Indoor Positioning Technology Assessment using Analytic Hierarchy Process for Pedestrian Navigation Services

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Abstract—**Indoor positioning is one of the biggest challenges of many Location Based Services (LBS), especially if the target users are pedestrians, who spend most of their time in roofed areas such as houses, offices, airports, shopping centres and in general indoors. Providing pedestrians with accurate, reliable, cheap, low power consuming and continuously available positional data inside the buildings (i.e. indoors) where GNSS signals are not usually available is difficult. Several positioning technologies can be applied as stand-alone indoor positioning technologies. They include Wireless Local Area Networks (WLAN), Bluetooth Low Energy (BLE), Ultra-Wideband (UWB), Radio Frequency Identification (RFID), Tactile Floor (TF), Ultra Sound (US) and High Sensitivity GNSS (HSGNSS). This paper evaluates the practicality and fitness-to-the-purpose of pedestrian navigation for these stand-alone positioning technologies to identify the best one for the purpose of indoor pedestrian navigation. In this regard, the most important criteria defining a suitable positioning service for pedestrian navigation are identified and prioritised. They include accuracy, availability, cost, power consumption and privacy. Each technology is evaluated according to each criterion using Analytic Hierarchy Process (AHP) and finally the combination of all weighted criteria and technologies are processed to identify the most suitable solution.**

Keywords- Indoor Positioning; Pedestrian Navigation; Analytic Hierarchy Process (AHP)

I. INTRODUCTION

Indoor Location Based Services market is growing rapidly, however it is still in its infancy in comparison with other applications and segments of LBS. Although people spend most of their time in their homes, offices and in general indoors, the indoor LBS generates less than 25% of LBS revenue [1]. This is because there are many challenges and issues still remaining; one of the most important challenges of indoor LBS is availability of seamless (indoor and outdoor), accurate, cheap, privacy preserving and low power consuming positioning service.

This paper focuses on analysing positional requirements of pedestrian navigation services, as one of the most demanding and challenging applications of LBS. This paper uses the Analytic Hierarchy Process (AHP) [2] to select the most appropriate technology among currently available stand-alone positioning technologies according to identified positional requirements for pedestrian navigation.

Pedestrian navigation faces several unique challenges due to the higher degree of freedom of movement for pedestrians, in comparison with vehicle drivers or cyclists; pedestrians are not restricted to move on the roads where Global Navigation Satellite Systems (GNSS) signals are generally available and can, for example, go through buildings to get their destinations. GNSS is the most widely used positioning service for outdoors, however when it comes to indoors selecting the best positioning technology is a big challenge.

There are many positioning technologies that can be adopted for indoor scenarios, however each have their advantages and shortages. Each application has its own positioning requirement, quality of service priorities. For a specific LBS application, availability, cost, power consumption, accuracy, privacy, required infrastructure, device modifications, can be considered for choosing each technology over the others. This paper provides a framework, based on AHP for selecting the most suitable positioning technology that can function stand alone for indoor pedestrian navigation services. Pedestrian navigation has been chosen due to its unique challenges and requirements despite its wide use.

The AHP is a powerful tool for systematic multi-criteria decision making, which considers both technical (such as accuracy and power consumption) and non-technical factors (such as privacy and cost). AHP helps to evaluate each positioning technology from identified criteria point of view and select the most suitable technology for the purpose of indoor pedestrian navigation. These standalone positioning technologies include HSGNSS, WLAN, BLE, UWB, RFID, US and TF.

Over the following section, several indoor positioning technologies are reviewed and compared based on their accuracy, coverage, cost and power consumption level. In total, eight stand-alone positioning technologies have been considered by this paper which can be applied independently (from users' point of view) for the purpose of pedestrian

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navigation. Section three explains the positioning requirements for pedestrian navigation, and enumerates the challenges and potential solutions. Afterwards, a discussion is made on the parameters and factors that users may consider to choose and prioritise one positioning technology over the others. These parameters include accuracy, battery consumption, coverage and availability, cost and privacy. Finally using AHP the best positioning technology according to the factors and their importance/weight is selected.

II. STAND-ALONE POSITIONING TECHNOLOGIES

While there are several positioning technologies available and currently reported in the literature for indoor positioning, they differ in several aspects, i.e. accuracy, availability, power consumption, cost and privacy. This makes it difficult to choose the best positioning technology for specific purpose among the others. Some of the most popular technologies, which can provide position independently, have been considered for this study. These standalone positioning technologies are HSGNSS, BLE, RFID, WLAN, UWB, US and TF. The following subsections provide a brief description for each of them, describing some of the above-mentioned aspects.

A. High-Sensitivity GNSS (HSGNSS)

High Sensitivity GNSS receivers are able to synchronise with heavily attenuated GPS signals. The sensitivity can reach down to -190 dBW. This enables the receiver to work indoors where the GNSS signal strengths are approximately -176 dBW. Building materials attenuate the GNSS signals. The reported positioning accuracy for brick buildings is approximately 10 meters. This is affected by the current satellite constellation. The receiver module cost ranges from few euros to hundred euros depending on the features the module offers. [14]

B. Bluetooth Low Energy (BLE)

Bluetooth low energy (BLE), also known as Bluetooth Smart, is a version of Bluetooth meant for low power applications. Its power efficiency allows some of these applications to operate in a continuous manner for extended periods of several months [3]–[5]. Due to its power efficiency and low cost, BLE is being deployed in several tags or beacons throughout the environment, in order to offer a more accurate indoor positioning solution [4]–[7]. A shorter operation range allows for a proximity based positioning, providing a better performance regarding the estimated position error. The specification does not set an upper limit for the BLE range of operation, but the manufacturer can optimise it for ranges above 60 m [3].

C. Wireless Local Area Networks (WLAN)

With the popularity of mobile computing devices such as laptops, tablets and smartphones, Wireless Local Area Networks (WLAN) can, nowadays, be found in most public and office spaces [8]. The massive infrastructure present in these spaces has contributed to the use of this technology for positioning and navigation purposes. Fingerprinting is one of the most common approaches to benefit from the increasing usage of these devices [9]. In fingerprinting, the received signal strengths at a certain point are matched to the ones present in a geo-coded database. This matching is not ideal due to channel effects, such as multipath and shadowing, which introduce a high variability in the observed received signal strength. For this reason, the estimated position error is usually found to be of a few metres, depending on the density of the WLAN network [8], [10], [11].

D. Ultra-wideband (UWB)

Ultra-wideband (UWB) ranging signals achieve a time resolution of nanoseconds. In comparison with Wi-Fi or Bluetooth the time of arrival measurements are more feasible with UWB technology. In signal strength or angle of arrival approaches, the benefit of high bandwidth is not fully exploited. Moreover, the multipath components are easier to detect and resolve within a UWB system [12], [13], [14].

E. Radio Frequency Identification (RFID)

RFID system consists of RFID readers and transceivers or tags. In the active approach, the user carries the reader and scans the tags in the environment. The reach of an active RFID interrogator and transponder system is approximately 30 m. In passive approach the user carries the tag and the environment has readers setup for positioning. The passive RFID detection range is very short (approximately 2 m) and in practice a stand-alone passive system would be costly to set up. Privacy is of concern especially in passive RFID tag systems where the computation capability of the tag can't support necessary cryptographic data protection. [15]–[19]

F. Ultra – Sound (US)

Centimetre level positioning is possible using ultrasound. The relatively slow speed of ultrasonic waves makes it feasible to use time of arrival measurements. The reach of an off the shelf ultrasound transceiver is approximately 10 m. Additionally, the noise components in the environment and the changing multipath component makes this technology more susceptible to errors [20], [21].

G. Tactile Floor (TF)

Smart floor concept offers a passive way for positioning indoors. The floor has sensing elements covered throughout the building. Pressure, force or capacitive sensors discern the presence of the person on top of the tile. The identification of the person is challenging. It is troublesome for the floor setup to distinguish correct users by itself without any additional information. Weight or capacitance difference can be used for approximate identification estimation. The resolution of the floor depends on the density of the sensing nodes. The infrastructure cost becomes very high the larger the space is. The smart floor system could send the location information to the identified user through local WLAN infrastructure [14], [22].

III. USE OF ANALYTIC HIERARCHY PROCESS FOR POSITIONING TECHNOLOGY SELECTION

Analytic Hierarchy Process (AHP) is one of the Multi Criteria Decision Making (MCDM) processes, which derives ratio scales from paired comparisons between criteria and factors [2]. AHP can systematically help decision makers to select between choices based on criteria and factors, which can represent priorities and preferences. One of the most valuable aspects of AHP is the flexibility to consider both quantitative and qualitative parameters and factors to prioritise the choices [2]. This enables decision makers to include almost any kind of criterion, from wide range of natures, allowing AHP to be practically applied in many real-world decision-making problems. In addition, AHP can accept human inconsistencies in judgments. AHP is based on pairwise comparisons, ideally done by experts.

The AHP has been applied to a wide range of problem situations, however one of the most widely used applications of AHP is selecting among competing alternatives in a multi-objective environment. It is based on the well-defined mathematical structure of consistent matrices and their associated right-Eigen vector's ability to generate true or approximate weights [2]. To do so, AHP methodology includes comparisons of objectives and alternatives in a natural, pairwise manner. The AHP converts individual preferences into ratio-scale weights that are combined into linear additive weights for the associated alternatives. These resultant weights are used to rank the alternatives and, thus, assist the decision maker (DM) in making a choice or forecasting an outcome.

This paper applies AHP to select the best stand-alone positioning technology for the purpose of pedestrian navigation. As it was explained previously, this paper considers eight possible positioning technologies for the purpose of pedestrian navigation, more specifically; HSGNSS, WLAN, BLE, TF, US, UWB and RFID passive and active.

In order to select the most suitable positioning technology among the above-mentioned technologies, the selection criteria are first set. According to a user-survey [23], [24] the most important factors to evaluate quality of positioning service, from users' point of view, are accuracy, availability and coverage, cost, power consumption and privacy. Therefore, this paper considers the same set of parameters to compare and evaluates the positioning technologies from the users' point of view. It is important to bear in mind that these criteria are from user side; this means this paper is interested in accuracy, availability, power consumption, and cost of the positioning service for users rather than infrastructure developers. From this point of view, cost of GNSS is pretty low as the chipset embedded in the mobile phones are cheap while billions of euros spent on development, deployments and maintenance of satellites are ignored, as users do not pay for them directly. If the process of calculations is being done on server side and the response is sent to users then it is likely to have a lower value for power consumption while it might require a supercomputer to provide the positioning solution.

In order to compare the importance of the five criteria, i.e. accuracy, availability, cost, power consumption and privacy, it is possible to pair-wisely compare them through two approaches. Each approach can be sufficient for choice selection applications. The first approach is to ask experts to fill out pairwise comparisons tables. These tables are filled with numbers in the range of 1-10 to express the importance of each parameter over the other ones. The lowest number (1) shows the equality of the choices and the highest (10) shows the extreme priority/importance of one over the other. Therefore, the values in Table I represent how superior the criteria on the left is, in comparison to the one on the right. For example, Taking the accuracy against availability in the first line, the 1/3 means that the value 1 was given to accuracy and 3 to availability, meaning that availability is 3 times more important for the user than accuracy. The study uses as expert opinion the discussion among the authors and all the tables considered are provided in [25] [23]. The second approach is to use the survey's results [24] to fill out the table. Users are not experts, however if large numbers of survey participants' responses are considered, the table inconsistency is at expert level (*i.e*. below 10%), see Table I.

When it comes to the second level comparison, *i.e*. choices pair-wise comparison from criteria point of view, in addition to experts and users, it is possible to use a more experiment-based approach. This approach is based on reviewed papers and reports on level of accuracy and availability, battery consumption and cost of each sensor and level of privacy preserving by the service, for each or some of stand-alone positioning technologies. The result of this literature review is summarised in table II. Using this table it is easier and more factual to compare positioning technologies to each other from different perspective. For example, according to Table III cost of GNSS high sensitivity antennas are ten times more than BLE and UWB.

TABLE I. PAIR-WISE COMPARISON MATRIX (CRITERIA)

Criteria	Accuracy	Availability	Cost	Power Consumption	Privacy
Accuracy	1	$1/3$	$1/5$	1	3
Availability	3	1	2	2	5
Cost	5	$1/2$	1	2	4
Power Consumption	1	$1/2$	$1/5$	1	3
Privacy	$1/3$	$1/5$	$1/4$	$1/3$	1

As expected, the consistency ratio of the pairwise comparison matrices are below 10% (expert level inconsistency level) because the numbers assigned to each technology are based on experiments and implemented system benchmarking rather than human judgements, which suffer from inconsistency. For example the consistency ratio for the pairwise comparison between positioning technologies from accuracy perspective matrix, is 2%. The consistency ratio for availability, power consumption, cost and privacy are 5%, 1.5%, 4.5% and 15.9%, respectively. As it can be noticed, the consistency ratio for privacy is above 10%, due to the subjective and abstract nature of privacy, which needs human judgment to quantify it. This matrix has been moderated according to experts' comments and got to the inconsistency ratio of 7.1%.

Using all the pairwise matrices, *i.e.* one matrix to compare criteria and five matrices to compare positioning technologies from criteria point of view it is possible to do the final step, which is priority/weight calculation.

Using AHP for each matrix a ranking list is generated. Followings are the results of calculations for each matrix:

- For the purpose of pedestrian navigation, according to the criteria pairwise comparison matrix (with consistency ration of 1.5% and eigenvalue of 5.067) the importance of sorted as follow: availability (38.3%), cost (25.5%), power consumption (15.8%), accuracy (14.5%) and privacy (5.9%). These values can generate the criteria priority vector (1).
- From the accuracy perspective the positioning technologies are prioritised (with consistency ratio of 2% and principal eigenvalue of 8.201) as RFID passive (18.3%), tactile floor (18.2%), UWB (16.7%), US (16.7%), RFID active (12.7%), BLE (10.2%), WLAN (5.1%) and HSGNSS (2.1%).
- From the coverage (availability) point of view, technologies are ranked (with consistency ratio of 5% and principal eigenvalue of 8.490) as RFID active (21.7%), WLAN (22.8%), US (10%), UWB (10.2%), RFID passive (7%), tactile floor (4.4%) and HSGNSS (2.2%).
- From the power saving perspective (users devices) with consistency ration of 1.5% and principal eigenvalue of 8.142 the positioning technologies are prioritised as follows: RFID passive (18.8%), tactile floor (18.8%), BLE (17.9%), US (15.7%), HSGNSS (10.6%), RFID active (7.5%), UWB (7.3%) and WLAN (3.3%).
- According to the low cost matrix values, the positioning technologies are ranked as: UWB (18%), tactile floor (16.7%), RFID passive (16.3%), BLE (15.5%), US (15.3%), WLAN (12.1%), HSGNSS (4%), RFID active (2.1%).
- From the privacy point of view, technologies are weighted as HSGNSS (33.8%), UWB (12.5%), BLE (12.5%), US (11.3%), WLAN (11.3%), RFID active (8.4%), tactile floor (6.1%) and RFID passive (4.2%).

Priorities of each positioning technologies from different criteria perspective can be summarised in a technology priority matrix (Table II).

$$\text{Criteria Priority Vector} \equiv \begin{bmatrix} \text{Accuracy} \\ \text{Availability} \\ \text{Power Consumption} \\ \text{Cost} \\ \text{Privacy} \end{bmatrix} = \begin{bmatrix} 14.5 \\ 38.3 \\ 15.8 \\ 25.5 \\ 5.9 \end{bmatrix} \quad (1)$$

TABLE II. TECHNOLOGY PRIORITY MATRIX

	Accuracy	Availability	Power	Cost	Privacy
HSGNSS	2.1	2.2	10.6	4	33.8
WLAN	5.1	22.8	3.3	12.1	11.3
BLE	10.2	21.7	17.9	15.5	12.5
US	16.7	10	15.7	15.3	11.3
UWB	16.7	10.2	7.3	18	12.5
RFID Passive	18.3	7	18.8	16.3	4.2
RFID Active	12.7	21.7	7.5	2.1	8.4
TF	18.2	4.4	18.8	16.7	6.1

Now it is possible to prioritise each technology based on the weight of each criterion and their corresponding priority value. The priority of technologies can be calculated using criteria priority vector and technology priority matrix as given by,

$$\begin{aligned} &\mathit{Technology\ Priority\ Vector} \\ &= \mathit{Technology\ Priority\ Matrix}_{8\times 5} \\ &\times \mathit{Criteria\ Priority\ Vector}_{5\times 1} \end{aligned} \quad (2)$$

This translates as:

Priority of each technology = (importance of accuracy * priority of the technology from accuracy perspective) + (importance of availability * priority of the technology from availability perspective) + (importance of cost * priority of the technology from cost perspective) + (importance of power saving * priority of the technology from power saving perspective) + (importance of privacy * priority of the technology from privacy perspective)

As final results, the most suitable stand-alone indoor positioning technologies for the purpose of pedestrian navigation are ranked as illustrated in Table IV.

The technology pairwise comparison matrices are filled out based on reviewed papers and practical experiments; the high consistency ratio confirms this as well. The criteria pairwise comparison matrix is mainly based on expert and also LBS users' opinion [23], [24]. However the result of analysis shows more suitability of BLE and WLAN for indoor positioning of pedestrians, very low priority value of all technologies shows that stand-alone positioning technologies may not be a good answer for pedestrian navigation applications.

TABLE III. POSITIONING TECHNOLOGIES' FEATURES

Positioning Technology	Accuracy	Coverage	Battery Consumption	Device Cost	Privacy
High Sensitivity GNSS receiver	~10 m (inside a brick house)	Satellite constellation dependent (value ~2 m used for comparison)	u-Blox Lea-5H 135 mW	~100 £	High
WLAN	~4 m	~30 m around access point indoors	WSN802GX 3.3 V*200 mA ~700 mW	~50 £	Medium
BLE Fingerprinting	~2m (Robust Beacon Placement)	~30m around beacon indoors	nRF51882 3V*10m ~30mW	~10 £	Medium
UWB Timing	~15 cm	~10 m	Transceiver (19) ~500mW	~10 £ active tag	Medium
RFID active	~2 m	~30 m	i-CARD CF350 interrogator ~250mW	~300 £	Medium
RFID passive	~15cm	~2m	Very small	~1 £	Low
US Timing	~2 cm	~5 m a beacon	HC-SR04 5V*15mA ~100mW	~10 £	Medium
Tactile Floor	~1 cm	Implemented Floor (value ~2m used for comparison)	very small	~1 £	Low

The priority values are all below 20% and more disappointingly they are mainly around 12%, which is the random priority value for 8 choices. AHP has shown that pedestrian navigation requirements (expressed by users and approved by experts) cannot be satisfied by any of currently available stand-alone positioning technologies and another solution may need to apply. This can be a multi-sensor solution or an upcoming sensor that this paper could not assess due to lack of evidence.

TABLE IV. POSITIONING TECHNOLOGIES' SUITABILITY RANKING

Rank	Positioning Technology	Suitability
1	Bluetooth Low Energy (BLE)	17.27%
2	Wireless Local Area Networks (WLAN)	13.75%
3	Ultra-Sound (US)	13.3%
4	Ultra-wideband (UWB)	12.81%
5	RFID Passive	12.71%
6	RFID active	12.37%
7	Tactile Floor	11.91%
8	High-Sensitivity GNSS	5.23%

IV. CONCLUSIONS

One of the biggest challenges for many LBS applications is calculating position of users in roofed areas where GNSS signals are generally not available. It becomes a major issue particularly for the purpose of pedestrian navigation as the target users, *i.e*. pedestrians spend most of their time indoors. This paper aims to identify the most suitable stand-alone positioning technology from the considered technologies; *i.e.* HSGNSS, BLE, WLAN, UWB, US, TF and RFID.

The paper identifies which of these technologies can address most of requirements of pedestrian navigation services. Firstly, the positioning requirements for pedestrian navigation service are identified. To do so, the opinion of users and authors are considered and used to calculate the importance/priority value of each criterion using Analytic Hierarchy Process (AHP). Then positioning technologies are evaluated from each criteria point of view and finally the priorities of all choices are calculated using AHP.

The result of analysis shows that the top two suitable positioning technologies among all stand-alone technologies are BLE (17.27%) and WLAN (13.75%). However the very low priority value of all technologies, *i.e*. all below 20% and mostly around 12% which is likelihood of randomly selecting one of these technologies. This shows that stand-alone positioning technologies cannot address the positioning requirements for pedestrian navigation. Other solutions, such as multi-sensor fusion or novel positioning technologies are still required.

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