realizing a highly organic system, in which the initialization and operation of the system require as little user input as possible. The system may ask users to contribute to maintain the system's accuracy, but this will happen only if no techniques that are transparent to the user are applicable.

We see two main aspects on which additional work is needed. First, ways to communicate with users in the least invasive and most fruitful manner need to be found. As part of this, schemes for giving users incentives to contribute are of particular importance. We also believe that empirical studies play an important role in designing, assessing, and improving proposals. Second, techniques for implementing self-awareness of the system need to be proposed and evaluated.

We believe that integration of different technologies is the key point in such a system. Experts from different fields are called on to contribute and to combine their knowledge and techniques in order to build a fully organic positioning system.

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6. REFERENCES

[1] P. Bahl and V. N. Padmanabhan. RADAR: An in-building RF-based user location and tracking system. In *Proc. INFOCOM*, pages 775–784, 2000.

[2] A. Baniukevič, C. S. Jensen, and H. Lu. Hybrid indoor positioning with Wi-Fi and Bluetooth: Architecture and performance. In *Proc. MDM*, pages 207–216, 2013.

[3] A. Barry, B. Fisher, and M. L. Chang. A long-duration study of user-trained 802.11 localization. In *Proc. MELT*, pages 197–212, 2009.

[4] P. Bhargava, S. Krishnamoorthy, A. Nakshathri, M. Mah, and A. Agrawala. Locus: An indoor localization, tracking and navigation system for multi-story buildings using heuristics derived from Wi-Fi signal strength. *LNICST*, 120:212–223, 2013.

[5] E. Bhasker, S. Brown, and W. G. Griswold. Employing user feedback for fast, accurate, low-maintenance geolocationing. In *Proc. PerCom*, pages 111–120, 2004.

[6] P. Bolliger. Redpin - adaptive, zero-configuration indoor localization through user collaboration. In *Proc. MELT*, pages 55–60, 2008.

[7] W. H. Dörre. Time-activity-patterns of some selected small groups as a basis for exposure estimation: A methodological study. *J. Expo. Anal. Environ. Epidemiol.*, 7:471–491, 1997.

[8] V. Filonenko, C. Cullen, and J. D. Carswell. Indoor positioning for smartphones using asynchronous ultrasound trilateration. *ISPRS Int. J. Geo-Inf.*, 2:598–620, 2013.

[9] E. Furey, K. Curran, and P. Mc Kevitt. Incorporating past human movement into indoor location positioning systems for accurate updates. In *Proc. IT&T*, pages 85–92, 2010.

[10] D. Gusenbauer, C. Isert, and J. Krösche. Self-contained indoor positioning on off-the-shelf mobile devices. In *Proc. IPIN*, pages 1–9, 2010.

[11] C. Hage, C. S. Jensen, T. B. Pedersen, L. Speicys, and I. Timko. Integrated data management for mobile services in the real world. In *Proc. VLDB*, pages 1019–1030, 2003.

[12] H. Hile and G. Borriello. Positioning and orientation in indoor environments using camera phones. *Computer Graphics and Applications, IEEE*, 28(4):32–39, 2008.

[13] Infiniti Research Limited. Global location based services (LBS) market 2010–2014. Feb. 2011. `http://www.researchandmarkets.com/reports/1552300/global_location_based_services_lbs_market`

[14] A. Isasi, S. Rodriguez, J. L. D. Armentia, and A. Villodas. Location, tracking and identification with RFID and vision data fusion. In *Proc. RFID Sys Tech*, pages 1–6, 2010.

[15] C. S. Jensen, K.-J. Li, and S. Winter. ISA 2010 workshop report: the other 87%: A report on The Second International Workshop on Indoor Spatial Awareness (San Jose, California - November 2, 2010). In *SIGSPATIAL Special*, 3(1): 10–12, 2011.

[16] H. Koyuncu and S. Hua Yang. A survey of indoor positioning and object locating systems. *IJCSNS*, 10(5):121–128, 2010.

[17] N. E. Klepeis, W. C. Nelson, W. R. Ott, J. P. Robinson, A. M. Tsang, P. Switzer, J. V. Behar, S. C. Hern, and W. H. Engelmann. The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *J. Expo. Anal. Environ. Epidemiol.*, 11(3):231–252, 2001.

[18] T. E. Lacroix. Indoor LBS market report. Sept. 2013. `http://www.indoorlbs.com/p/market-report.html`

[19] J. A. Link, P. Smith, and K. Wehrle. FootPath: Accurate map-based indoor navigation using smartphones. In *Proc. IPIN*, 2011.

[20] H. Liu, H. Darabi, P. Banerjee, and J. Liu. Survey of wireless indoor positioning techniques and systems. *IEEE Trans. Systems, Man, and Cybernetics*, 37(6):1067–1080, 2007.

[21] T. Lovett, E. O'Neill, J. Irwin, and D. Pollington. The calendar as a sensor: Analysis and improvement using data fusion with social networks and location. In *Proc. Ubicomp*, pages 3–12, 2010.

[22] H. Morimitsu, R. Pimentel, M. Hashimoto, R. Cesar, and R. Hirata. Wi-Fi and keygraphs for localization with cell phones. In *Proc. ICCV Workshops*, pages 92–99, 2011.

[23] T. Nick, S. Cordes, J. Gotze, and W. John. Camera-assisted localization of passive RFID labels. In *Proc. IPIN*, pages 1–8, 2012.

[24] J.-g. Park, B. Charrow, D. Curtis, J. Battat, E. Minkov, J. Hicks, S. Teller, and J. Ledlie. Growing an organic indoor location system. In *Proc. MobiSys*, pages 271–284, 2010.

[25] S. S. Saad and Z. S. Nakad. A standalone RFID indoor positioning system using passive tags. *IEEE Trans. Industrial Electronics*, 58(5):1961–1970, 2011.

[26] J. t. Sythoff and J. Morrison. Location-based services market forecast, 2011–2015. *Pyramid Research*, May 2011. `http://www.pyramidresearch.com/store/Report-Location-Based-Services.htm`

[27] Technavio. Global indoor LBS market 2012–2016. Aug. 2013. `http://www.researchmoz.us/global-indoor-lbs-market-2012-2016-report.html`

[28] S. Van den Berghe, M. Weyn, V. Spruyt, and A. Ledda. Fusing camera and Wi-Fi sensors for opportunistic localization. In *Proc. UBICOMM*, pages 169–174, 2011.

[29] A. Yilmaz, O. Javed, and M. Shah. Object tracking: A survey. *ACM Comput. Surv.*, 38(4), 2006.