Indoor SLAM based on crowdsourced data with multiple smartphone sensors

Master Thesis

by

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Master Program in Space and Engineering Systems

Supervisor

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Abstract

We perform this research to create an indoor positioning system with special features. The objective of this research is to develop all algorithms needed to obtain these features. The specified context states that no GPS data are available at hand, which makes the use of common navigation services impossible.

For human navigation in buildings the common approach is to use smartphones as a tracking device. We add a magnetic sensor to this model. We develop the algorithms magnetometer data fusion and mapping with given sensor.

We develop a simulation tool for estimation the accuracy of algorithm performance and visualization purposes. We generate all observations with observation and motion model. Using probabilistic approach with particle filter we reconstruct true map and poses from noisy input data.

We propose a recursive map reconstruction procedure from noisy filtered data based on graph matching and hierarchical clustering.

We support the choice of technology and algorithm specifications with a technological roadmap.

The innovation of this research is in ability to provide same navigation services with less information and in more natural way, which means also the reduced cost of the system overall.

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Chapter 1

Introduction

Let me introduce to the topic of my Masters work at Skolkovo Institute of Science and Technology (SK).

The project topic is related to the problem of human indoor navigation and positioning. The specified context states that no GPS data are available at hand, which makes the use of common navigation services impossible.

Most of existing indoor navigation systems require a special mapping stage. This is due to the reason we need to have a map for localization. A map usually consists of observations with recorded locations being organized in a special way.

Novel position systems can utilize the data recorded from users. This is called the crowd-source approach in positioning systems design. This approach makes the data collection cheaper and faster by orders. This allows to create a maps of public buildings and other locations, similar to Google maps or other products. These maps data are available online and several companies are working on this data collection specifically.

For real-time indoor navigation, in conditions where is no initial data is available, we have to perform multiple stages of localization and mapping. This can also be done simultaneously in SLAM approach.
We aim to utilize both SLAM and crowd-source approaches for the best performance of positioning system.

The innovation of this research is in ability to provide same navigation services with less information and in more natural way, which means also the reduced cost of the system overall. Given paper focuses on implementation the data from magnetic field to localization and mapping framework. This technology choice is supported with additional technological research materials.

Motivation

Indoor navigation is a market solving different problems with logistics inside buildings. The problem is important because more than 90% of time people usually spend inside the buildings [21].

Time spent for logistics such as path choice, search for special places / people can't be measured, but we will agree that it's a wasted time.

Hundreds different applications, dozens of existing technologies, and no really perfect and universal solution. By word perfect we assume comparing to GPS - global, universal, precise enough for usual tasks, stable and free to people.

Existing technologies such as WiFi localization and others will be covered where possible, but the focus of paper is mostly on Indoor positioning as a product it should be: product with price, business plan, technology inside and with the need from customers.

Understanding the technology doesn't bring us to the product. There are different researches of positioning technologies[14, 18, 10, 3]. We have a vision of the product that is based on human localization in buildings. To develop this product we have to choose technology, methods, hardware and software if needed. This part is covered specifically in Section 3.

Terminology

IPS - indoor positioning system

RTLS - reat-time location service

BLE - bluetooth low energy

1.1 Thesis Structure

Chapter 2 - Background The literature review and common concepts of the problem scope. Evaluation of current state-of-the-art approaches and technologies.

Chapter 3 - Techonogical research. Technological roadmap states various possible solutions to human indoor positioning problem.

We develop a model for taking decision of technology / product choice; understanding physical limits. We highlight the landscape of related technologies. We use this model for technology choice and for the problem statement.

Chapter 4 - Thesis Objectives We define the objectives of our work. Hypotheses we test and a system requirements.

Chapter 5 - Methodology Methodology and ideas behind the research. Algorithms and experiments explained.

Chapter 6 - Conclusion Conclusion on our results we obtained.

Chapter 2

Background

2.1 General problem / Introduction / Background

2.2 Related work

We review the field of human indoor localization. We focus on crowd-source mapping, or mapping with limited sensor model (limited to existing infrastructure in building space and to sensors in human smartphones). In this field there are many approaches so solve the sub-problems or parts of given problem.

For the positioning technologies comparison, we may refer to the paper of [12] which provides evaluation and comparison of different indoor location technologies and covers the almost most important of them.

While the information about technologies itself is more or less clear. What performance we can reach with given technology? What is the best approach to work with the given technology?

The answer to some questions is simple. The best accuracy is achieved with the biggest database and computational power. But for realistic implementation this is not good enough. The similar approach is to merge all information available in current location and time. The problem again is that how to localize when there is no information available at the current state. The answer is to use the correspondences between previous and future information, to reconstruct the current information. This formulation can be related to the classical SLAM formulation, even if some parts are different.

Different from existing work, we want to re-estimate or post-process all distance and orientations after measurements with information about previous steps are collected. This is called the loop closure process in SLAM literature [16, 5]. In fingerprinting literature, there is low number of researches working with re-localization and loop closures. We have to recursively post-process existing data, which has to give us better localization during mapping, and thus better map for future localization.

If magnetic map is not given, the model training can be done by manually collection measurements and marking the locations by special trainers, then the localization model can be generated.

Why magnetic field localization is not a SLAM? SLAM techniques build a map of an unknown environment and localize the sensor in the map with a strong focus on real-time operation [16]. With magnetic field localization, in every new point we obtain only local information, which is not enough for real-time operation. The difference between camera-based and magnetic fingerprints based localization is significant. Because of this fact, magnetic field localization can't operate independently in unknown conditions and can't be considered as SLAM. Nevertheless, we may introduce special aspects of SLAM system to magnetic field localization for better robustness.

The usual camera-based SLAM has the ability to automatically close loops, which means the correction of the accumulated error in exploration after we detect the sensor has returned to a mapped area.

During mapping stage of magnetic field localization, we are constantly accumulating error.
We have no tools for error correction because IMU and magnetic field provide both only relative information, and for error correction we need a prior spatial information.
The prior information can be collected from other sensors (e.g. beacons, such as WiFi and BLE beacons), information can be human input of location, the prior location can be obtained with camera based place recognition. The most interesting approach is to utilize the information we have in our conditions: previous measurements from magnetic mapping.

It would be prefect to have loop closure features for robust magnetic field mapping. In practice this is almost never possible. Because of constant growing integration error and small amount of information from magnetic sensor, we have no possibility for conditioning until we mapped the region.

Luckily, conditioning on magnetic field is possible. Once we have a trajectories and observations somehow covering the region, we can try localize on this data. Using the recursive re-localization of existing data we can obtain better solution than initial one. This part of research is covered in Section 5.

Why does this even possible to use magnetic field information for localization? The magnetic field in buildings is changing near metal objects, conductive and big structures. In opposite to traditional idea of compass that is always directed to the north pole, now we have a compass that is slightly deviating. The idea of localization is that these compass deviations are repetitive in time and space. Once we reconstructed the magnetic map of the building, we can use these patterns later.

The magnetic field in buildings is changing with time. Even after measurements collected, it is important to update map sequentially. The updates can be done by collecting and processing localization data from all system users. This way we will have the latest data and the system will be more precise.

An interesting localization system was introduced in Maloc [23]: magnetic field based particle filter includes a dynamic step length estimation method. Human step length prediction can be introduced in the localization model, but this is only a part of information possible for given conditions.

Several researches states that the best performance is achieved in multi-sensor or hybrid localization steps. And for walking human localization we may consider a dynamic step length estimation method proposed in [23].

Filtering or global optimization (GraphSLAM)

We know the paper GraphSLAM based Crowd sourcing framework for indoor Wi-Fi fingerprinting[15]. The approach of GraphSLAM is promising. The reason for not using GraphSLAM with magnetic fields is only in complexity of system construction. We have to write a gradient descent problem and solve it with GraphSLAM. The problem is that there is no clear gradients in observation model of magnetic field so we can only use filtering methods.

The most promising results in terms of cheap sensor spatial information are magnetic maps. For magnetic fingerprinting there are well developed approaches.

One of well-known papers in magnetic fingerprinting is [7]. The authors present an approach for magnetic field mapping, in terms of not fingerprints, but a full grid mapping procedure. As a result of this mapping procedure we obtain a full filed image that is easy to work with. The problem with this approach that we have to collect full grid measurements, which is a time consuming procedure. We want to get magnetic field map without additional mapping procedure, this approach is called crowd-source mapping. We collect the data from a set of human travel trajectories. Then we merge them in single noised image (only analogy representation for better understanding), and apply optimization procedure. We require the resulting image be smooth, so the optimization constraints must be set to satisfy the image denoizing procedure. This is just our idea and assumption that is have to be proved in further research. We see some similarities here with [25].

However they are highly dependent(?? prove statement) on the data collection procedure. This algorithms also are not intended for standalone usage in terms of sensors fusion. E.g. requires either special mapping procedures or additional hardware devices - beacons.

There are few papers on magnetic and inertial based navigation. However they were not implemented in SLAM frameworks such as [24]. Some of frameworks are a part of commercial interest and are not open source.

The interesting map construction algorithm were proposed in [25].

The full system consists of three subsystems, i.e. Dead Reckoning Subsystem (DRS), Map Construction Subsystem (MCS), and Localization and Navigation Subsystem (LNS).

Our intuition gives that Dead Reckoning Subsystem performs sensor fusion and smoothing. The localization and navigation subsystem utilities the existing map and the output of smoothed sensors measurements.

The map construction process is an optimization problem with some constraints.

In [25], authors propose universal framework with no prior information of building map structure. But for real situation, the map of the building is known. We can define an indicator function similar to SLAM occupied cells mapping (????) With indicator function defined, we may fit the graph of trajectories to the building inner structure graph - topological map.

The similar approach with map constraints correction and re-sampling was shown in [22]. The paper utilizes a particle filter that combines PDR and RSSI data.

Chapter 3

Technological research

This section reports on modern indoor positioning system (IPS) technologies. There are hundreds of applications for IPS technology. IPS systems are usually based on smartphones (used as a tracking device) and we focus on this application.

Objectives:

- show the evolution of IPS technology
- perform or repeat the research of indoor positioning systems review to compare other IPS publications
- visualize IPS usage and work principles (different technologies, connections, FOMs, applications)
- create financial and technical models for different IPS technologies
- calculate the possible effect of merging different technologies for different applications
- calculate in FOMs / prices (novelty)
- connect different technologies into single model (where possible)
- create system / strategy for optimal* technology choice decision
- map / compare existing products and trends over defined figures of mer

3.0.1 Background / Context

[9]

Indoor navigation solutions is a wide range of products and services. While "indoor routing" functionality that guides people through the buildings is important, there are lots of services which support it, such as content management system, mobile and web applications, indoor and outdoor localization, social networks, data analytics and many others.

Why do we need indoor navigation and positioning? This is because of convenience of global Geo-services, and because of GPS reception problems inside buildings.

One of understandable example of such kind of products is a Google Maps, which are scaled to work inside the buildings.

The situation is much more complicated, the market of indoor positioning is resegmented - different applications from security applications and assets tracking in business and manufacturing to the proximity advertising in retail - from fully protected to broadcast solutions, from cheap high range proximity to high precision solutions in robotics. Indoor positioning systems is a growing industry with hundreds applications.

Different applications have different technologies behind it. Over 15-20 different working technologies is known, about 3-5 of them are widely used now (WiFi, Bluetooth Low Energy, Image Based).

[9]

In this paper, we present analysis of indoor positioning techniques.

Different technologies provide different positive sides and can be complementary to each other. Combination of complementary technologies can improve the total performance (ultra wide band communication uses a wider range of frequencies and thus have good signal strength and range and allow more precise positioning than single band solutions such as Bluetooth). The implementation process, usage cost and usage scenarios are different for each technologies.

Several technologies are developed to work on a different scales of the environment (local $<$ 1m accuracy, room level $<$ 2m accuracy, floor level 5-10m accuracy, etc.).

For the company developing the products, it is important to consider resources and productiveness. That's why, when we trying to bring product to the market, it's important to create strategy and consider resources we obtain. For this we may use models also.

3.0.2 General Objective

Indoor navigation is a market solving different problems with logistics inside buildings. The problem is important because more than 90% of time people usually spend inside the buildings[?].

Time spent for logistics such as path choice, search for special places/people can't be measured, but we will agree that it's a wasted time.

Hundreds different applications, dozens of existing technologies, and no really perfect and universal solution. By word perfect we assume comparing to GPS - global, universal, precise enough for usual tasks, stable and free to people.

Existing technologies such as WiFi localization and others will be covered where possible, but the focus of paper is mostly on Indoor positioning as a product it should be: product with price, business plan, technology inside and with the need from customers.

Understanding the technology doesn't bring us to the product. Indoor positioning applications is a high promising market, which has a lot of uncertainty behind it. First it is a multi-sided and resegmented market, that's why it can't be understood easily. Second, there are many promising technologies in this market which have different behavior. With this level of uncertainty it is important to have information which will allow us to make choice of technology and market segment.

There are several important points in this scientific area to assist in:

- Taking decision of technology / product choice - Understanding physical limits with a feasible model of technology - Understand Timeline and Market scenarios - Landscape of technology with literature and patent review

We have to define a strategy and calculate the future effect of applying this technology. This can be used as a base, for technological investments, product and services development. Although we can't make the optimal technology choice, the reasonable decision can be taken after mapping existing solutions on a single landscape. Benchmarking, patent and literature research, competitors positioning are also important to define right strategy.

Even knowing the filed in not enough,when we make strategy choice, we have to understand feasibility of this strategy, understand the cost and possible future performance. We can understand technical feasibility of possible future products using system models. In model we want to understand optimal figures of merits for the different possible strategies.

Existing solutions have a high level of complexity. Usually they use a combination of complementary technologies to cover gaps of specific tecnologies. We have to manage the complexity of technical solution with system model if possible. We know that understanding capabilities of each technology and their combination can provide better products and thus important.

3.1 Approach

First we define current state of the art, we build the model for existing technologies, analyze products on the market, list key players and IP owners, create Pareto frontier. This part is intended to make a visible and understandable landscape of this technology segment.

We use several tools for this: generate artificial intelligence patent classifier with cipher.ai platform, analyze annual market reports and roadmaps from companies [9], [20].

Figure 3-1: Patent keywords search highlighting cipher.ai platform

Patents search highlighting categories which were used to build the classifier.

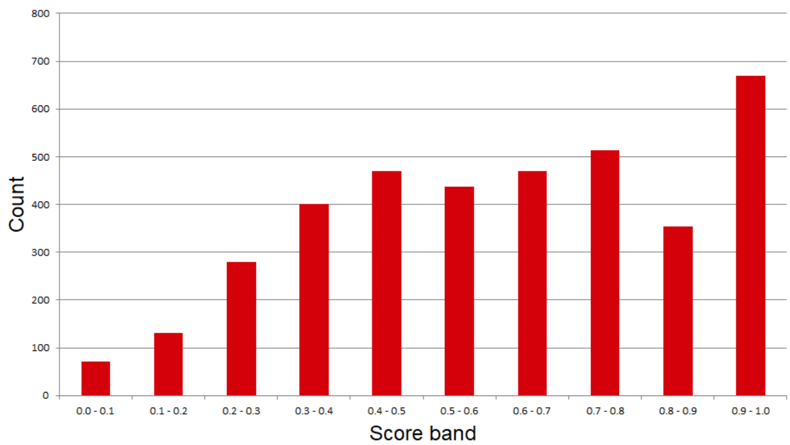

Figure 3-2: Patents result score of final report

Result score shown on the 3-2 show how patents fit the classifier.

Second part is focused on building a model of a product and optimizing it for several criteria. We focus on the system architecture of indoor positioning solutions. The system architecture provided by the Indoor Location Alliance is used as the main reference. Next we use the data from the Microsoft indoor positioning competition. This is a valuable data, because it provides data about development of indoor positioning technologies and their performance. Data of teams who are competing in the same conditions are perfect for benchmarking. Having the data of benchmarking, we may define technology complexity in real numbers and use it when building the strategy.

Third we do a financial valuation. We collect all data about product, market, marketing channels and model of sales together. Having existing business model which is outside of the scope of this paper, we may identify numbers of sales and revenues. We use the costs and amount of investments we need to complete this project. We tune the financial model to obtain the positive NPV. To be coherent with the product figures of merits, we also adjust values of the model to receive a non-dominated product on the market.

Next we do value at risk analysis. With the value at risk gain curve, we check different financial models.

After all procedures we come up with bunch of strategies from where we can choose one. Again, we can't make decisions based on this models, but we can check strategies performance and for different technical decisions.

3.1.1 Intellectual Property, Publications

3.2 Results

Figures of merit

Lower figures in table are affecting the technology choice, but cannot be added into model, so they are not considered as the figures of merit, but listed in table to explain the reason of excluding them.

We focus on the figures of merit which are important for product development, and we use product FOM's mostly3.2.

Technological limits

3 types: radio (distance), image (angle), fingerprinting (position).

Radio (multilateration, distance measurement), fingerprinting: noise level, wave reflections, sensor errors are main limitations. Because of noise, the technology limit can't be reached, only on frequencies where is no external noise, wave reflections - scanning error depends on geometry of signal way. Image based: accuracy/precision of localisation depends on camera angle resolution. Because trilateration with camera is not possible, error is a linear function of range.

Table 3.1: Technology FOM's

cost hardware, software	USD	cost or hardware rent to provide coverage of needed area with normal operating accuracy
accuracy	m	accuracy of localization, difference between real position and measurements
cost	f(USD/sqm)	the cost itself cannot be directly compared because of different types of implementation. Instead, the overall cost presented in several roadmaps is shown.
range	m	Not important factor, complexity and scalability are affected by this factor. Not representative, because of different types of implementation. Excluded from FOM's
additional requirements	USD; year	If yes, product is not applicable until they are not solved. Not implemented into model, technologies with additional requirements are mot mapped. (Infrastructure Requirements, Impacts and Notes)
Scalability	low/med/high	range of scalability, important factor to consider in strategy choice
Complexity	low/med/high	range of complexity, important factor to consider in strategy choice
Robustness		additional information of what affect the performance of technology

Table 3.2: Product FOM's

accuracy	m	accuracy of localization, RMS error between real position and measurements
development time	month	time to develop the product based on technology with specified accuracy

3.2.1 State of the art

Positioning

We have to find products of this companies and other popular products to provide the landscape of market.

Number of patents is a valuable metric but it doesn't show us a value of patent, for

Table 3.3: Performance of different technologies from the indoor positioning competition

Team	Technical Approach	dev.time	RMS error	Team's Affiliation
1	2.4GHz Phase Offset	60	0.72	Lambda:4 Entwicklungen
2	WiFi+Modulated LEDs	12	2.04	MSR Asia
3	2.4GHz Time-of-Flight	72	2.03	Freie Univ. Berlin
4	Ultrasonic Time-of-Flight		2.09	CMU
5	IR/Radio Time-of-Flight	18	2.35	Rutgers
6	2.4GHz Time-of-Flight	5	2.58	Wroclaw Univ. of Tech. MT-Silesia Sp.
7	WiFi+Bluetooth+IMU	24	2.72	NextoMe
8	Modulated Magnetic Signals	24	3.83	Univ. of Oxford
9	SDR Time-of-Flight	4	3.87	Humboldt Univ. of Berlin
10	Modulated Magnetic Signals	90	3.96	DFKI
11	2.4GHz Phase Offset	24	4.04	Greina Technologies
12	WiFi+Sound Time-of-Flight	12	8.91	Xian Jiaotong Univ.
13	Steerable Antennas ToF	12	10.22	I.E.C.S.
14	Bayesian Filter + WiFi Fingerprinting	96	1.56	Cork Institute of Technology
15	WiFi+IMU Fingerprinting + Neural Network	36	1.96	Univ. of Cyprus/Cywee
16	WiFi Fingerprinting + Neural Network	12	2.22	Nanyang Tech. Univ.
17	WiFi+IMU Fingerprinting	9	2.81	Ubee S.A.
18	WiFi+IMU Fingerprinting + Particle Filter	24	3.19	MSR Asia
19	WiFi Time-of-Flight + Adaptive Filter	12	3.47	ETH/IMDEA/Armasuisse
20	WiFi+IMU+Maps + Conditional Random Fields	12	3.71	Univ. of Oxford
21	WiFi+Magnetic Fingerprinting + Particle Filter	12	4.86	Nanyang Tech. Univ.
22	WiFi+IMU Fingerprinting + Clustering/Decision Trees	3	5.23	Tata Consulting Services

example, IndoorAtlas OY obtain patents for magnetic fingerprinting technology which are more valuable now. Some huge companies such as Google LLC and Hitachi are not properly listed. They obtain higher number of patents that shown here, but all of them are not related to indoor navigation, so they are excluded from analysis. Excluding several companies is possible because best products are well known and we want to map products especially.

[?] It provides information about relative accuracy, mobile device battery usage and other system performance factors to help support early IPS planning and preliminary product evaluation.

[14]

IndoorAtlas research of 2016[8] is a market landscape, which covers most popular tech-

Table 3.4: Technology comparison. Linking grid.

											Products				
											current				future
										Markets	p1	p2	p3	p4	p5
										positioning	x	x	x	x	x
										marketing	x		x		x
										analytics			x	x	x
	Technologies														
	T1	T2	T3	T4	T5	T6	T7	T8	T9	Processes					
	x	x	x					x	x	geofencing			x		x
			x	x		x			x	asset tracking			x	x	
	x	x	x	x	x		x	x		human real-time positioning	x	x	x	x	x
		x	x	x						queue management			x	x	
			x		x	x	x		x	Sensor Fusion SLAM			x		
	x	x	x	x	x	x	x	x		map creation	x	x	x	x	x
										Product phase					
mature				x						Research			x	x	x
growth			x		x	x		x		Development	x	x	x	x	x
emerging		x								Delivery			x	x	
declining	x						x		x	Support	x	x	x	x	

nologies, market drivers and future trends. The paper covers adoption and drivers of indoor positioning systems, perspectives of geomagnetic indoor positioning.

Paper [3] present a comparison of indoor positioning approaches.

We use the linking grid to map products 3.5 to technologies 3.6. To make table more compact, we use indexes.

In linking grid 3.7, we map technologies to possible processes in indoor positioning systems. For each technology, we identify the technology adoption or readiness level in simplest form. After that, for each process, we mark all possible technologies involved. Then we mark products to markets and identify which processes are involved into each product, on which markets the product is positioned and what the level of this product on the market.

Table 3.5: Product index

	Products
P1	Mapsted navigation deluxe
P2	HERE Indoor Positioning (SDK & radio mapper)
P3	IndoorAtlas
P4	VisioGlobe indoor navigation
P5	Google VPS (visual positioning system)

Table 3.6: Techologies index

index	sensors
T1	GSM / 3G / 4G (LTE)
T2	compass, magnetic fields
T3	Wi-Fi
T4	Bluetooth
T5	accelerometer, gyroscope, pedometer
T6	UWB antennas
T7	Barometer
T8	Camera
T9	RFID, NFC, QR code

Patents

In patent research of current field, we use patent classifier with the training set of 590 positive and 136 negative patents marked. Using this classifier and AI patent platform cipher.ai, we do the organization search which is presented on 3-3 . On the Figure 3-3 category of "Unrelated" is the category of patents that does not fit the classifier.

Table 3.7: Technology comparison. Linking grid.

											Products				
											current				future
										Markets	p1	p2	p3	p4	p5
										positioning	x	x	x	x	x
										marketing	x		x		x
										analytics			x	x	x
	Technologies														
	T1	T2	T3	T4	T5	T6	T7	T8	T9	Processes					
	x	x	x					x	x	geofencing			x		x
			x	x		x			x	asset tracking			x	x	
	x	x	x	x	x		x	x		human real-time positioning	x	x	x	x	x
		x	x	x						queue management			x	x	
			x		x	x	x		x	Sensor Fusion SLAM			x		
	x	x	x	x	x	x	x	x		map creation	x	x	x	x	x
										Product phase					
mature				x						Research			x	x	x
growth			x		x	x		x		Development	x	x	x	x	x
emerging		x								Delivery			x	x	
declining	x						x		x	Support	x	x	x	x	

Table 3.8: Portfolio size: Active patent families, by organization and technology

	Univ Beijing	Here Global	MAPS	Tile	Navteq	REALTIMETECH	TeleNav	Private owner	Next 398	TOTAL
indoor navigation	459	258	3	6	10	5	64	41	492	1597
Unrelated	568	778	32	27	27	31	124	0	42	2445
TOTAL	1027	1036	35	33	37	36	188	41	534	4042

3.2.2 Building a model

Architecture

One way of AI usage with indoor positioning system is shown in post of IBM-research group [6]. This gives us some view of architecture and data transactions in modern IPS applications.

On figure 3-5 we present possible architecture of indoor positioning application. We use

	Univ Beijing	Here Global	MAPS	Tile	Navteq	INRIX	REALTIMETECH	TeleNav	Private owner	Next 398	TOTAL
indoor navigation	459	258	3	6	10	1	5	64	41	492	1597
Unrelated	568	778	32	27	27	38	31	124	0	42	2445
TOTAL	1027	1036	35	33	37	39	36	188	41	534	4042

Figure 3-3: Portfolio size: Active patent families, by organization and technology. Currently active patent families (granted or pending) by organization and technology.

Table 3.9: Geography: Granted patents, by country and organization

	Belgium	China	France	Germany	Ireland	Japan	Netherlands	Switzerland	United Kingdom	United States	Next 47	TOTAL
Univ Beijing Inf Sci & Tech	0	483	0	1	0	0	0	0	0	15	0	499
Here Global BV	55	28	113	131	63	59	70	51	114	992	721	2397
Mapsted Corp.	0	0	0	0	0	0	0	0	1	37	13	51
TRX Systems, Inc.	0	0	2	2	1	0	0	0	2	36	15	58
Tile Inc	0	0	1	1	0	0	0	0	1	98	1	102
Navteq B.V.	5	4	8	10	6	7	6	5	8	39	66	164
Here Global BV	55	28	113	131	63	59	70	51	114	992	721	2397
INRIX Inc	2	0	2	10	3	0	0	2	10	53	7	89
REALTIMETECH INC	0	2	0	0	0	1	0	0	0	2	34	39
TeleNav Inc	9	51	31	32	9	0	2	13	31	171	126	475
Next 398	3	187	8	10	3	11	3	3	9	111	113	461
TOTAL	129	783	278	328	148	137	151	125	290	2546	1817	6732

blue colour for dead-reckoning application. Because of different smartphone sensors, signal processing will be different for every smartphone model, that's why signal processing should be done on the smartphone itself.

After first signal filtering from inertial and others complementary sensors (barometer), all information from sensors has to be matched with fingerprint database and map databases. This process can be done on the remote server or locally, this depends on system architecture chosen.

The technology choice of system architecture can't be explained, because there is no single strategy for system design.

Only several assumptions can be presented:

- Server based systems can be provided by an external vendor - buying a service
- Server based systems are enough cost effective to be used (development of server plat-

	Belgium	China	France	Germany	Ireland	Japan	Netherlands	Switzerland	United Kingdom	United States	Next 47	TOTAL
Univ Beijing Inf Sci & Tech	0	483	0	1	0	0	0	0	0	15	0	499
Here Global BV	55	28	113	131	63	59	70	51	114	992	721	2397
Mapsted Corp.	0	0	0	0	0	0	0	0	1	37	13	51
TRX Systems, Inc.	0	0	2	2	1	0	0	0	2	36	15	58
Tile Inc	0	0	1	1	0	0	0	0	1	98	1	102
Navteq B.V.	5	4	8	10	6	7	6	5	8	39	66	164
Here Global BV	55	28	113	131	63	59	70	51	114	992	721	2397
INRIX Inc	2	0	2	10	3	0	0	2	10	53	7	89
REALTIMETECH INC	0	2	0	0	0	1	0	0	0	2	34	39
TeleNav Inc	9	51	31	32	9	0	2	13	31	171	126	475
Next 398	3	187	8	10	3	11	3	3	9	111	113	461
TOTAL	129	783	278	328	148	137	151	125	290	2546	1817	6732

Figure 3-4: Geography: Granted patents, by country and organization Currently active and granted individual patents per country, by organization.

forms in 2020 is enough to not care about signal processing on the local devices)

- Mobile device based are harder in development and support
- Mobile device based systems may not require external server and can be run locally - stable work with no internet connection
- Once operating, mobile device based are cheaper, because no server support and rent needed - costs are on user side. Important for scalability (if one million of users will use system, some additional traffic management will be required)
- Emergency help services shall not depend on internet connection - broadcast systems, mobile device used as transmitter - mobile device initiated systems
- In some cases network initiated positioning can be useful. For example, if ultrasound waves are used for positioning, sound transmission will happen over short periods of time defined by network, this will reduce level of noise.

For the most common case of human tracking with no special requirements on internet connection, scalability and sensors used, architecture shown of 3-5 can be used.

InLocation Alliance (ILA) was founded in 2012 and worked on indoor positioning solutions. In 2014 the ILA created an open, technology-independent architecture in support of

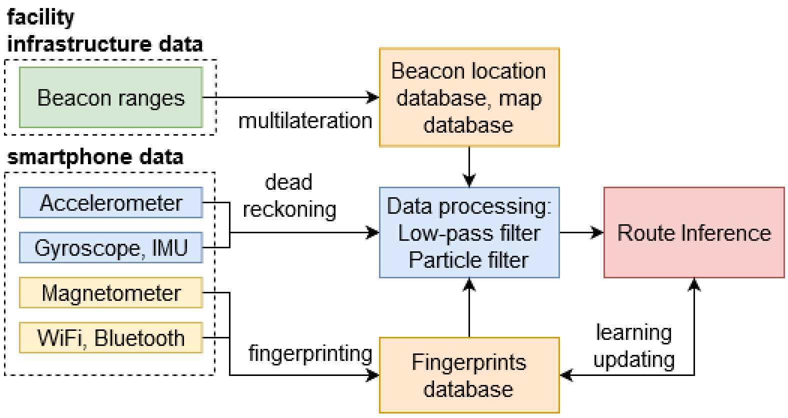

Figure 3-5: Signal processing system architecture

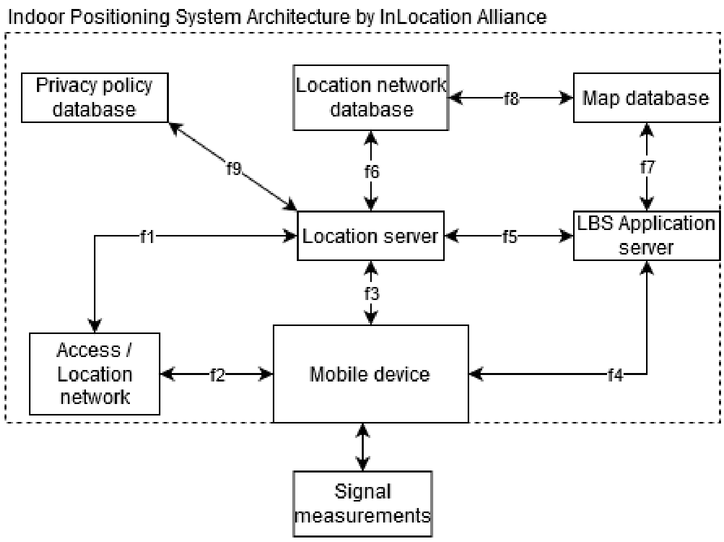

Figure 3-6: InLocation Alliance (ILA) system architecture

accurate location of mobile devices within different types of indoor venues (see Figure 3-6), which presents seven key system elements and nine interfaces.

What we see from Figure 3-6, is that only mobile devices are considered as input, current architecture don't have beacons in it.

Results of ILA work and standards they make are not open and published, so they are not a standard now and we may freely update this structure. Moreover, in [?] author propose to define both system architecture diagrams 3-5 and 3-6 and use them as a product documentation to describe interfaces and so on.

Roadmap system modelling

From [?], the process of documenting architecture can be described as:

At the appropriate times, take steps with prospective system providers:

- Provide the two architecture diagrams to prospective vendors
- Ask vendors to document the architecture and positioning mode(s) of the IPS being considered, relative to these architecture diagrams.
- Plan and document any data import or export functions.
- Review the existing system's reporting capabilities against what reporting requirements apply for business uses of the system.
- Review what applications reside where, such as an on-premises server or a cloud server.

We will create an OPM model using this approach and Figures 3-5 and 3-6.

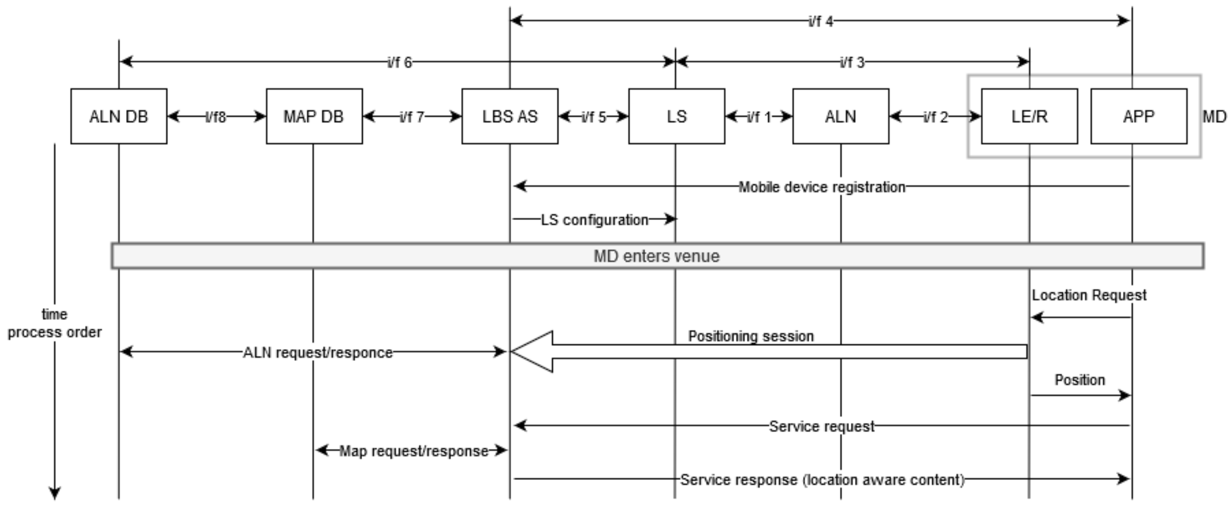

Figure 3-7: Location aware content example by ILA.

We present an example from [1] of how location aware content is delivered to users. On Figure 3-7, we see the order of steps, used to provide location aware content to user, e.g. geo-targeting or geo-fencing. This diagram doesn't explain much the structure and interfaces of system architecture, but shows some connections between them. All short naming are the same as in Figure 3-6.

3.2.3 Technology Strategy Vision

From annual reports[19, 20] we can get history of trends in mobile marketing. When and where it is possible,different technologies and services are implemented in IPS. We will list several trends of indoor positioning systems.

Merge of indoor and outdoor positioning systems: It is visible that IPS technologies are converging to some set of technologies. When this will happen, the connection between

IPS and GPS or other outdoor positioning systems can be done. Right now, several IPS products support this feature, but this is not a global solution.[3] Privacy and security in IPS development: Current trends with protection of users in web (GDPR policies) bring us to the point that some steps in this direction are done by government. Development of a product which is privacy safe can improve the adoption of use, which is important factor now. This factor directly affects the scalability of specific technologies and products.[3] Crowd-source mapping: Most of technologies used in IPS systems requires hours of measurements inside the facilities to create a map of a building. Regular users can provide big amount of measurements, needed to create map of building and update it regularly. This approach is important for applications that don't require special equipment for measurements and need regular map update (magnetic fields, WiFi, ambient sound localization technologies).[3] "China Crisis Ebbs, But Tracking Apps Are Going Strong" - the article of today's paper in The New York Times [26]. Having the great need of tracking people, new products of human tracking were developed rapidly. "But the authorities have set few limits on how that data can be used. And now,officials in some places are loading their apps with new features, hoping the software will live on as more than just an emergency measure." Indoor Location of E911 Mobile Callers: Enhanced 911 Services enable 911 operators to: Immediately pinpoint the location of the 911 caller based on the calling number Callback the 911 caller if a disconnect occurs Tracking location of people in emergency situation is an important challenge and one of the most important drivers of current IPS technology. The initiative shown some results in 2013, but USA government requires universal service that will be implemented across the USA. One of the key points of this measure, that it has to work indoors. Importance of E911 point is that several actions are already done and several technological steps may change the state of USA market which may happen in future 2-5 years.

The overall strategy is to deliver the product in least development time, while reaching the average accuracy.

3.2.4 Timeline

We use data of Microsoft competition as a starting reference. In table 3.3, we have time of development and resulting accuracy for the different technology choice of different teams participated. We may use these dependencies to understand, what time is needed to achieve each level of accuracy for different combinations of technologies.

On figure 3-8, we see the team competitors performance versus time for development in

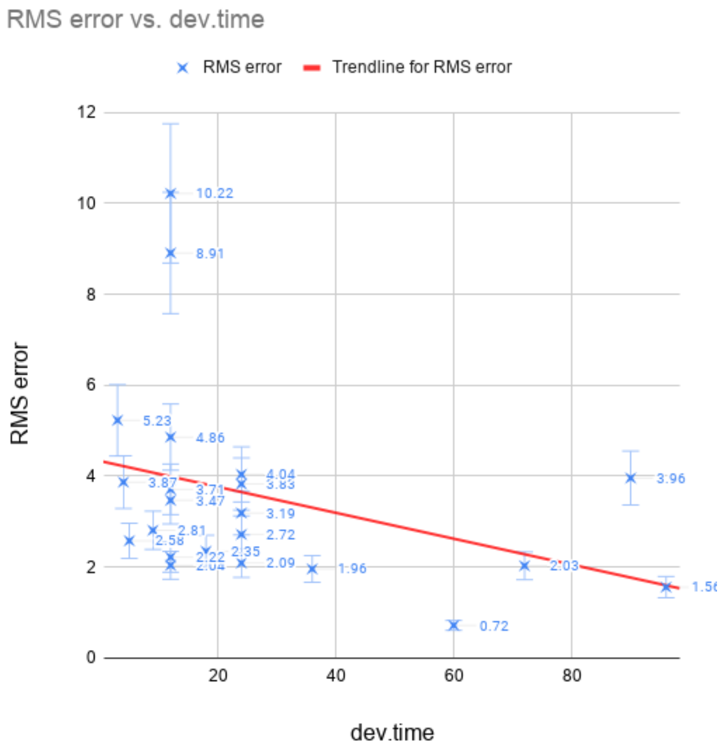

Figure 3-8: Root mean square error of positioning versus time of development

months.

We choose the best performance in technologies 3.10 by multiplication of all of parameters. We define the metric as:

$$\text{performance} = \frac{1}{(\text{development time}) \cdot \text{accuracy}}$$

We predict the accuracy of or product in between of optimal scenario (non-dominated points) and the trend line. From this we may present a timeline.

On 3-9 we show the action plan for development the product with different alternative strategies.

The overall trend is that IPS products are converging to a global ecosystem - digitization of cities. After human and assets will be tracked constantly, this will be a big supplementation to a smart cities technologies. Before that, there is the market of IPS in retail applications (asset tracking, geofencing, way finding, proximity marketing)[9].

By speaking of current situation on the market, we can say that human indoor tracking is growing, but it is not mature. We are building product with the main function of human indoor positioning as shown on Figure3-9.

Magnetic field navigation is another perspective factor in the timeline, some progress is

Table 3.10: Technology choice.

Technical Approach	dev.time	RMS error
SDR Time-of-Flight	4	3.87
2.4GHz Time-of-Flight	5	2.58
WiFi+IMU Fingerprinting	9	2.81
WiFi+Modulated LEDs	12	2.04
WiFi Fingerprinting + Neural Network	12	2.22
WiFi+IMU Fingerprinting + Neural Network	36	1.96
2.4GHz Phase Offset	60	0.72
Bayesian Filter + WiFi Fingerprinting	96	1.56

already achieved by IndoorAtlas company in this field, but this technology will might become global and will assist the usual dead reckoning and existing WiFi and BLE technologies.

UWB localization can be better than existing radio-based technologies, but until there is no UWB communication equipment in smartphones and facilities worldwide. Spreading of 5G may change this situation.

3.2.5 Technical feasibility

Physical limits of indoor positioning system come from the environment. Real usage limits are more flexible and are directed by human limits (reaction time).

Applicable limits of each of FOM-s are different for different applications. For people to navigate, the accuracy of (1 m) and response frequency of (5 s) may be enough. In big environment, the accuracy of 1-3 meters (similar to GPS performance) is enough. For the high performance applications, the accuracy must be lower than 1m (0.1 -0.5)m and response frequency near (0.1-0.5)s. In ARkit research[1] proposed model, where accuracy required is equal to 10 percent of the distance between various points of the destination, which gives us same 0.4-0.5m for rooms and 4-5m for big halls.

The range for RSSI method is calculated by formula:

$$\mathbf{dist} = \mathbf{10} * ((\mathbf{RSSI_{1m}} - \mathbf{RSSI_{rec}})/(\mathbf{10} * \mathbf{Pathloss}))$$

Main limitation with this type of distance calculation is sensor's sensitivity and field

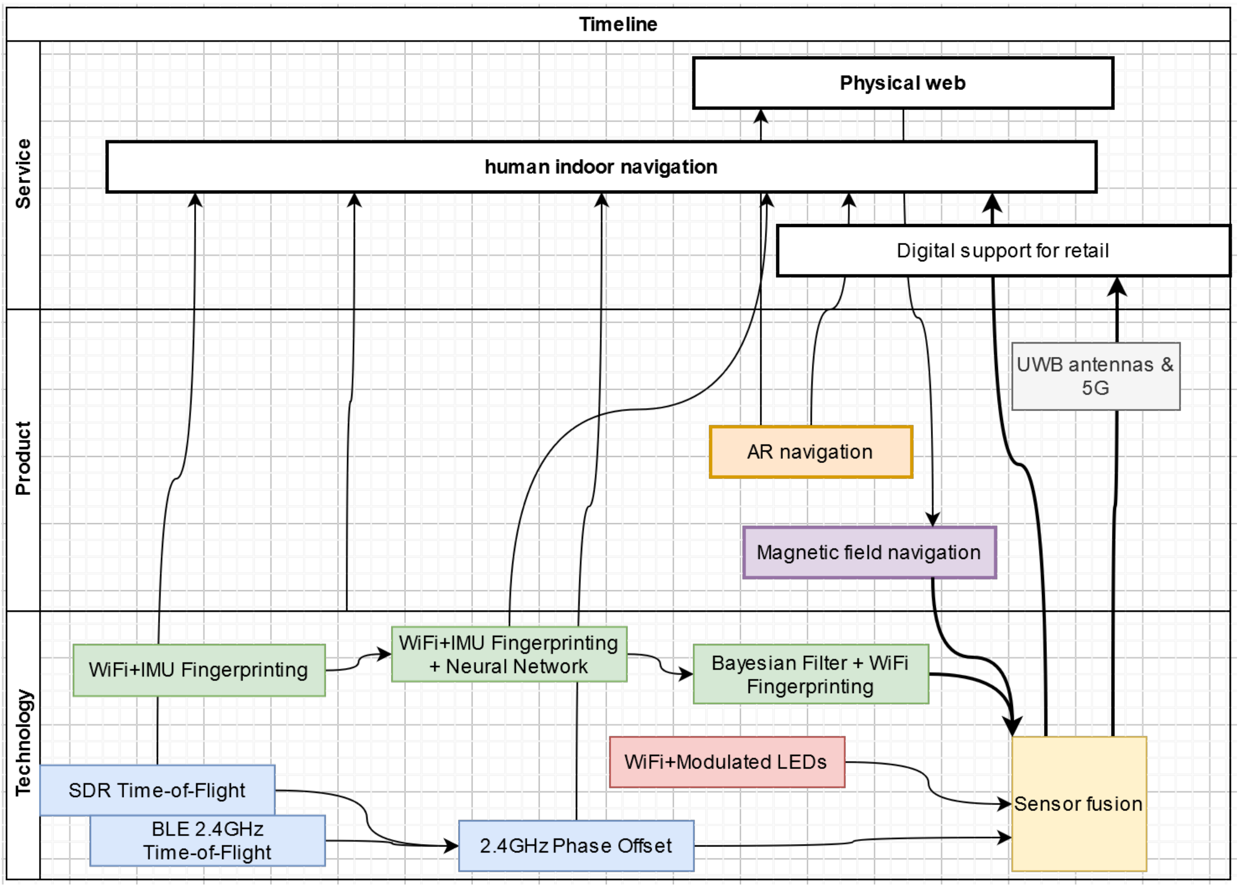

Figure 3-9: Timeline diagram. Left to right: Passed term, Short term (1-2 years), Long term (2-5 years).

noise. Having -96 DBm sensitivity and 4 DBm transmit power, system will be operable in range of 30m.

To calculate the signal distribution, we use Free-space path loss formula and Log-distance path loss model.

We use constants from signal measurements in [21], and Log-distance path loss model.

This gives us the information that signal transmission quality depends of distance, transmitter power and receiver sensitivity.

For BLE, we the normal conditions are as in figure above: with normal operating range of 30m, transmitter power in [4 DBm, -20 DBm] range, receiver sensitivity in range of -40 DBm, -60 DBm.

The limits for tracking technologies are not strict, they are only affecting accuracy and precision of localization. We can use table of normal ranges for technologies as a reference, but the performance will depend of huge amount of factors which can't be modeled accurately.

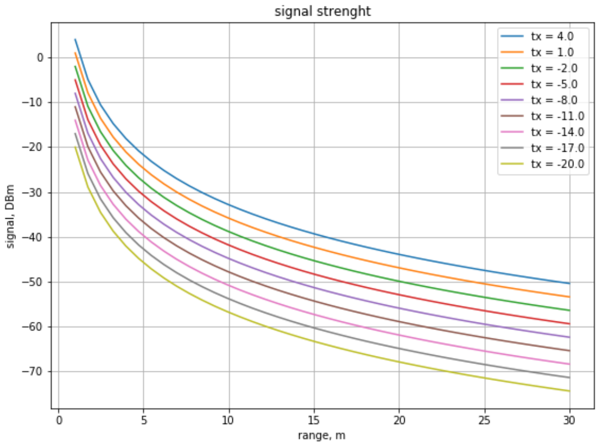

Figure 3-10: Radio signal strength distribution model.

3.2.6 Financial Valuation

$$\text{Customer Acquisition Cost (CAC)} = \frac{\text{(product cost)} + \text{sales} + \text{marketing}}{\text{(number of customers)}} \tag{3.1}$$

$$\begin{aligned}\text{Life-Time Value (LTV)} &= \text{(average value of sales)} \times \text{(number of repeat transactions)} \times \\ &\times \text{(average retention time)}\end{aligned} \tag{3.2}$$

$$\text{Profit} = \text{LTV} \times \text{(average margin)} \tag{3.3}$$

Assumptions:

1. an exhibition area of 1000 sqm, needs 9 BLE anchors for full coverage
2. Calculations for 1 day
3. 1000 visitors per day
4. Mobile app development needs 4hrs of programming
5. 1 person for hardware installation and removal

Assumptions on revenues rate are shown on the figure above.

Plan A:

CAC a to charge each booth (participating company) to benefit from indoor navigation facilities per day

Daily costs of operation = 1200 USD; Fixed costs = 3000 USD;

Plan B:

CAC B to charge each booth (participating company) to benefit from indoor navigation facilities + additional product features

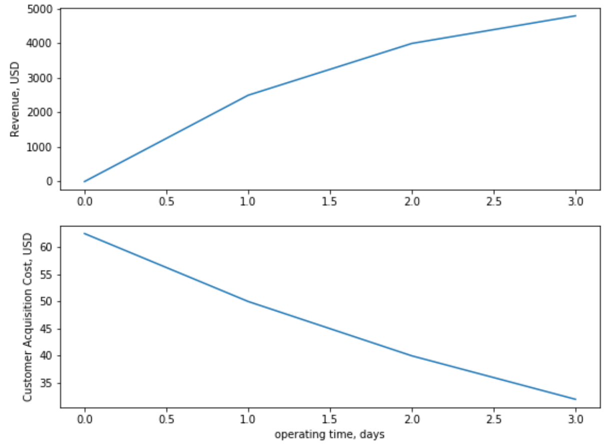

Figure 3-11: Customer acquisition cost

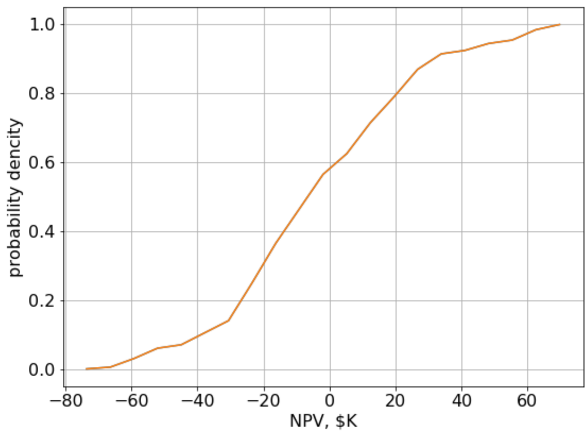

Figure 3-12: Value at risk gain curve

Daily costs of operation = 1700 USD; Fixed costs = 2000 USD;

We assume that in strategies, CAC is different, and costs are different. Number of customers is assumed probabilistic as a triangular distribution. We use the assumption in the model, that for the longer operation time, customers get a discount as a power function of power 0.8.

The total revenue and customer acquisition cost are presented on the Figure 3-11. This is an example for one strategy, average customer acquisition is about 45 USD per day. Average revenue is about 1800 USD per day.

3.3 Validation

The tech background is validated by comparison of scientific publications [1], [3, 10, 11, 14, 6] and analysis of the existing solutions. The business model was sequentially developed to satisfy four fits model. Expert validation (IndoorAtlas expert's interview, customer's interview).

One of the most valuable tools for the roadmap developing was benchmarking with existing researches [13].

3.4 Conclusions

The indoor navigation product strategy tool is in development now. It was proven to be viable by customer discovery process and by revenue model & calculation.

However, in order use this tool efficiently, this strategy tool requires:

1. to be accurate - proved to be possible but requires lot of engineering
2. to be convenient - depends on the way of realization and would require continuous improvements
3. acceptance of the market segment, which shall be accurately chosen
4. complexity of either software or hardware

This paper shows the usage of different modelling approaches, which allows to develop the strategy based on the product model.

Paper provides a roadmap, technology landscape and technology strategy choice that is based on the timeline and all relevant roadmap elements. Each statement is supported by a quantitative fact or analytics defined by the models of product and technology.

System model, created in this paper, list all important figures, components and capabilities. The key functions and system architecture are identified using common standards. Figures of merit identify capabilities and limits of technology and provide information about product development strategy. The demonstrators, patents, known products and products which can be used as a components of indoor positioning system are listed in paper and implemented into strategy.

In paper, we identify the limit for the product development performance as an average performance (root mean square trend line). This allow us to make a strategy choice, to develop a product/technology or to buy it.

The financial valuation was developed, based on product model and sales models. We use probabilistic models to develop strategy under uncertainty. Different scenarios (pessimistic, baseline, optimistic) are defined.

Chapter 4

Thesis Objectives

In this chapter we define the goals and derive the specific questions to be addressed in our research.

We perform this research to create an indoor positioning system with special features. The objective of this research is to develop all algorithms needed to obtain these features.

We define an approach for dealing with the dead reckoning system. We propose a mapping algorithm using ARcore visual odometry for training and all-time pedestrian dead reckoning and magnetic mapping for operation.

We aim to develop the system, working without complicated sensors or physical landmarks as beacons. This is only a research interest because the current SOTA PDR systems are only secondary to other approaches.

We design the algorithm of data collection and for the purpose of mapping indoor location and localization usage. We evaluate algorithm's robustness, by means that it should converge if sufficient data is given.

Criteria for the proposed system

We can write the criteria for the positioning system we develop.

1. no prior map is available: the system can work as SLAM system (real-time navigation with no prior map)

2. no special hardware for operation except smartphones: positioning accuracy enough for practical usage (1-2m is the usual accuracy in this conditions)

3. the system aggregate data from many sources (crowd-source) and improves the localization accuracy

Hypotheses

We formulate several hypotheses we evaluate during research:

Hypotheses:

1. The technology of magnetic field navigation can be implemented and fine-tuned for indoor crowd-source SLAM

2. The data from magnetic field and inertial sensors is enough for running SLAM

3. The crowd-source system satisfies defined optimality conditions and improve the accuracy

The hypothesis 2 is not clearly explained in existing systems. For most system, the additional prior knowledge is needed for localization. Several papers present the system able to localize with only inertial data.
This is more the an academic interest to prove this hypothesis and develop such kind of system. The common real world systems use the sensor fusion approach and collect the data from multiple sensors. The presence of precise localization devices or sensors improves the location accuracy drastically. However, for the most applications, there is a lack of technical resources and sensor fusion is not possible. We simulate the problem of partial absence of such devices and model the system without them.

Two other hypotheses are more engineering questions. We have to compare performance and robustness of our algorithm and systems to other state of the art approaches. In our problem statement, there is no much systems that have outperformed the usual reasonable accuracy of 1-2m. So we aim to achieve comparable or at least some reasonable accuracy that can be compared to other similar methods.

Chapter 5

Thesis Methodology

5.1 Methodology

With the development of microelectromechanical systems(MEMS), a few MEMS-based sensors have been built and incorporated into smartphones: accelerometers, gyroscopes, magnetometers, etc. These sensors can be used to provide information on the user's actions. Pedestrian dead reckoning (PDR) is a relative navigation technique that uses these sensors.

We propose a PDR-based indoor positioning method, that integrates RSSI and magnetic field measurements with indoor environment map constraints by using particle filters.

For proper evaluation of algorithm performance, we have to obtain ground truth data. There are several methods of doing this process:

- usage of verified tracking / positioning system with better accuracy
- manual recording of position, using the constant measured track as ground truth (straight line, circle, rotation)
- usage of public dataset with available ground truth

In our conditions, we choose to first simulate all motion and sensor data.

We use the approach similar to [17]. We take the vision of spatial observations representation as a continuous surfaces.

We rely on the dataset of IMU & MEMS and ground truth measurements provided by RuDaCoP: "The Dataset for Smartphone-based Intellectual Pedestrian Navigation" [2].

We write the motion and observation models to be similar as in [17].

Then we aim to develop a smartphone data-logging app for dataset collection to run the algorithm on smartphone data.

The methods we are planning to use are Graph-SLAM, Gaussian process latent variable models [4], magnetic fingerprinting 3-axis magnetic field mapping and fusion by E. Grand and S. Thrun [7].

5.2 Theoretical framework

Graph matching

Our case: formulate situation with no wifi available data in local area

(A specific case of this problem) The graph matching problem is the "maximum weighted bipartite matching",

which is defined as a matching on a bipartite graph with maximum sum of the weights of selected edges.

This problem is also known as the "assignment problem". We utilize factor Graphs for such assignment of new data.

Matching problem proposed:

We now describe the problem formulation by modelling two graphs: the ground truth graph (location based information - building map) and the data graph, constructed during the online training phase of system from the crowd-sourced data of users walking in the environment.

We do not obtain a radio map which is needed for RSS-based localization. Instead, we collect a data-set of magnetic field fingerprints, tagged with their relative physical coordinates to previous position. This relative coordinates (graph type trajectory with approximate information on edges lengths).

From the data of two graphs: location map and fingerprints collection, we perform matching procedure, using multiple available methods.

The first procedure to apply is accept-reject method: all points in restricted location are blocked (person can't go through walls and etc.). Secondly, we perform loop closure and data association using common algorithms:

probabilistic approach (hidden Markov models)

Similarity measures:

What data we obtain in the data graph: heading, relative position, magnetic field direction. For multiple locations in same domain there can be lots of point with same of similar magnetic field direction. Instead, between any two points, there can be enough magnetic field disturbances, which will create enough information for distinguishing data, and mapping only location related data.

We can measure the similarity only between long enough tracklets(parts of trajectory e.g. frames) / edges.

The signal similarity measure cab be just a cross-covariance

5.3 Clustering and data tricks

We will highlight different possible solutions on how to deal with noisy collected data we have.

Factor graph tricks

Marching the curves: state to state connection + distance + uncertainty

We have some solutions that are out of the allowed region.

We can't directly solve this with differential factors.

Smoothing and mapping: search for best allowed solution from distribution.

What we can do:

- Add constraints to the problem
- Iteratively recalculate the problem until all conditions will not be satisfied
- Delete trajectories that doesn't fit the model. Delete all connected factors to deleted trajectories.
- Add new or deleted trajectories again to the model.

Out of region recalculate

Select on trajectory and with accept/reject method solve/integrate this on static building map.

Once we have a trajectory known, fix the points which are out of allowed regions: set the covariance of given points to zero e.g. to not recalculate this trajectory during graph optimization.

The method is dead reckoning combined with particle filter conditioned on magnetic field data and accept/reject on indicator function procedure (PDR + magnetic field PF + accept/reject).

Add border constraints

The alternative or similar idea. We add the constraints to the task. We add points on border to the map and add the constraints for close points.

Not feasible yet.

Distance metrics

We have a need of matching trajectories and solving warping problem not in time, but in state/action space.

If we can limit to one dimensional signals we can solve this step using traditional time-warping techniques.

Alternatively formulating we have all to all matching technique for close near-linear trajectories.

Same approach was used in two papers on localization and mapping. (Cimloc and magnetic mapping using chess coverage pattern)

We say that this technique can be used to solve some part of our problem: for straight collinear trajectories.

This time-warping does not provide us the factors we can implement in factor graphs, but a residuals to current solution. After time warping we have to somehow recalculate graph positions and recalculate the map.

This idea has similarly in several computational methods. We separately optimize likelihood function and the problem itself.

Because of bilinear structure of magnetic field, we doesn't expect the system be able to organize the curves in direction where the field perturbations are small. If we have the corridor, the only direction we detect features is along the corridor direction.

To obtain exact positions of all states we have to condition on other information.

Our main source of information is a pose graph with loop closures. *Being conditioned on the known building map, it may be used as*

If we performed trajectory conditioning in orthogonal directions, the uncertainty in normal direction will be reduced.

Our goal is to solve mapping problem both for normal and tangential uncertainty.

Chapter 6

Conclusion

In this last chapter, we discuss the results, the limitations of our work, and provide an outlook on future work.

Chapter 7

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Appendix A

Additional Resources