GNSS quality in pedestrian applications – a developer perspective

Dirk Ahlers, Martin Pielot, Daniel Wichmann
OFFIS Institute for Information Technology
Oldenburg, Germany
{ahlers|pielot|wichmann}@offis.de

Susanne Boll
University of Oldenburg
Oldenburg, Germany
susanne.boll@uni-oldenburg.de

***Abstract*— Localization is a vital part of mobile applications. However, the quality of predominant GNSS-based localization remains inadequate for high-precision scenarios for mobile users. Based on previous work, we discuss the relevance of GNSS for mobile applications focusing in particular on mobile pedestrians. We present selected pedestrian-oriented application types and derive quality requirements towards GNSS-based positioning technologies. Drawing from our experience, we present current shortcomings of GPS-based positioning. We discuss their impact on application design and outline exemplary strategies of how developers could address these. We argue for an integration of GNSS quality considerations into the design process to enable applications to transparently deal with inaccuracies even for future, more demanding scenarios. Then we can provide innovative pedestrian applications to users on-the-spot, enriching their daily lives.**

I. INTRODUCTION

Knowing one's position and finding one's way are basic requirements for human movement and important aspects of everyday life. While most movement tasks are done automatically, there are situations when we become aware that our intuition does not carry any more and we have to make a conscious mental effort to find our way. When travelling in/to a foreign city, visiting a museum, looking for friends, hiking in unknown mountains or searching which platform the next train leaves we cannot necessarily rely on experience any more but need assistance to find our way such as signposts or specialized mobile applications. Even within a known environment one might want to know the exact position to find a certain object or give precise input to a virtual game.

Natural environmental parameters that have been used for ages include celestial objects by which one could navigate by certain stars and their visual locations. The alignment of a magnetic compass needle with the magnetic North further served to establish one's own orientation within a given frame of reference. This celestial navigation is now highly augmented by GNSS (Global Navigation Satellite System). GNSS is a large-scale artificial instrumentation of the planet to facilitate positioning on the earth's surface. It utilizes a series of satellites emitting their precise transmission time and parameters to describe their orbital location. Based on this information, receivers can derive their own position according to a known referenced grid of the earth. For most celestial measurements, latitude was the component that was measurable by celestial observation, but for determining the longitude, exact clocks were necessary. Today, when GNSS need highly accurate timings for precise triangulation they can provide latitude and longitude along with elevation and exact clock timings. GNSS technology has been available for over 20 years and has fostered a multitude of useful applications as a technological enabler. Such applications in particular include those that are aimed at a mobile user as location-based applications.

Access to the actual coordinate of a user allows a developer to integrate the current location as a vital prerequisite into mobile applications. A user's locations is a major context information to exploit for tailored applications, especially for those that are aimed at a pedestrian user. Most developers rely on GNSS sensors to gather this context information. The existing issues of signal availability, reliability, accuracy and ease-of-use have to be appropriately hidden from or unambiguously relayed to the user. Depending on the actual mobile application scenario, requirements towards a positioning technology can vary within a wide range. The variance of requirements for localization with regard to accuracy, availability, and reliability has to be assessed and evaluated as part of the design process of a mobile location-aware application to properly match the scenario with the employed technology. A further important aspect to consider for an application developer is the awareness and trust of a mobile user into GNSS services. This can be rather ambiguous as applications only partly address the specific requirements of positioning for the mobile user and therefore not necessarily meet the end users needs and expectations. Questions of needed accuracy for a certain user task, what amount of unavailability the application and the user can cope with, or how the quality of the signal and a deviation from a certain route is visualized or signalled to the user are questions that must be integral part of a GNSS-based mobile application project.

In this paper, we will first briefly introduce GNSS principles in Section II, elaborate on specific pedestrian-oriented requirements in Section III and discuss previous experience in Section IV. We discuss the impact of GNSS on application design in Section V before we conclude the paper in Section VI.

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II. GLOBAL NAVIGATION SATELLITE SYSTEMS

For outdoor positioning, a developer usually relies upon GNSS as a localization technology for quick and easy positioning of a user. Exceptions are special instrumented environments, Cell-ID-positioning etc. Of the existing systems today, GPS is the most prevalent with a global coverage and a mean accuracy of currently about 5-20m. In this section, we present existing systems and discuss some some known drawbacks of GPS including problems with availability and accuracy [1], [2], [3].

A. GNSS technology

1) Global Positioning System (GPS): GPS (Global Positioning System) [4] is the American GNSS started in 1978. To date, it is the only system with a worldwide coverage. The satellite constellations and orbits of GPS are calculated to ensure that of the available 24–30 satellites at least six should be visible most of the time from almost any point on earth. A minimum of at least 4 satellites is needed for triangulation to counter error sources due to timing but positioning accuracy increases with added satellites. For technical details of GPS we refer to [5], [6].

2) Augmented GPS: Augmentation techniques such as differential GPS (D-GPS) [5] install additional receivers on the ground in fixed positions and provide derived correction data for their designated area. This covers mostly athmospheric issues and can improve the GPS accuracy up to 2-3m if available. DGNNS then allows additional channels to the receiver to transmit this correctional data. Additional channels for DGPS can also include access by GSM or via Internet protocol [7]. The european augmentation service EGNOS [8] provides wide-area differential corrections via three geostationary satellites above Europe; WAAS [9] provides a similar service over Northern America. With industrial-grade DGPS receivers and antennas (such as used in geodesy) this higher accuracy is possible at the disadvantage of higher cost and much more equipment to carry for the user.

3) Future alternatives to GPS: The European system GALILEO [10] is expected to push the accuracy down to 1m when it becomes operational in 2012. The improved accuracy and availability will present a large benefit to mobile users and is expected to overcome shortcomings of existing systems for end users. Another GNSS is GLONASS [11] developed for the Russian military since 1972. Currently, 13 satellites are in orbit. In the final stage 24 satellites will surround the earth on three different planes for a complete coverage. Although GPS and GLONASS have technical differences, it should be possible to make positioning more precise and robust by integrating the different satellite systems [12].

B. GNSS positioning shortcomings

Due to the satellite basis of the system, some specific errors can occur. Signal delays are added by athmospheric effects and reduce the positioning quality. Noise within antennas and receiver electronics and small clock errors can further degrade the quality. Visible satellites near each other can lead to an increased error that a distribution that is more wide-spread accross the sky. However, as satellites are orbiting the earth twice every day, the constellations are subject to change. [13] notes moving positions and fluctuating precision during the day for fixed positions. Other issues are signal reflection and resulting multipathing which can degrade the signal or lead to incorrect calculation of position due to longer signal paths. These have a worse effect on slowly moving receivers compared to fast ones as these are highly site-dependent and fluctuate with movement near vertical surfaces such as walls, buildings, and slopes. Finally shadowing is a large source of errors where line of sight to one or more satellites is lost due to coverage of the receiver under canopy or foliage, bridges and within buildings. Urban canyoning is a combination of these two effects when only few visible satellite are observed in a multipathing environment. Some of these effects can average out on longer observation spans with accordingly adjusted processing software [14].

Using in-vehicle navigation a user usually only sees few little deviations. When a system occasionally remarks “Off Road” we can mostly assume that its maps are not current. Within the dynamic vehicle system, much more reliable assumptions can be made regarding, e.g., velocity, acceleration and heading changes, which allow for rather reliable heuristic filtering. These include Kalman filters and other dynamic processing as a method for improved dead reckoning. With assumptions on accessible roads and current map data, methods of map matching can further aid in hiding some of the imperfectiony of current GNSS from the user. The usual speed of cars further hides imperfections as the margin of error is often well below the distance a car travels within a few seconds and can thus easily be smoothed out by dead reckoning. These can even be enhanced by inertial sensors or, as widely deployed with in-car integrated systems, by sensor fusion from steering wheel, speedometer etc. to accurately track and predict movements of mobile units (MUs) [15]. According to [16], common GPS receivers for in-car-use benefit from the metal structure of the vehicle making them less effective when worn on the body.

The problem of urban canyoning can be extremely severe for pedestrian use since pedestrians move mostly on sidewalks where more than 50% of the sky is obstructed by built-up on the side of the user and by the buildings on the other side. [13] noted that due to the decreased visibility of the GPS satellites the positional error is much larger orthogonal to the street than parallel to it. They also note that newer receivers do not necessarily lead to better positions since they can even detect weakly reflected or obstructed signals and integrate despite their bad quality into the computations which then get biased. Modern GPS receivers conduct more complex signal processing and thus can lower the positional accuracy under 15m in good conditions, but inherent errors leave a continuous reliable accuracy of below 5m unrealistic. We will further discuss these deficiencies, their implications, and possible corrections and development adjustments to handle them throughout the rest of this paper.

III. GNSS QUALITY REQUIREMENTS FOR PEDESTRIAN APPLICATIONS

A. Location-based applications

We can roughly distinguish different types of applications by the presentation of position within their individual interfaces. We present a selection in the following.

Map-based applications show users' position, tracks, movements, points of interest (POIs), and similar data on a map interface. The map view allows cognitive filtering of position signal, spikes, etc. by the user who can evaluate and judge the positioning.

Position usage by applications for internal functions are demanding in terms of accuracy and identifying positioning errors which are only countered by internal filters and heuristics preprocessing. Examples are navigation for the blind or similar scenarios where a map view would be distracting to a user (skiing, biking, even car), velocity estimates etc.

Measuring tools directly focus on the position and the GNSS technology itself such as specialized handheld GPS receivers and according software.

In the following we present different application scenarios that can drive location-based applications:

Navigation uses the current position and the position of a destination along with knowledge of the terrain between to assist a user in moving. For complex environments, routing information is provided and assistance on the way. Examples are applications of local guidance.

Orientation and *exploration* present a model of the environment to the user where orientation is mostly accomplished by the user without interference of the system. Exploration of information spaces is also possible such as local search, tourist information systems or applications for sports and recreation.

Information needs are addressed by location-based search in the vicinity of a user [17], weather updates for the current region or timetables for public transport. In a following stage, this can serve as input to navigation.

Interaction with the environment can be provided by cooperative location-based applications such as mobile games, friend-finders etc.

Annotation is an upcoming field of applications that aid users to organize their personal media collection from a mobile lifestyle. "Location and time metadata are powerful organizational metaphors for images" [18] and thus users synchronize their personal photos with GPS tracks from external GPS receivers [19] and we even see cameras with integrated GPS chips.

The scenarios presented allow the derivation of location-related tasks such as *identification of a user's current position*, *orientation*, and his/her *relation to other positions* of other users or objects, the *identification of user movement*, *directional assistance*, and *distance estimation*.

B. GNSS requirements for pedestrian applications

The requirements for a pedestrian-oriented application are first of all the ease-of-use and a satisfactory user experience. Regarding GNSS-specific features, the main requirements are availability and accuracy. Blackouts in positioning are of course unwanted but can be compensated for small periods of time. Losses of more than 1 minute or a dislocation of 50m are very noticeable to the user, while a loss for a few seconds or a few meters can usually be compensated. The main problem for pedestrian assistance is that it often operates within the margin of error of current GNSS technology since pedestrian movement is very small. Similarly, many map-based applications are highly detailed for the pedestrian to orient himself, with the map scale smaller than GNSS can accurately provide. In detail, the GNSS-dependent requirements can be described as follows:

Accuracy. The precision requirements for a pedestrian application fall in different groups. For rough or very rough guidance of a user and hinting to junctions or crossroads on sparse routes a precision of 10-50 meters is sufficient; for vicinity search or very coarse navigation even a larger radius is acceptable. Active POIs or proximity sensors [20] can vary between 5-50 meters. For a guidance of a user along a route and identification of junctions or crossroads, interaction and collaboration with nearby users a precision should be 5 to 10 meters. To actually identify the side of the road or track a user is on, e.g., for navigational assistance for blind or vision-impaired people [21] an accuracy of 1-5 meters is needed. A precision below 1 meter is needed for precise guidance on paths or sidewalks and distinction between multiple users on the same spot. Requirements also arise due to the terrain or the inclusion of safety-critical functions.

Reliability and Quality Awareness. One task in developing applications for GNSS-based pedestrian applications is to communicate the actual quality of the position but to still present a meaningful position to the user. Although the position seems to be reliable to the user, it is not known whether this is really the case and what the current accuracy is. Certain types of errors are much more likely to be accepted by the user than others. If the signal is systematically shifted in one direction, the user easily recognizes this since his/her own track does not match the paths s/he has walked. Applications should anyway be aware of such inaccurracies for prioritized filtering, to decide whether to use a possibly inaccurate position or to discard it.

Availability. The availability of GNSS-based positioning restricts the possible application scenarios. Today, the use of GNSS is mostly limited to use under open sky conditions. Newer receivers are sometimes able to keep the position fix inside building but the quality then degrades rapidly. The point where a user enters a building is however very difficult to determine. When the user starts an application or leaves a building, he or she expects the application to work immediately.

Performance and Update time. This refers to the time the receiver needs to obtain the current position. When the user is moving this is crucial, because with every step s/he takes, the position loses accuracy. Thus, the update time determines the spatial and temporal resolution an application can rely on. Applications that are expected to react fast to the user's movement need updated position information in very short intervals. A position converging in less than 1s would be sufficient in most pedestrian circumstances, but this is also co-dependent on the expected speed and the desired accuracy. With applications that require accuracy in sub-meter areas, much higher update cycles and faster response behaviour for receivers is needed.

Ergonomics. To achieve an easy-to-use and satisfactory experience, pedestrian-oriented applications have to be designed for ergonomic usage. The required devices such as a position receiver or a computing plattform should be small and lightweight, so that they can be carried without discomfort. The system should not require carrying technical equipment in uncommon, inconvenient places, like for example the head. Instead, the integration of these devices into existing, well-accepted items such as mobile phones or worn clothes is preferable. The application should also not require the user to behave unorthodoxly to keep the application working, like for example staying only in areas with good quality of the satellite signal.

Power consumption. Another limiting factor for the use of mobile devices is their battery durability. Especially the excessive use of device components and computationally expensive algorithms drain the battery's energy very quickly. Reducing the energy consumption by e.g. using hardware components less often or applying performant algorithms is desirable to maximize the time the application can be used without recharging the devices.

IV. EXPERIENCES WITH GPS-BASED POSITIONING

In our work, we have gained experience with mobile, location-based application development, specifically in mobile pedestrian users and their special information and navigation needs [22]. The applications range from mobile games [23] over location-aware multimedia access to cultural heritage walks [24] and tourist guides [25], [26]. The development on different hardware platforms and our evaluations revealed a broad field of aspects that are relevant for the development of location-based mobile applications with a pedestrian focus [2], [1].

In summary, positioning is crucial for pedestrian applications but currently remains inadequate for some scenarios due to a number of shortcomings that we proceed to discuss in the following.

A. Initialization delay for position acquisition

Before a GPS receiver is able to calculate a position, it needs to acquire satellite signals and navigation data which are referred to as fix. The Time to First Fix (TTFF) is the time the receiver needs to acquire such a fix. During the TTFF the receiver calculates its position, velocity, the current time and the visibility of the GPS satellites. It also requires the approximate information on all satellites as an almanac. It is stored on the device and valid for up to 180 days. The TTFF period depends on the currency of this information within the receiver [5]:

The receiver performs a *Factory or Cold TTFF* if its information is outdated for months, e.g. after a factory reset. During that process the receiver obtains the information about all satellites, which is called almanac. Only then can it calculate position, velocity and the current time. Since the almanac is only transmitted every 12.5 minutes, this duration is typically under 15 minutes. A *Normal or Warm TTFF* is needed if the receiver has good estimates of its position, velocity, the current time and a valid almanac. The receiver obtains each satellite's orbital information, the ephemeris data, which is broadcasted every 30 seconds and valid for up to four hours. A *Hot or Standby TTFF*, also referred to as Time to Subsequent Fix (TTSF), is required, if the receiver has valid information about position, velocity, and the current time as well as valid almanac and ephemeris data. The TTSF is typically very short.

Since power is limited on mobile devices, GNSS receivers are typically started on demand only. Thus, every time a GNSS-based application starts, the receiver requires obtaining a fix before determining its current position. In a typical situation where the user frequently uses the application a Normal or Warm TTFF for re-acquisition is needed. According to the specification of the GPS, it should be around 30 seconds until the ephemeris information of the visible satellites is obtained. In our group while testing and evaluating our GNSS based applications we experienced much longer TTFF from time to time. There are several reasons which negatively affect the TTFF. If buildings are nearby, the TTFF takes significantly longer. This is most probably caused by the deflection of the signal which makes it more difficult for the receiver to obtain the ephemeris data. The weather, especially clouds and rain degrade the overall signal quality, which also results in a longer TTFF than under optimal conditions. While in cars the GPS receiver can be mounted at a prominent location, mobile devices would normally be carried at the user's body. Since the body is another source for degrading the signal, this also lengthens the TTFF. Another factor is the velocity of the receiver. We observed that the TTFF increases drastically if the receiver is moved, e.g. by a walking or driving person. An unexpected exception we observed is movement with very fast speeds ($>$130 km/h). While using a GPS receiver in a car on an autobahn the Warm TTFF took only a few seconds.

This affects for example GNSS applications that are targeted for pedestrians in urban environments. These applications are typically started when the user leaves a building. During their use the user might enter buildings for some time. After leaving a building, it is most likely that the user starts walking to another destination. Thus, in most cases the position fix has to be obtained when the user has just left a building and moves. At the same time it is likely that the user puts the receiver into his or her pockets. According to our experience all of these conditions negatively affect the TTFF. Thus, in the described scenario, the GNSS-based part of the application will most probably not work for some minutes, which limits the value of the application for the user.

B. Accuracy of positioning

As motivated before, accuracy is an important aspect for pedestrian application, but is also the one with the most issues. [13] found that due to moving satellites, the position of a fixed receiver can have a mean error of 15m with a maximum of up to 50m while even be as accurate as below 5m with a mean error in urban errors of about 24m.

Using state-of-the-art, but off-the-shelf components, the situation has improved considerably over the years so that much more precise assumptions about the actual user position can be made. Usually, GPS works quite well under open-sky conditions. However, many situations exist where its accuracy and even availability drop substantially. The positional error with modern receivers would be around 5-15m, in extreme cases up to 50m in difficult areas. Spikes in position data often jump in excess of 30m. Sometimes identical or similar devices under identical circumstances would record quite different positions. This means that while mapping one's own position is feasible within tolerances, correlating positions, nearness and spatial relation for several users is error-prone and hinders scenarios such as convergence or collision detection. Operation in urban canyons, under canopies, near steep slopes or overhangs mostly only leads to increased positional errors, seldomly to complete loss of availability. This is then due to issues such as hidden-satellite situations, attenuation issues, multipathing, atmospheric conditions, or shading. This matches the observations of, e.g., [3] who also note that GPS receivers lack performance under cover, indoors, and in urban canyons. While the accuracy observable after the fact is often already within 1-3m, frequent dislocations reduce the *reliable* accuracy down again to about 15–20m. We exemplarily present a set of tracks demonstrating specific issues of GNSS positioning. Mapping was done with [27].

1) Positional inaccuracy: Figure 1 shows a track where the user walked straightly along the path indicated by the blue dashed line. The red solid line indicates the position recorded by the GNSS receiver. This position diverges up to 25 meters from the user's position.

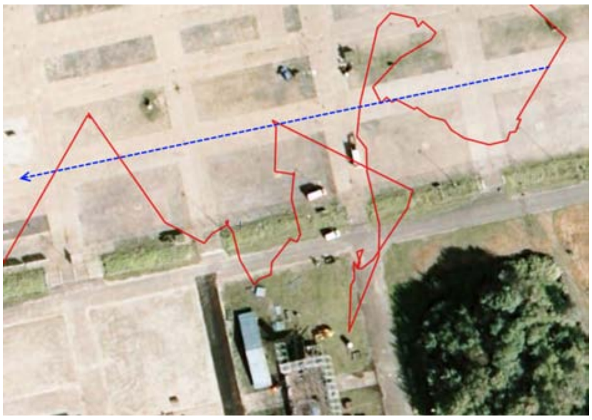

Fig. 1. Dislocation during straight movement

2) Sky occlusion: Figure 2 shows a thin red track mostly following the user's motion (solid blue) within a few metres but with two dislocations. The first on the left occurs near a higher-rising part of the circled building which falls back near the lower parts and a second one while walking through an underpass within the courtyard.

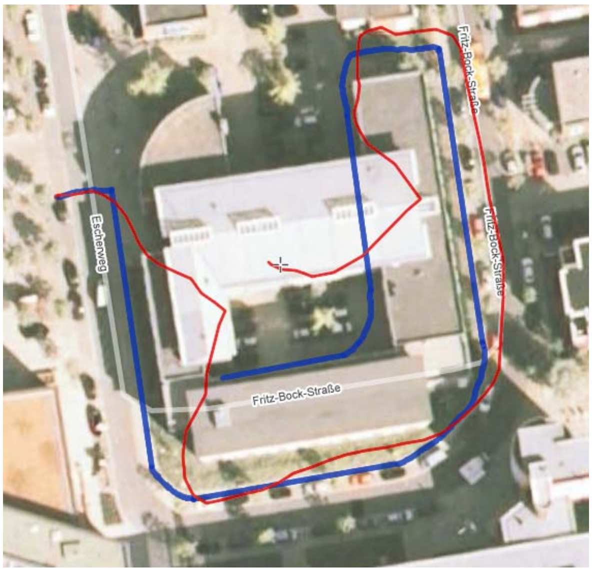

Fig. 2. Dislocation near buildings and walls

3) Receiver quality differences: Another observation we made is the the position accuracy provided by GNSS receiver strongly depend on the receiver device itself. Figure 3 shows two devices running the same application at the same location, but showing different routes. This is due to the different GPS receivers that were used with each device. The device on the left side with the very accurate positioning obtained the position from an external GPS receiver. The device on the right side used the built-in receiver which provided a significant worse position. Our experience shows that external receiver often provide the more accurate position compared to built-in receivers.

4) Standstill-fluctuations: Figure 4 shows the recorded position of a user who did not move for a while. When standing still, the position moved and jumped around the user's true position. This happens in a fashion that could – apart from spikes – also be interpreted as orientation along a path with frequent reversals and changing of sides and thus as valid pedestrian movement. To suppress this sort of movement, filters for an automotive use suppress changes in position below a certain speed threshold, which is obviously of no use in the pedestrian context.

5) Orientation: We currently cannot get a reliable bearing/orientation from GNSS data alone. For car navigation assumptions can be applied such as, e.g., cars cannot turn on the spot, and integrated sensors can be taken into account to gain the orientation information as an enhanced dead reckoning. These assumptions are not valid for pedestrians

Fig. 3. Differing tracks of same route depending on devices

Fig. 4. Fluctuations of position during standstill

and extrapolation of orientation from past movements is only reliable at higher speeds. Still, the direction the user is facing can be derived with reduced reliability by extrapolating from past movements. This option would be needed for accurate alignment of the user with a map of his surroundings and could actually take the user's own body-centric reference system [28] into account to give hints such as "the entry is slightly to the left".

C. Reliability of positioning

An application also has to cope with the fact that it usually has no further point of reference apart from a GPS signal. If the receivers loose too many satellite signals, it cannot obtain the user's position anymore. Figure 5 visualizes a situation where the receiver did not give any position for a while, resulting into a gap which is indicated by the dashed line.

For some receivers, the dynamic compensation can be fine-tuned to activate different modes such as stationary, pedestrian, or automotive use, which manipulates the way data is handled and extrapolated internally. Without in-depth knowledge of receivers, the current status of a receiver cannot be determined by an application which basically must treat it as a black-box component which only emits the protocol-defined messages. This also includes filtering within the device which remains an unknown factor in subsequent processing.

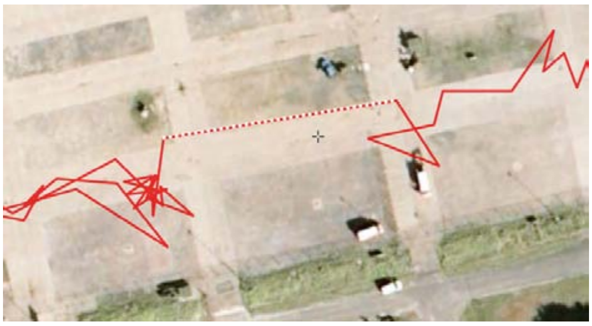

Fig. 5. Loss of signal during movement

These experiences confirm that applications cannot rely on having an always up-to-date position. Thus, using GNSS as positioning technique also is inappropriate for application scenarios where an always up-to-date position is needed.

D. User acceptance of GNSS in alpine tourist assistance

The recent Loccata project[1] [29], [26] was aimed to develop a location-based and context-aware mobile multimodal hiking guide for the Austrian region of Montafon, a well-known alpine hiking region. For fast realization, GPS was used with an option of moving over to GALILEO. We take this project as an exemplary case for mobile applications with GNSS integration.

The integration of the users was a highly important issue in Loccata. Right from the beginning, the project idea was publicly presented to tourist officers in the Montafon in Austria, and the requirements and ideas they gave were carefully considered. During the development, several live tests and preparations of the system were made, by actually going on short hiking tours. These real-life-tests proved to be very valuable, ensuring that the resulting system is not only technically operational but can also practically be used. All test persons were already very familiar with mobile phones and other mobile devices and had no problems operating the applications. One of the outcomes of the real-life tests was that the selection of the proper hardware is important for the operation of the system. The users liked to have a system with integrated GPS receivers, so they had to carry just one device with them. Therefore, external GPS receivers were used just for prototypal tests at the beginning and later only mobile devices with integrated receivers were employed. But some of theses devices were optimized for car navigation usage whereas others had weaknesses regarding availability as well as accuracy issues.

V. IMPACT ON APPLICATION DESIGN

Despite constant improvement of GNSS-receivers and expectations of even higher accuracy by GALILEO, there still

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[1] This work has in part been supported by the GJU/GSA; project number for the loccata project: GJU/06/2423/CTR/LOCCATA-CA.

are challenges to developers of GNSS-based systems who have to work with the system-inherent limitations as best as possible to create a smooth user experience.

From a development perspective, it is mandatory that the mobile applications address the issues of current GNSS adequately. Simple filter mechanisms that filters out invalid positions or massive jumps in the signal are not always helpful for pedestrians or might even introduce more errors or omissions of movement. For example, heuristics for pedestrian context have been developed by [1] who also note that filtering can actually counteract predictions at a later stage or degrade the derived position. [30] extend the well-known Kalman filter to also deal with larger nonlinearities and non-gaussian noise. Complementing these filters, several approaches for precise pedestrian location are dead reckoning by acceleration-sensors, sensor-fusion, or augmented installations.

Waiting for a more precise systems with next generation receivers does not solve the problem as positional errors especially in difficult surroundings will remain. Mechanisms have to be developed for mobile applications to overcome the imprecision or communicate the changing accuracy and availability to the user in a suitable fashion. Depending on the scenario, visualizing a "jumping" signal may be much more confusing to the user who expects the position to at least follow his or her movements. Small occasional jumps or deviations are instead often recognized as glitches in the system and, while distracting, do not hinder the overall user experience if dealt with accordingly.

Especially for twisty hiking trails, narrow paths, ways in the forest, or small streets in the city center the user experiences inaccuracies as mentioned above which might disturb or even ruin the intended application task such as following a route or finding a specific spot.

Within our project mobiDENK [24] we realized different mobile tourist guides, e.g., we are currently preparing a multimedia tourist application for the castle gardens in Jever. We frequently experience a jumping position with many devices that partially moves completely off the castle's grounds due to canopy environment. Since users can roam freely around the grounds and may even venture outside for additional sights, map matching is not feasible. We currently filter out spikes and outliers with a filter chain based on invalid position, satellite constellation and speed (cf. [1]), but quickly reach the limits of correction. Especially with invalid or deemed invalid positions, we have to use a time measure as well since we cannot suppress questionable positions forever. To eventually present any position to the user, we then have to use even imprecise measurements in this demanding environment instead of showing no position at all. Users here are aided by a map view which clearly marks positions of interest in relation to the grounds so users can orient themselves.

A. Awareness for quality of position

Location is commonly seen as one of the most important context features for a mobile context-aware application. Imprecision of the available data however makes this a noisy channel and an unsound basis for information derivation. Therefore, a location-aware application should not only model location, but also a well-defined accuracy annotation as a further context feature.

A commonly used indicator for the accuracy of positioning is the dilution of precision (DOP) that describes the influence of the satellites' geometric constellation on the accuracy. The lower the DOP value, the higher the positional accuracy. A value of 1 represents the ideal gemetric constellation of satellites used for retrieving the current position. However, this is a purely orbital geometric measure and cannot reliably predict the quality of actual accuracy, only predict numerical and triangulation errors in calculation.

GPS receivers are able to calculate the DOP of the currently retrieved position. Following the paradigm of context-aware applications, an application should always be able to adapt to situations where the receiver cannot obtain a good position or any at all. During that time, the user may have to be informed that his or her position is not available to the application at the moment. Parts of the application that are independent from positioning should of course keep working. The positioning-dependent parts need to degrade gracefully with structured fallback steps. This allows applications to discard position information when its quality if insufficient. This presumes that the application works even if the receiver does not update the user's positions for some time.

B. Designing with inaccuracy

Since position obtained through GNSS cannot be guaranteed to be sufficiently accurate, application developers should consider that fact from the early design stages on. In the following we propose possible topics for consideration.

1) Using correction methods: Standard correction methods such as map matching move a position deemed invalid on a map back to the nearest street. Obviously, this works best when the amount of streets is low and their distance is large, and also when the map material is current and matches the actual situation. Still, this is a technique which is difficult to use in the pedestrian context since a pedestrian is not confined to streets as a car and can walk everywhere [1]. Methods of dead-reckoning and extrapolation can be used during signal outages only for a short time, as a pedestrian's movement contains highly spontaneous parts. Since the movements of pedestrians are much slower and also much more random (a user may stop, change the street, go back a few metres etc.) this correction can prove countereffective. Active position correction by user intervention may be possible within some application types. If the position fluctuates between two possible places, the user can select the one s/he is actually at.

2) Evaluating requirement priorities: The design of pedestrian applications needs to take the expected environment into account. For casual use under open sky conditions, less concerns and fallbacks will have to be implemented compared to an inner-city operation with more inherent inaccuracies. Thus, if higher accuracies are needed, developers can try relaxing contrary requirements like the environment the application is planned to be used. For example, the requirement of higher accuracy could be traded against the requirement of limiting the user to a known network of walking paths.

3) Negotiating accuracy requirements: A similiar approach is to negotiate the accuracy requirements by negotiating the desired position visualization. Sometimes the solution can also be to simply offer no full map interface. We followed this approach as an evaluation for our MontaPhone system [26] which displayed distance-ranked POIs in the user's vicinity. This reduces the requirements towards the accuracy, since the user will not notice deviations of a few meters. If a map is desired, the inaccuracy can be countered by choosing a zoom level that corresponds to the level of inaccuracy and choosing no representation of the precice current user position. Today, it is impossible to direct a user to take two steps to the right to find a hidden secret. For coarse navigational uses the quality in conjunction with a map view is often sufficient, similar to car-based navigation systems. The problem here lies rather in the data and routing algorithms which have to be properly prepared for pedestrian use.

4) Using additional techniques for fine navigation: Most of the time during a navigation task, coarse navigational accuracy is sufficient. This can be complemented with different localization methods to find the current target. [31] use such a hybrid systems to lead mobile users to prepared virtual information cards hidden on real-world items. They describe a mean accuracy of within 3m but experience frequent GPS inaccuracies identified to occur near high-rise buildings or at overcast sky. To cope with these issues, the authors define several concentric regions of search for a user to locate a virtual card with different methods of navigation within them. For a coarse navigation, GPS is used, for finer navigation a digital compass and an accelerometer is added and the actual discovery of the virtual card is aided by matching the camera feed of the mobile phone to prepared images of the card's location. [32] uses a system that transmits photos of critical junctions onto a user's mobile phone to help in local wayfinding even without exact positioning. The Transit system [33] tries to avoid information overload by reducing the amount of location-based information users have to process. Personalized navigation allows to give abstract hints on well-known routes and only delivers greater detail for changes or new routes and thus leaves the user more autonomous.

5) Communication of inaccuracy: Even if no minimum accuracy is required, communicating the accuracy to the user helps her or him to interpret the information correctly. The most often used indicator is a visual bar lighting up in accordance to received quality such as used for battery status or network coverage on mobile phones. Sometimes also the positional indicator of a user can change color. Another possibility is to directly visualize the precision to the user on a map-based interface by demonstrating the variance of position by size-changing concentric circles or colour indication as shown in Figure 6.

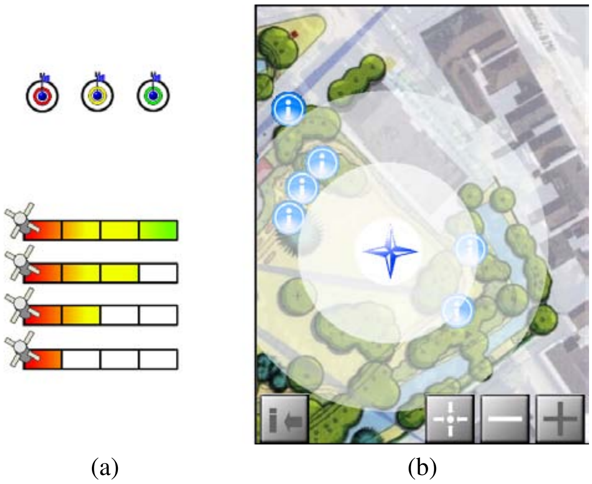
(a) (b)

Fig. 6. Possible UI solutions to visualize positioning accuracy: (a) Colour-based and bar graph indicator, (b) Area-based indicator

For other modalities the information presentation to a user would have to change. When the position would be only accurate within 30m, a navigational output cannot be "turn left in 20 metres" but would indeed have to be "turn left at the next junction" if it can be ensured that no other junction with left-branching streets occur within the accuracy radius or simply "turn left into Hillstreet". With an exactly mapped detailed environment we could even hint "go left after the gas station" or use images of the surroundings [34] to indicate junctions or POIs to a user [32], [35], [33]. Again, visualizing the route on a map can aid in resolving ambiguities if the user's situation allows the use of a map.

Situations as described by [35] "Due to failures in positioning caused by GPS inaccuracy, users blindly following instructions [..] are led wrong more often than users who have to orientate and plan a route themselves" can be avoided by relaying the positional accuracy to the user and also to approach and use the users spatial perception and mental capabilities to resolve ambiguities. Most often, this can be done by providing a map interface for the user to orient and locate him/herself. Other well-prepared sources of information can also help in relaying information in a way matching the user's perception. Additionally, the use of a color scheme within a map which draws the intended route with a more saturated colour than the actual track can further aid in unobtrusively guiding the user.

6) Using GNSS deficiencies as feature: Another approach especially suited for game design is to include the possible inaccuracy into the design itself. For example, if a game required players to avoid certain positions, the user could try to exploit satellite signal deflection by walking close to a tall building. Thus, the user would be appearing far away from the actual position, allowing her or him to pass the mentioned position. Including inaccuracy explicitly into the application's design also enables users to explore the basic principles behind GNSS.

C. Investigating further positioning technology

Addressing some of the presented shortcomings, for application scenarios where GNSS alone is insufficient or unavailable, various systems are under development. Some of this work is also driven by the wish to be independent from external devices and thus uses signals available to the handheld device itself with a reduces accuracy. These can use cell-id of mobile phone network transmission towers computed directly on the device or WLAN positioning and other short-range positioning beacons. The requirement to accurately locate users in indoor environments also drives some systems. Combination of the different technologies reduce dependency on one technology alone and allows seemless following of a user through indoor and outdoor environments.

[36] describe a system based on GSM cell-IDs which can work provider-independent on the mobile client using triangulation and filtering of received signal level on a known basis of transmitting stations. The serving station alone only yields a 1-10 km radius but with additional triangulation and filtering on signals of multiple base stations, more accurate measurements are possible down to 100m [37].

PlaceLab [38], [3] uses WiFi and GSM and has built up a massive database of access points and cell-ids along with their geographic coordinate, signal propagation and strength; a process called fingerprinting. The accuracy can be down to about 100m in densely-covered urban areas but also much lower in less-covered regions. [39] present an open source framework for positioning using WLAN, ZigBee, RFID as a basis. Fingerprinting can be more acurate within well-covered buildings as an indoor location system. Other methods within instrumented environments are location by ultrasonic sound or infrared beacons.

Other “ubiquitous” location techniques usually have some limitation or other. Most WiFi-based solutions will basically only work in instumented environments. Compared to earlier systems that needed exactly positioned highly expensive transmitters, this is a rapid development, but they still have only poor coverage in rural areas and many areas vital for e.g. tourism applications. For urban areas however, they may be a good complement or sometimes even a substitute for GNSS for loose accuracy requirements. However, it must be noted that these techniques also have several drawbacks concerning accuracy, with fallbacks relying on GPS location.

[40] presents a location recognition system that uses markers on widely deployed city maps to present additional information to users as a step towards augmented reality. In this case, fine navigation in front of a map is achieved by image processing.

The dead reckoning by external sensors as used with in-car systems is also pursued by groups that use a combination of GPS with IMU (inertial measurement units, accelerometers) [16], [41] to improve the positioning of a mobile user. Measuring movement as well as individual steps with GPS as initial positioning, ongoing calibration and mapping of extrapolated data is possible. Using an additional barometer, fluctuations in measured air pressure can be used to determine changes in elevation and for example, given assumptions about buildings, determine the level of a building a user is in. Since barometer measurements are noisy, context detection is used to determine whether the user is stepping up or down a stairwell and could have ascended. This is usually computed using several filters and sensor fusions to arrive at displacement information. [37] uses inertial measurements, cell-ID triangulation and mapping to achieve a positioning error of 15–20m. Other sensors used are digital compasses in combination with accelerometers to gather orientation and tilting angle [31] and thus to further augment the user’s context information.

VI. CONCLUSION

GNSS technology forms the basis for a multitude of useful mobile applications. To achieve a satisfying user experience, the positioning technology needs to fulfill non-functional requirements such as high accuracy, availability and reliability. However, GPS, the only GNSS with worldwide coverage, cannot always meet these requirements. Still, this is often not properly considered in the design and development process of location-based pedestrian applications. For example, when designing an application for urban areas the urban canyoning effect which decreases the position accuracy has to be taken into account.

Based on the experience of our group with mobile, location-aware pedestrian applications we analyzed the most frequent encountered issues. Although GPS devices have improved significantly during the last years, it is for example still not possible to simply ”‘start up and walk”’ since GPS receivers require open sky and need time to obtain a position fix. Even if the receiver provides a position there are many circumstances that can degrade the position quality and remains intransparent whether the position information is reliable and accurate.

We argue that in order to overcome the shortcomings related to GNSS based positioning they have to be considered as an integral part of the design process. We exemplarily discussed how these shortcomings could be addressed by raising the awareness for the position quality, including inaccuracy into the application’s design and investigating further positioning technologies to provide pedestrian users with innovative, reliable mobile applications.

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