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Evaluation of Indoor Positioning Technologies for Prototyping at Kettering University

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Abstract—**This paper presents research performed on indoor positioning technologies to identify a technology that would be best to implement in a prototype at Kettering University's campus. The indoor positioning techniques evaluated are mainly based on beacon sources including Bluetooth, Wi-Fi, Geomagnetic, Visual Light Communication (VLC), and Ultra-Wideband (UW). Target-side wearable sensors will be considered. The algorithms commonly used for calculating the user's position will be discussed, including Trilateration, Fingerprinting, and K-Nearest-Neighbor.**

Keywords—Indoor Positioning System, Bluetooth, Wi-Fi, Geomagnetic, Visual Light Communication, Ultra-Wideband, Fingerprinting, Trilateration, K-nearest-neighbor

I. Introduction

Location information is becoming a critical piece of information for many diverse applications. Some examples are implementing location-aware services in commercial, industrial and consumer applications. For the outdoors, the GPS has established itself as the main source of localization. However, in indoor environments, GPS may not be available or becomes too weak to be usable. Many companies are currently developing different technologies for indoor positioning applications. Just as satellites are used to provide reference information to enable GPS receivers to calculate locations, most indoor positioning applications rely on some sort of beacon sources to aid the positioning algorithms. The beacon sources could rely on one or a combination of the following: RF transmitter, ultrasonic sources, IR source, Wi-Fi signals, Bluetooth beacons, VLC, UW, or Geomagnetic.

A project was conducted at Kettering University that consisted of two main phases. The first being extensive research of existing and applicable indoor positioning technologies with an analysis of which technology would be best for implementing on campus. The second phase was focused on using the selected technology from phase one to create a prototype indoor positioning system on campus. This paper covers the first phase of the project.

The focus of this paper is to highlight the researched indoor positioning technologies and provide an explanation as to how they can be used for an indoor positioning system (IPS).

The goal of this project was to showcase an indoor positioning technology to meet the needs of a system to be implemented at the Electrical and Computer Engineering Department of Kettering University. If the prototype was successful, it could be expanded to include the rest of the campus and be used for navigation and routing purposes.

The foundation of this research originates from technologies which were identified from products currently in the market. After we see how these technologies can be used to create an IPS, key features of the technology will be overviewed.

II. Bluetooth

A Bluetooth Low Energy (BLE) beacon is a wireless device that broadcasts an advertising packet at consistent, sometimes customizable, intervals. This packet can be received by a smart device and can be used to estimate the distance between the receiving device with respect to the beacon. If three or more BLE broadcasts are received from the smart device, trilateration can be used to calculate the position of the user. This requires that each BLE beacon's placement is known and leveraged in the calculation of the position.

Beacons are separated into two major categories or protocols. The first released was iBeacon, which is proprietary to Apple, but is supported with many Android SDKs. The second is Eddystone, which is an open protocol released by Google. Either of these protocols could be used in a beacon implementation. Each protocol broadcasts unique identifiers that the receiver devices can pick up, along with the received signal strength indicator (RSSI) values. Upon receiving the broadcast on the smart device, the identifier is used to look-up the position of the beacon from a look-up table hardcoded in the mobile application. By using a beacon SDK provided, this RSSI value can be converted into an estimated distance [4].

For example, in Fig. 1 above, we can visualize what a BLE beacon implementation might look like. Beacons would be scattered among the target area and would broadcast at a consistent rate, perhaps twice a second.

Fig. 1. Mock-up of BLE beacon IPS system in ECE department.

As a user (yellow circle) would walk through these broadcasts, the user's smart device would constantly receive new broadcasts from the beacons. Once three broadcasts are received from unique beacons, the position of the smartphone can be calculated.

A major consideration that needs to be addressed for the implementation of this technology is the broadcast signal strength and interval. Increasing broadcast signal strength improves the distance that the broadcast will travel, at the cost of increased power consumption. Most BLE beacons are battery powered. Thus, an increase in power consumption will lead to quicker battery usage and would require more frequent maintenance for the IPS. The broadcast interval follows a similar trend, increasing the frequency of broadcast leads to the higher power consumption, and inherently, more maintenance. However, the more frequent the signal, the more often and better the IPS can estimate the users' location.

Key Characteristics:

1. Position Accuracy: 1m - 3m
2. Beacon range: 70m
3. $3 - $30 per Beacon
4. Beacons placed every 7m - 10m
5. Batteries last anywhere from ¼ year up to 8 years

One of the downsides of this technology is that its interference with 2.4 GHz Wi-Fi may degrade its signal strength.

Note: Beacon range, battery life, and the distance between beacons depend on beacon broadcast customizable characteristics.

III. Wi-Fi

Wi-Fi access points (APs) can be utilized as a beacon source for indoor localization. There are many different techniques for using Wi-Fi RSSI values to estimate location. Each technique offers advantages and disadvantages, and it can be difficult to identify the best technique for the indoor environment. Out of the three techniques overviewed here, fingerprinting is the most widely used.

Key Characteristics:

1. Position Accuracy: 5m - 15m
2. Existing Wi-Fi access points can be used
3. Minimal maintenance
4. Wi-Fi access points must provide Wi-Fi coverage to entire area
5. At time of research, only Android supports an API for Wi-Fi access

A. *Trilateration*

A trilateration approach using Wi-Fi RSSI values is nearly identical to the BLE beacon implementation, except the beacon sources are not BLE modules, but APs instead. With three APs broadcasting RSSI values, the smart device can convert the RSSI values into a distance using an RF signal propagation model, and then use trilateration to determine the position of the receiver. An explanation of the Trilateration algorithm was taken from [5].

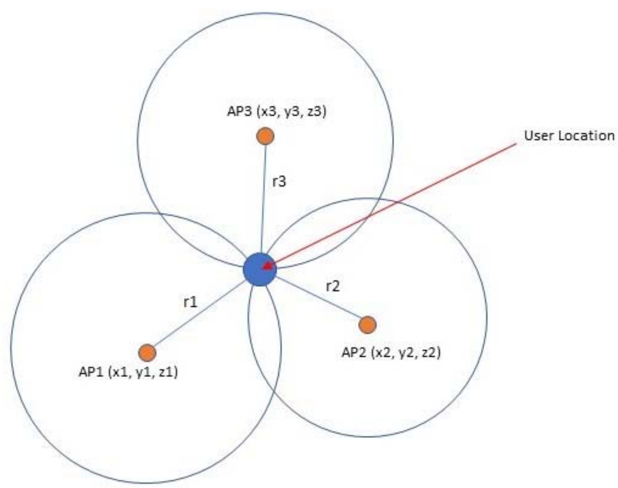

Fig.2: Wi-Fi Trilateration Algorithm Example. Similar to the approach presented in [5].

The three AP's in Fig. 2 have known center coordinates. The intersection point of the three circles is the position of the receiver. Knowing r1, r2, r3 i.e. distances from the AP's coordinates (x_i, y_i, z_i) to the unknown user's receiver location (x, y, z), a simple set of distance equations can be applied to solve the unknown user location coordinates (x, y, z) [5].

$$(x_1-x)^2 + (y_1-y)^2 + (z_1-z)^2 = r1 \quad (1)$$
$$(x_2-x)^2 + (y_2-y)^2 + (z_2-z)^2 = r2 \quad (2)$$
$$(x_3-x)^2 + (y_3-y)^2 + (z_3-z)^2 = r3 \quad (3)$$

The trilateration approach may not provide very accurate results because obtaining the distance value from the RSSI values is difficult. Indoor radio signal propagation is very complicated because of signal attenuation due to distance, penetration losses through walls and floors, and the effect of multipath propagation. Interference from other signals is also a problem. 802.11b uses the same frequency band as that used by microwave ovens, cordless phones, and Bluetooth devices. Any device that operates in the 2.4GHz frequency band can be a source of interference. Furthermore, the orientation of the receiver's antenna and the location and movement of people inside the building can affect the RSSI significantly. It is extremely difficult to build a sufficiently good general model of signal propagation that coincides with the real-world situation [6].

B. *Fingerprinting*

A fingerprinting method to determine location uses RSSI values to estimate the location of a smart device. Fingerprinting is a unique method because instead of leveraging the incoming RSSI values to calculate the position, it uses stored AP and RSSI information to estimate the user's location based on the current RSSI values.

The location fingerprinting consists of two phases: 'training' and 'positioning.' The objective of the training phase is to build a fingerprint database. To generate a database, reference points (RPs) must first be carefully selected. A mobile user moves to a known and chosen RP location and all the RSSI values from each AP are measured. This measurement is stored in the database. This process is repeated at another RP and so forth until all RPs are visited.

In the positioning phase, the smart device measures the RSSI at a place where it requires its position. The measurements are compared with the data in the database using an appropriate search/matching algorithm. The outcome is the likeliest location of the smart device [6].

To visualize this process, Fig. 3 shows a small area which contains twenty two APs. Each blue dot represents a location where RSSI measurements are taken and stored in the database. The beauty of this method is that it avoids the requirement of developing an RF signal propagation model. It side-steps this by just using it as is. The weakness of this method is that it requires a significant amount of time during the offline, or training stage. Additionally, if the indoor environment changes, with the moving of machinery, large furniture, and other objects, the accuracy could suffer, and a new training stage may be required.

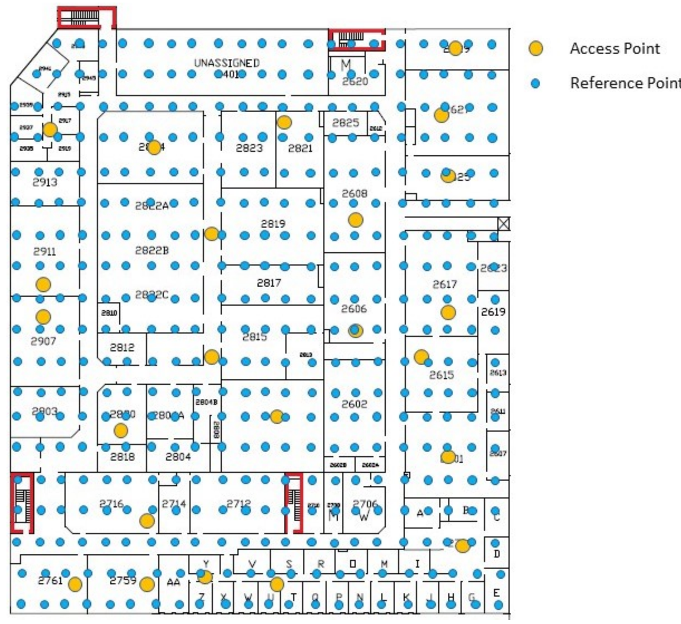

Fig 3. Wi-Fi Fingerprinting Reference Point Selection. Similar to approach presented in [6].

C. *K-nearest-neighbor*

The K-nearest-neighbor (KNN) algorithm is often used in conjunction with fingerprinting. The KNN algorithm is a tool that entails selecting the nearest K neighbors around a device to determine its own position [7]. For a Wi-Fi RSSI implementation, the K-nearest-neighbors are selected based on the RSSI values. The largest RSSI values are chosen. The K value is selected based on the indoor environment. Some algorithms, like the one proposed by [7], enhance the KNN algorithm by dynamically selecting the appropriate value of K. Many implementations of KNN use weights to improve the influence of close neighbors, these algorithms are called weighted K-nearest-neighbor (WKNN). This positioning technique was selected for prototyping at Kettering University's campus. The details will be provided in another conference paper.

IV. GEOMAGNETIC

The geomagnetic positioning system is based on the Earth's magnetic field. Each building has a unique magnetic landscape through the steel and other magnetic materials used in its construction. A smart device with a compass (built in) can utilize the magnetic field inside the building to pinpoint the smart devices location.

This technology relies on magnetic interference. Each building has a unique magnetic footprint with pillars, doors, elevators, or other steel structures. Like fingerprinting, this type of positioning system requires an online and offline phase. In the offline phase or training phase, these unique footprints are identified, and then stored, including the (x, y) location, in a database for reference. In the online phase, when these landmarks are located, the mobile application can look up the landmark and estimate the user's position [1].

Key Characteristics:

1. Position Accuracy: 1m - 2m
2. No new infrastructure needed in steel/concrete reinforced buildings
3. Minimal maintenance

V. VISUAL LIGHT COMMUNICATION (VLC)

A visual light communication (VLC) technology based indoor positioning system functions by a custom install of lighting apparatus in the desired indoor location. Each lighting fixture can emit information that a smart device's camera can detect. The LEDs modulate their signals in frequency to broadcast the information. The phone, through a mobile application, can identify the modulating LEDs and demodulate the signal to receive the information.

One system implementation could have the lights broadcast a specific identifier. From the light identifier, a mobile application with location data already installed could calculate the position based on the light ID. In other systems, 3D coordinates are emitted. Based on the broadcasted 3D coordinates of the LED and 2D coordinates of the image from the phone's camera, the position of the mobile device can be determined [2].

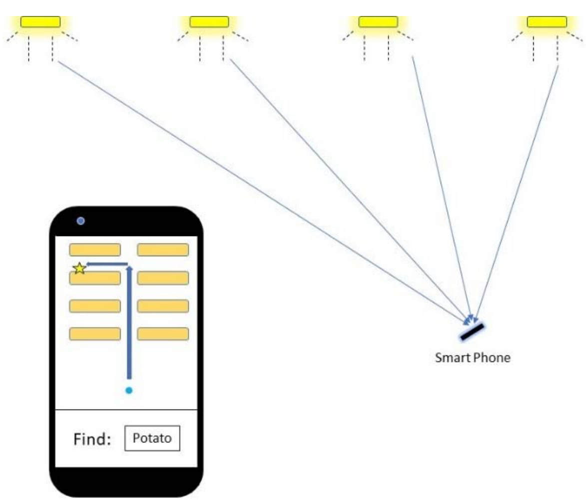

Fig. 4: VLC IPS High-Level explanation.

VLC technology requires lighting infrastructure that emits information. Either an identifier that can be referenced in the mobile application or a 3D coordinate of the light itself. This technology also requires the smart device has a self-facing camera that is always pointed upwards to capture the lighting information.

Key Characteristics:

1. Position Accuracy: < 1m
2. Requires custom LED fixtures

VI. ULTRA-WIDEBAND (UW)

Ultra-wideband technology can be used to drive an indoor positioning system similar to a BLE beacon solution. The two technologies both use trilateration from three or more sources to calculate a module's position. The difference in technologies comes from how the location information is gathered. With ultra-wideband technology, infrastructure called anchors need to be installed as reference points. At least three anchors are needed to describe a two-dimensional coordinate system for positioning. For three-dimensional positioning, four anchors are needed. In addition to these anchors, one must have a tag or target module for communication with the anchors. This is the 'smart device' in the previously described technologies.

Each anchor module uses radio waves to connect to the moving target module. These radio waves are in frequencies ranging from 3.1 to 10.6GHz with communication bands at widths of 500MHz each. The distance between the anchors and the tag modules is calculated using the time of flight (TOF). It measures the time light takes to reach the target module from the anchor and divides by the speed of light to obtain the distance. Once the distance to three or more sources has been calculated, the position of the device can be calculated through trilateration [3].

Key Characteristics:

1. Position Accuracy: 10 - 30 cm
2. Range: 100m in clear line-of-sight, loses range in indoor environments with obstructions
3. Anchor modules for emitting radio waves (3+ every ~30m)
4. Module to track position of (cannot use typical smart device)
5. Batteries to be changed every 1-5 years
6. No interference in ISM bands (Wi-Fi, Bluetooth, etc.)

VII. WEARABLE SENSORS

The previously evaluated technologies are completely dependent on the IPS infrastructure. The target device must interact with the IPS infrastructure to estimate its location. This dependency can be problematic if the IPS beacon sources are unreliable in portions of the indoor environment. Wearable sensors can be included in the position estimation to reduce this dependency and improve the position accuracy. From a known reference point, wearable sensors, such as inertial measurement units (IMUs), can be used to estimate the location of the target device. This estimation is independent of the IPS infrastructure. In [8], IMUs are proposed to be used in conjunction with GPS signals to provide a reliable location when GPS signals are no longer available. This dead-reckoning concept can be applied with an IPS to improve the accuracy and dependability of the location estimation.

Modern IMUs are found within your average smart phone. This typically consists of a 3-axis accelerometer, a gyroscope and potentially a magnetometer. Integrating the translational acceleration over time will produce the target device's velocity. Integrating the velocity over time will produce the target device's position. A position estimate of where the user is with respect to an initial reference point can be generated using dead reckoning [8].

VIII. COMPARISON OF THE DIFFERENT IPS FOR KETTERING UNIVERSITY

The goals or needs of an IPS at Kettering University include:

- Scalability
- Accuracy within 5m
- Low Cost

A. *Criteria for evaluating effectiveness of technology*

The criteria used to evaluate the effectiveness of technology is as follows:

1. Features offered
    a. What does the technology offer? Accuracy, scalability, etc.
2. Deployment cost
    a. How much will it take to get this technology implemented?
        i. Can we utilize existing infrastructure?
3. Run-time maintenance
    a. How much will it take to maintain this technology?
        i. Battery Life - How often will batteries need to be changed?

B. *Technologies Comparison*

Table 1 displays an overview of features for the infrastructure based IPS technologies. This gives you a quick reference for ruling out technologies that do not meet your criteria.

Table 1: IPS Technology Comparison

Technology	Accuracy	Scalability	Deployment cost	Battery Lifetime
Wi-Fi	5-15 m	High	Low	NA
BLE	1-3 m	Medium	Medium	High
VLC	< 50 cm	Low	High	NA
UWB	< 30 cm	Low	High	Low
Geomagnetic	1-2 m	High	Medium	NA

Wi-Fi offers a low deployment cost. A Wi-Fi IPS can be implemented using the already existing access points within a building. There are no infrastructure costs. Likewise, scaling the system requires no additional infrastructure if access points are present. Additionally, since access points are supplied power from the building, there are no maintenance costs associated with batteries. The main drawback is the accuracy error which is at a minimum of 5m.

A BLE beacon system with a high density of beacons offers an accuracy that meets our goal. The deployment cost is the purchasing of enough beacons to cover the entire indoor area. At every point location information is required, three or more beacons must be broadcasting to the area. Beacons are required every 7m – 10m, for the ECE department area, this requires at least 70 beacons. To keep maintenance costs down and to ensure accuracy, a high-end beacon is desired. This costs around $20 per beacon. This means it will be roughly $1500 just for initial deployment. Scaling the system requires more infrastructure, roughly every 800 square feet requires an additional beacon.

VLC technology offers the accuracy needed but is not scalable nor low cost. A VLC system would require replacing all the lighting in the target area with custom LED fixtures. Such an excessive cost is not practical for Kettering University.

Likewise, UWB technology offers the accuracy required but not the scalability nor cost. In addition to this, UWB technology does not integrate easily with a typical smart device. Without the ability to use a modern smart device as the location reference, this technology is not feasible to implement as a navigational aid for our University.

Geomagnetic technology is a new method of indoor positioning. Based on the numbers provided by IndoorAtlas, this technology meets the accuracy requirement. However, the methodology of geomagnetic technology was largely proprietary and there were not many academic papers to reference at the time the research was conducted. Due to the limited scope and resources of this project, this technology was not pursued for prototyping.

IX. CONCLUSION

UWB and VLC systems are simply too costly for implementation. Geomagnetic technology is largely proprietary and would be too difficult to develop. This leaves Wi-Fi or BLE. BLE offers everything needed but at a cost of initial infrastructure and maintenance, while Wi-Fi falls a little short on the desired accuracy, it was found to be an attractive solution for our implementation. Since Wi-Fi access points are already available there is no installation costs and the system is easily scalable to cover larger areas as the project grows. The implementation details of the Wi-Fi based localization and its Android App development will be presented in another paper.

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