Adapting Navigation Support to Location Information Quality: A Human Centered Approach

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Abstract. Variations in the quality of location information can negatively affect the users of pedestrian navigation support systems (PNSS). Current approaches to handle these variations mainly focus on improving the quality of location information by improving sensor technology and improving localization algorithms. This research introduces a different approach called "Adaptation to Quality" that adapts the behavior and output of the navigation application to the level of quality. Rather than treating location quality variations as exceptions or trying to improve the quality of location information, adaptation to quality focuses on still providing continuous navigation support even when the location quality is very low or when location information is no longer available. We carried out a series of experiments to investigate ways to facilitate Adaptation to Quality. This paper summarizes the findings and insights.

Keywords. Pedestrian navigation, Location information quality, GPS, Human-centered, Application behavior and output

1. Introduction

Pedestrian navigation support systems (PNSS) have completely changed the modus pedestrians used to find their way in unknown areas. Variations in the quality of location information however make it sometimes difficult or challenging to rely on wayfinding using PNSS. This can have negative impacts on user experience and on user trust on navigation applications. Current approaches to handle this variation in the quality of location information mostly focus on sensors or the processing that calculates positional information from raw measurements. Common strategies of this type include improving the sensor technology (e.g. integrating better clocks into GPS receivers, designing better chips, receivers, and antennas), fusing sen-

LBS 2019
15th Conference on Location Based Services
Vienna, 11–13 November 2019

Published in "Adjunct Proceedings of the 15th International Conference on Location Based Services (LBS 2019)", edited by Georg Gartner and Haosheng Huang, LBS 2019, 11–13 November 2019, Vienna, Austria.

This contribution underwent double-blind peer review based on the paper. https://doi.org/10.34726/lbs2019.66 | © Authors 2019. CC BY 4.0 License.

sor data (e.g. combining WiFi and GPS data) and developing better algorithms (e.g. by including contextual factors to eliminate unreachable positions). Due to these efforts, the average quality of positional information has continuously been increasing over recent years but new approaches to pedestrian navigation such as electrical muscle simulation (Pfeiffer et al. 2015) and haptic feedback (Pielot & Boll 2010) require much higher quality as they rely on high quality location information to trigger instructions. Despite these improvements, there still are and most likely always will be situations where location sensing will either produce low-quality location information or fail to provide location information at all. Such situations can be caused, for example, by technical failures, by user mistakes, or by the inherent dependency of sensors on contextual factors. The latter aspect refers to situations such as strong magnetic interference, difficult weather conditions and urban canyons, which can result in the complete loss or very low-quality location information.

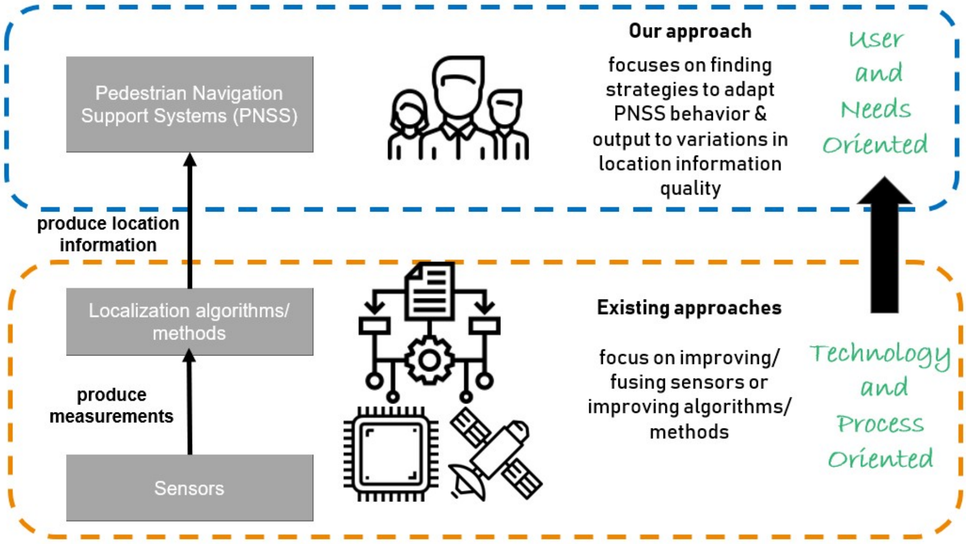

Figure 1. "Adaptation to Quality" focuses on adapting the behavior and output of the PNSS to the level of location information quality rather than on improving sensors or localization algorithms.

This research focused on investigating a new and complementary approach called "Adaptation to Quality" in solving this problem. "Adaptation to Quality" adapts the behavior and output of a PNSS to the location quality to continue to support the user rather than stopping support or exposing erratic behavior due to location quality variations. This new approach complements existing ones operating on the sensor or processing level. Our research focuses on the navigation support layer, and puts special emphasis on the interaction between the PNSS and the user (see *Figure* 1).

2. Related Work

Mobile pedestrian navigation support systems highly depend on the positional information from various sensors. In outdoor environments, the main source is satellite-based positioning information obtained from global navigation satellite systems (GNSS) such as the Unites State's Global Positioning System (GPS) and Russia's Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS). In addition to GNSS, PNSS also use other sensors of smartphones such the accelerometer, gyroscope (Pei et al. 2013), WiFi (LaMarca et al. 2005) and the mobile network (Fang 2012). Many factors such as multipath reflections, interferences, weather conditions and user related factors however cause variations in the quality of location information produced by these sensors. Consequently, the quality of location information can vary from very accurate and timely information to no information at all (Ranasinghe & Kray 2018). One approach to handle this problem is by improving sensor technology. For example, by developing better chips, antenna designs and receivers (Blunck et al. 2011). Also, the development of receivers with multi-constellation capabilities (Zhu et al. 2018) has enabled receiving signals from more than one satellite systems. Fusing sensors is also another method used for improving the accuracy and availability of positional information. For example, GNSS is often combined with inertial navigation (Godha et al. 2006). Apart from improving and fusing sensors, current systems also improve localization algorithms to improve the quality of location information (Zhu et al. 2018), (Reuper et al. 2018). All these existing approaches, improving sensors, fusing sensors and improving algorithms focus on improving the quality of location information. However, there are still situations caused by various factors that hard to model that positioning systems produce low quality location information (or no information).

3. Facilitating Navigation Adaptive to Location Information Quality: Methods and Outcomes

In previous work, we conducted a series of experiments and employed a combination of methods to investigate ways to facilitate navigation adaptive to location information quality (cf. *Figure* 2). This section briefly summarizes these methods and the findings in order to relate and discuss how these individual experiments contribute to the overall aim of finding ways to facilitate navigation adaptive to location information quality.

3.1. Methods

Understanding location information quality is crucial to understand how to deal with quality. We first conducted a thorough literature analysis of location quality to identify, to analyze and to characterize the aspects of location quality, factors causing quality variations and the existing approaches for dealing these factors (cf. *Figure* 2). Understanding users is integral to design human centered strategies to deal with quality variations. We conducted three user experiments for this purpose (Study 1, 2 \& 3 - cf. *Figure* 2). Study 1 investigated the impact of low-quality location situations on PNSS users, user strategies and needs of users when facing quality variations using a field-based user study (N=21) that exposed users to three types of location quality variations (low accuracy, no coverage and delay). Study 2 and study 3 investigated the use of visualizations to support users when facing low quality location information. Study 2 introduced two new visualizations to communicate location uncertainty and to assist users with landmark-based visualizations based on the level of quality of location information. The efficacy of the two new visualizations were compared to the state of the art using a field-based user study (N=18). Study 3 (lab-based, (N=52)) investigated the cross-cultural differences in how users perceive visualizations of location uncertainty. Finally, we developed a framework (LUIF for “location uncertainty injection framework”) for designing and evaluating strategies to adapt the behavior and output of a PNSS to location quality variations.

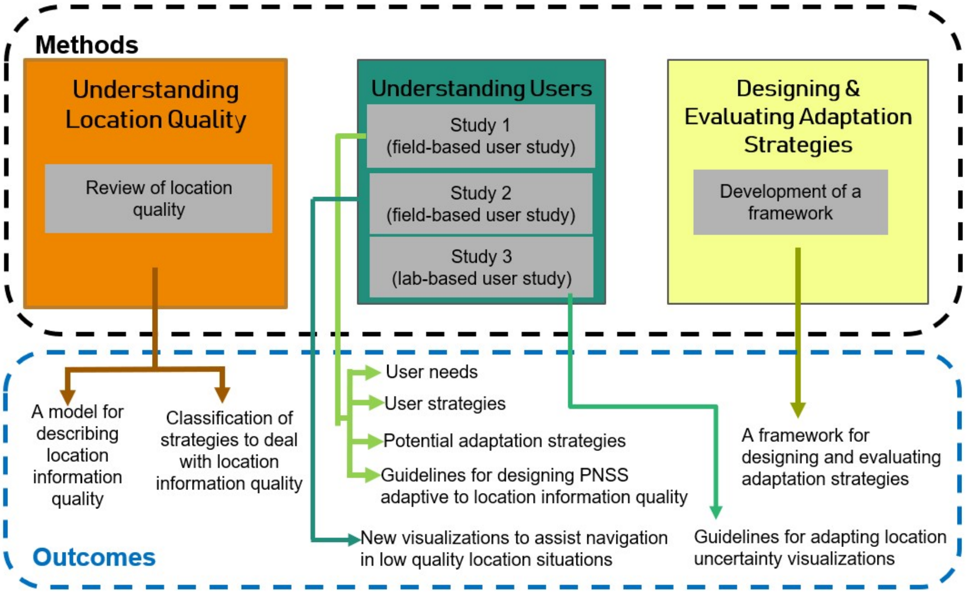

Figure 2. Facilitating navigation adaptive to location information quality: methods and outcomes.

Details of the literature review, study 1 and study 2 can be found in (Ranasinghe & Kray 2018), (Ranasinghe et al. 2018b) and (Ranasinghe et al. 2019a) respectively. Study 3 is described in more detail in (Ranasinghe et al. 2018a) and (Ranasinghe & Kray 2016). Further details of the framework are available in (Ranasinghe et al. 2019b).

3.2. Results and Implications

The literature review on location information quality resulted in two contributions: a model for describing quality of location information (cf. *Figure* 3); and a classification of strategies for dealing with quality variations (cf. *Figure* 4). The former describes location quality as a multi-faceted concept that includes seven aspects of quality (cf. *Figure* 3). These aspects were further categorized into two dimensions, spatial and temporal. Spatial dimension of location quality includes, accuracy, precision, granularity, coverage and conflicts whereas the temporal dimension consists of update rate and recency.

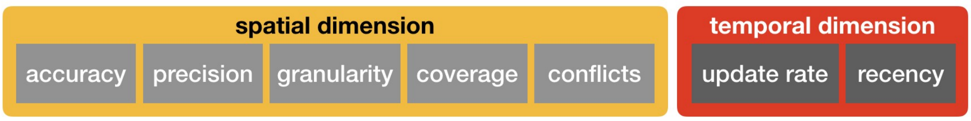

Figure 3. A model for describing location information quality (Ranasinghe & Kray 2018)

Designers of location sensing systems can use the quality model as a standard vocabulary to report and describe the quality of location information of their systems. This makes it easier and useful for the designers of PNSS to plan for and design adaptation strategies. Usually, location sensing system designers report the accuracy of their systems but rarely the other aspects of quality. It is also useful to report under what conditions the reported quality applies. This in turn helps designers of adaptation strategies to compare location sensing systems and to design adaptation strategies at different levels (eg. sensor level, algorithm level, application level). Use of a standard vocabulary to report quality also makes it easier to evaluate and benchmark location sensing systems. This is helpful in selecting suitable location sensing systems for PNSS as well as to identify future research directions. An interesting future research direction along this line is to develop a central platform for reporting quality of location sensing systems. Currently, there is a large volume of research on better location sensing and improving the quality of location information. For example, there is a lot of research on mitigating the impact of multipath reflections on WiFi based positioning. Many sensor and algorithm level approaches have been introduced. The current means of reporting the quality of the location information produced by these approaches is through the corresponding publications. This makes it practically difficult to compare those approaches along different dimensions (for example, comparing the accuracy of WiFi fingerprinting based approaches). A common platform for reporting the quality, preferably together with the source data and other settings would make it easier to benchmark location sensing systems, compare them and to identify future research directions.

The classification of existing strategies for dealing with the variations of location quality categorizes the existing approaches into three classes: sensor level adaptation, algorithm level adaptation and application level adaptation. These classes are organized in three levels and are also aligned with the popular software engineering model for ubiquitous applications, the Location Stack (Hightower et al. 2002). Designers and developers of PNSS can use the classification of existing strategies to design strategies for avoiding problems due to quality variations or to design strategies for dealing with quality variations on three levels that are aligned with the Location-Stack model (Hightower et al. 2002). This classification implies that application level adaptation strategies can be planned and designed in the three top layers of the LocationStack, intentions, activities and contextual fusion.

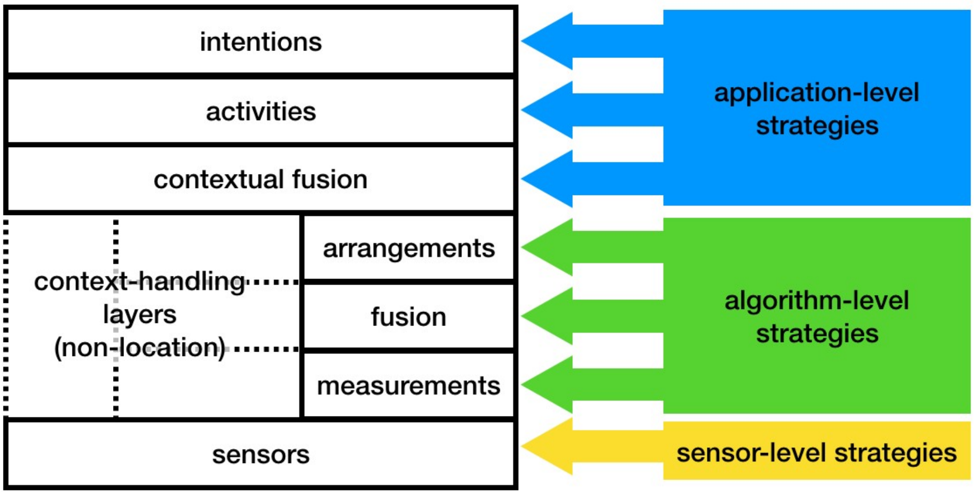

Figure 4. Classification of strategies (right) to deal with location quality variations (Ranasighe & Kray 2018) aligned with the Location Stack (Hightower et al. 2002).

This classification also provides a basis for benchmarking PNSS. For example, to see what PNSS provide adaptation at all three levels (sensor, algorithm, application) or what PNSS provide adaptation strategies at all three application layers of the location stack (intentions, activities and contextual fusion). Furthermore, this classification can be used as a basis for benchmarking adaptation strategies for different aspects of quality. For example, to compare the adaptation strategies (sensor level, algorithm level, application level) for no coverage. It will also be useful to dig deeper into each class and identify subcategories of strategies in each class. Extending the classification to other types of positional information (eg. orientation, speed), to other types of contextual information or even to other types of LBSs would be an interesting future research direction.

Study 1 (Ranasinghe et al. 2018b) showed that user performance, user experience and user trust in the navigation application are negatively affected by location quality variations. The degree of impact of these variations on users varied a lot based on different factors such as personal navigation techniques, situation, type of quality variation and the magnitude of the problem. The study revealed five principle user strategies to deal with low quality location information : (a) slow down and pay more attention until the location quality is good; (b) ignore the location marker but keep referencing the map to assist navigation; (c) walk back to a known location and start to reorient and navigate from there; (d) asking from someone; and (e) use local information such as 'you are here' maps. Study 1 also identified four classes of user needs in situations of low location quality (detailed in (Ranasinghe et al. 2018b)): (a) notification about the problem; (b) rendering; (c) more information; and (d) ability to control the options and offline support.

Based on the results of study 1, we derived four application level adaptation strategies and guidelines for designing PNSS adaptive to location information quality: (a) notifying about the problem; (b) emphasizing landmarks along the suggested path; (c) displaying landmarks based on location accuracy; and, (d) asking the user to slow down and pay more attention. Furthermore, based on the results of study 1, we also derived two classes of design guidelines for facilitating adaptation: (a) map and data quality; (b) empowering users. The results imply that maps with high level of detail such as embedded landmarks with on-demand information such as photographs are helpful to users in situations of low location quality. In order to support the differences in users, their navigation strategies, preferences, perceptions, situations, context and severity of the low quality situations, these guidelines recommend designing of different strategies, functionalities and interfaces to cater for a diverse and a large user base and to empower users to select the options to match their requirements.

Figure 5. Visualization of landmarks based on the level of accuracy to support navigation in GNSS degraded situations (Ranasinghe et al. 2019a).

Study 2 (Ranasinghe et al. 2019a) showed that landmark-based visualizations (cf. *Figure* 5) significantly reduced the number of wrong turns, and it helped users to judge their true location in the environment when faced with low-quality location information. In addition, users preferred this new visualization over the existing circular one. Despite its unfamiliarity, the subjective workload (mental and physical) and user experience of landmarks-based visualization were similar to those of more familiar circular visualization. Therefore, we see a great potential of visualizations of landmarks in supporting users in navigation under GPS-degraded situations. We thus encourage further research on using landmarks for this purpose.

Study 3 (Ranasinghe et al. 2018a, Ranasinghe & Kray 2016) studied the existing adaptation strategy of communicating location uncertainty to users and derived guidelines for adapting the visualizations of location uncertainty to the quality of the location information. These guidelines provide instructions on how to adapt the visual representations to modify people's perception to align them with the quality of location information. Designers of PNSS can use these guidelines to better communicate the location uncertainty to the users. Studying the impact of uncertainty visualizations on user perceptions in situ and comparing the results with the lab studies is a promising future research direction. Researchers can also further investigate the impact of uncertainty visualizations on aspects such as navigation performance, physical workload and mental workload. Furthermore, it makes sense to explore how to visualize other aspects of quality such as no coverage and delay and how users understand such visualizations.

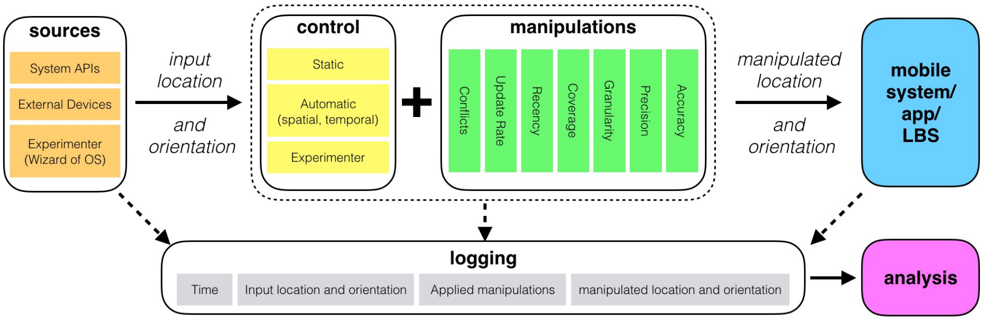

Figure 6. Location uncertainty injection framework (LUIF) for designing and evaluating adaptation strategies in-situ with users (Ranasinghe et al. 2019b).

The proposed framework LUIF - location uncertainty injection framework – (cf. *Figure* 6) (Ranasinghe et al. 2019b) provides a platform for evaluating how PNSS users behave and interact with the application when faced with low-quality location situations in the real world. A preliminary evaluation based on expert reviews confirmed the validity of theoretical and methodological aspects of LUIF. These types of in-the-wild user evaluations also provide useful insights for designing adaptation strategies. For example, they could trigger new insights to the developer that are otherwise undiscoverable. In addition, it can be used as a tool for evaluating adaptation strategies. Since it can be used to evaluate different users under different types of quality variations and in different environments, it facilitates developing further adaptation strategies and comparing them systematically.

Promising future extensions to LUIF include functions such as incorporating experience sampling, dynamic triggers such as social encounters, additional logging such as feelings of users using behavioral sensors and enabling combined manipulations or layered manipulations.

4. Discussion and concluding remarks

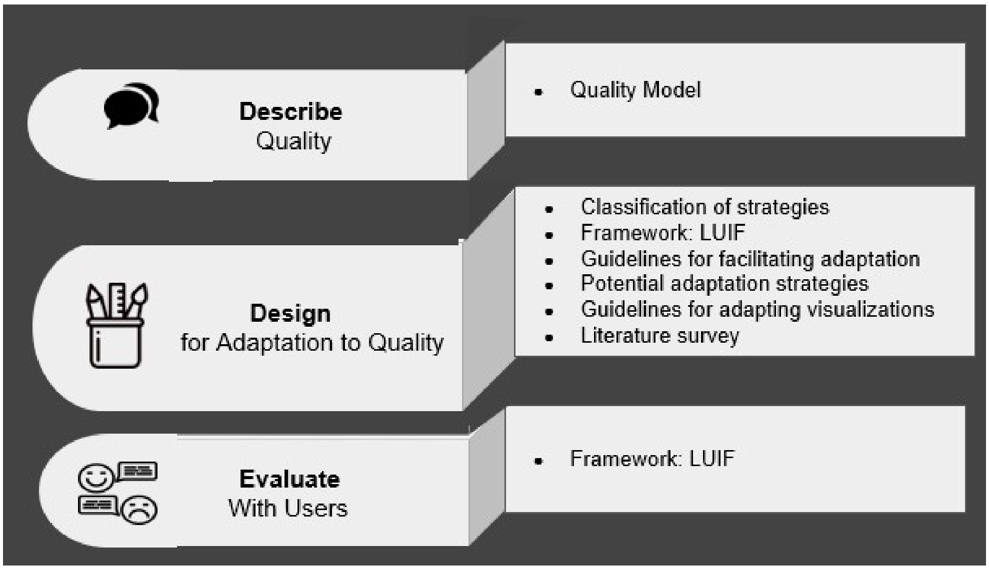

Figure 7. Outcomes of this research provides three types of means to facilitate adaptation to quality: tools for describing, designing and evaluation.

The goal of this research was to find ways to facilitate the development of pedestrian navigation applications that adapt their behavior and output to the level of location information quality in a human-centered way. The outcomes of the series of experiments in this research provides means for this purpose in three ways: (i) tools to describe quality; (ii) a set of tools to design for adaptation to quality; and (iii) a framework to evaluate the designs with users. These are summarized in *Figure* 7.

Based on the outcomes of our research, we can define five pillars that determine successful facilitation of pedestrian navigation support that is adaptive to location information quality (cf. *Figure* 8).

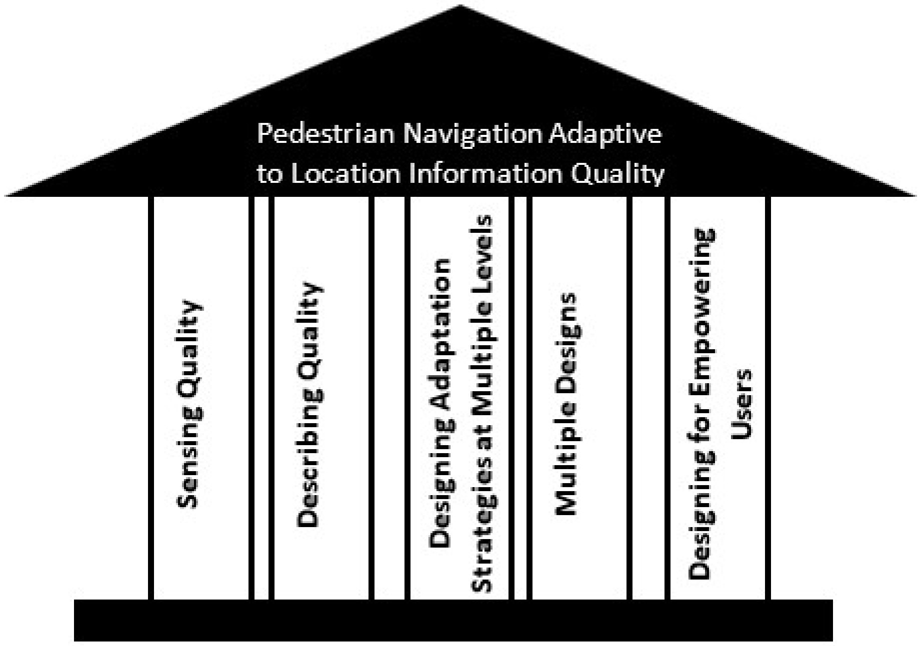

Figure 8. Five pillars of facilitating pedestrian navigation adaptive to location information quality.

Sensing quality is an important factor in determining the effectiveness of adaptation strategies. Applications can have different adaptation strategies for different aspects of quality as well as for different levels of quality of the same aspect. Therefore, sensing quality is required for triggering different adaptation strategies. An explicit description of different quality levels also contributes towards specifying adaptation strategies. For example, identifying what sensor parameters can be used to better describe different aspects of quality and further research on quantifying quality would be highly relevant and useful.

It is also important to research adaptation strategies that can be used when sensing quality accurately is not possible or to find alternative parameters to use when proper sensing of quality is not possible. Dealing with quality variations at the sensor level, algorithm level or application level in isolation would not guarantee navigation support all the time. Consequently, adaptation strategies need to be designed at all the three levels and in combination to ensure better navigation support. Beyond just the accuracy of a system, detailed descriptions of the quality of location information produced by location sensing systems are useful in designing adaptation strategies at multiple levels. Aspects such as granularity and recency or under what conditions the reported quality applies allow for comparing location sensing systems (e.g. to select potential localization techniques) and for designing adaptation strategies at different levels (e.g. sensor level, algorithm level, application level).

Design, realization and practical use of adaptation strategies in PNSS are challenging due to various factors such as individual differences between users, their navigation strategies, perceptions and contextual factors. Ways to overcome this are to improve map and the data quality, to design interfaces and functionalities for a diverse and wider use base, and to empower users to choose options and adaptation strategies that best match their preferences, situations and contexts. Overall, following a user-centered approach for designing and evaluating adaptation strategies could help to address many of the challenges that arise due to these aspects. Further research with users from different age groups or with different backgrounds would also contribute towards developing effective adaptation strategies and guidelines. The same applies for studies on different usage scenarios.

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