Geo-Information Fusion for Time-Critical Geo-Applications

Dissertation

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Abstract

This thesis is addressing the fusion of geo-information from different data sources for time-critical geo-applications. Such geo-information is extracted from sensors that record earth observation (EO) data. In recent years the amount of sensors that provide geo-information experienced a major growth not least because of the rising market for small sensors that are nowadays integrated in smartphones or recently even in fitness wristbands that are carried at the body. The resulting flood of geo-information builds the basis for new, time-critical geo-applications that would have been inconceivable a decade ago. The real-time characteristics of geo-information, which is also getting more important for traditional sensors (e.g. remote sensors), require new methodologies and scientific investigations regarding aggregation and analysis that can be summarised under the term geo-information fusion.

Thus, the main goal of this thesis is the investigation of fusing geo-information for time-critical geo-applications with the focus on the benefits as well as challenges and obstacles that appear. Three different use cases dealing with capturing, modelling and analysis of spatial information are studied. In that process, the main emphasis is on the added value and the benefits of geo-information fusion. One can speak of an "added value" if the informational content can only be derived by the combination of information from different sources, meaning that it cannot be derived from one source individually.

Another goal of this thesis is the prototypical integration of the fusion approach in spatial data infrastructures (SDIs) to increase the interoperability of the developed methods. By doing so, the fusion can be provided (e.g. over the internet) and used by a multitude of users and developers. Above that, the integration is of high importance regarding systems and concepts like the Global Earth Observation System of Systems (GEOSS), the INSPIRE directive for Europe or the European monitoring system Copernicus.

The results and findings of this thesis can be seen as the first advances and can be used for further research and studies in the field of geo-information fusion which will gain further importance and relevance for all spatial questions in the future.

Zusammenfassung

In dieser Arbeit wird die Fusion von Geo-Informationen aus unterschiedlichsten Datenquellen speziell für zeitkritische Geo-Anwendungen untersucht. Diese Geo-Informationen stammen in der Regel aus sog. Earth Observation (EO) Daten die von Sensoren gewonnen werden. In den letzten Jahren wächst die Anzahl an Sensoren die Geo-Informationen liefern enorm, nicht zuletzt auch durch den großen Markt von Kleinstsensoren, die in Smartphones oder neuerdings z. B. auch in Fitnessarmbändern am Körper getragen werden können. Die daraus resultierende Flut an Geo-Informationen schafft die Grundlage für neue, zeitkritische Geo-Anwendungen, die vor Jahren noch undenkbar gewesen wären. Der Echtzeit-Charakter von Geo-Informationen, der auch bei traditionellen Sensoren (z. B. Fernerkundungssensoren) eine immer größere Rolle spielt, erfordert neue Methodiken und wissenschaftliche Untersuchungen ebendieser hinsichtlich Aggregation und Analyse, die sich unter dem Begriff Geo-Information Fusion zusammenfassen lassen.

Das Hauptziel dieser Doktorarbeit ist es, die Fusion von Geo-Informationen für zeitkritische Geo-Anwendungen zu Untersuchungen und dabei Vorteile und auch Herausforderungen sowie Hindernisse aufzuzeigen. Drei unterschiedliche Anwendungsfälle aus den Bereichen Erfassung, Modellierung und Analyse von räumlichen Informationen werden hierfür untersucht. Dabei steht immer die Frage im Vordergrund, welchen Mehrwert und welche Vorteile sich durch die Fusion von Geo-Informationen ergeben. Ein Mehrwert ergibt sich nur dann, wenn der Informationsgehalt lediglich durch die Kombination von Informationen unterschiedlicher Datenquellen gewonnen werden kann und nicht bereits aus einer der Datenquellen allein ableitbar ist.

Ein weiteres Ziel dieser Arbeit ist die prototypische Einbindung des Fusionsansatzes in Geodateninfrastrukturen (engl. spatial data infrastructures, kurz: SDI) zur Steigerung der Interoperabilität der entwickelten Methodiken. Die Fusion kann so für eine Vielzahl von Nutzern und Entwicklern beispielsweise über das Internet verfügbar gemacht und verwendet werden. Diese Integration ist von besonderer Wichtigkeit vor dem Hintergrund von Systemen und Konzepten wie dem Global Earth Observation System of Systems (GEOSS), der INSPIRE-Richtlinie für Europa oder dem europäischen Monitoring System Copernicus.

Die Ergebnisse und Erkenntnisse dieser Doktorarbeit bilden einen ersten Aufschlag für weiterführende Forschungen und Studien im Bereich der Geo-Informationsfusion, die für alle räumlichen Fragestellungen zukünftig an Wichtigkeit gewinnen wird.

Danksagung

Es gilt sehr vielen Leuten zu danken, die einen enormen Anteil an dieser Arbeit haben und ohne die ein erfolgreicher Abschluss meiner Promotion in weite Ferne gerückt wäre. Zunächst möchte ich allen Personen danken, die mich über die Jahre hinweg begleitet haben und aus denen neben der Wissenschaft auch teils gute Freundschaften entstanden sind. Die Liste an Personen würde zu lang werden, daher komprimiere ich meinen herzlichsten Dank an die folgenden Personengruppen in der Hoffnung, dass die entsprechenden Personen sich angesprochen fühlen: Allen Angehörigen des **IGF** (aktuell und ehemalig), den lieben Kollegen des **DLR** sowie allen Kolleginnen und Kollegen die ich über die Arbeit in der **ISDE** kennenlernen durfte!

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Abseits der Wissenschaft und des Hochschullebens möchte ich ebenfalls einigen Personen meinen Dank aussprechen. Zunächst möchte ich **meinen Eltern** danken, die schon immer meine Neugierde förderten und mich während des Studiums und auch in der Zeit danach immer enorm unterstützt haben! Durch die Freiheit, die ihr mir gegeben habt bin ich zu dem geworden, der ich heute bin – Danke!

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1 Introduction

1.1 Motivation

22nd of April 2015 – Earth Day. For the last 45 years, it has been the day when the whole world focuses on problems and challenges regarding our planet and our environment. Climate change, global warming, sustainability of resources, industrial pollution and environmental protection in general are topics that are discussed all around the world. Earth Day has the goal of raising awareness among citizens and especially among young people of problems that affect the present and the future.

Environmental scientists are studying our planet and the natural phenomena on it to tackle those problems which concern us all - not only on Earth Day. Precise and up-to-date geographic information (or briefly geo-information) about such phenomena are crucial for researchers and likewise for political decision-makers. According to Sugumaran & Degroote (2010; pp. 3-5), "Geographic information is crucial to decision making by all manner of organizations" and that an "increased use of spatial information at all levels of government, business, and academics" is apparent. This geo-information is extracted from Earth observation data (EO) gathered by remote sensors (e.g. satellites and aircraft) as well as surface and subsurface geo-sensors. The number of sensors is increasing in recent years and its data is available through systems like the Global Earth Observation System of Systems (GEOSS) or Copernicus and INSPIRE in Europe, often even in real-time. Above that, the ubiquity of sensors integrated in smartphones as well as the rising trend of wearable sensors is pushing this development even further. Meaning that almost every person is able to provide (real-time) geo-information. All this allows for thinking about novel **time-critical geo-applications** that were not foreseeable one decade ago and imply several special challenges, e.g. computational efforts and up-to-date information. However, the large amount of geo-information in combination with its (near) real-time characteristics requires new methods and scientific investigations regarding aggregation and analysis that are not yet available, especially not in typical GIS software. This is the context in which this dissertation with its main topic "geo-information fusion" is embedded.

The term "fusion" relating to geo-data or geo-information is often ambiguous. Terms like "data fusion", "image fusion" and "sensor fusion" are wide-spread in geo-information science and especially in remote sensing (cf. section 2.2). They are normally associated with the combination of images or spectral channels for the same investigation area from different remote sensor systems e.g. using transformations. However, the general idea behind every fusion is to combine data or information from different sources to generate new information that could not be derived from only one of the sources. The same applies for geo-information fusion. However, as the name implies it deals with combination on the information level rather than the data level. The information level is the lowest common denominator for every data set. For instance, one can imagine a traffic monitoring application that combines traffic density information derived from image data gathered by static traffic cameras as well as in situ sensor data from mobile phones of car passengers. It is not possible to directly combine image or video data from the traffic cameras and the in situ sensor data from mobile phones in a reasonable way on the data level because of different data types. If information, or more specifically geo-information, in this case the traffic density, is derived from both data sets, this information can be fused for a specific application like the above-mentioned combined traffic monitoring. Hence, this work is not dealing with geo-data fusion but with **geo-information fusion**.

The required geo-information for the fusion can be extracted from any possible data source (e.g. image from satellite and data from a water level gauge). One can argue that such combination of various information has already been done in typical GIS software for decades. However, existing methods (e.g. within a GIS) cannot efficiently handle and exploit real-time geo-information apart from simple visualisation. Thus, extensive scientific investigations are conducted in this thesis to develop and evaluate appropriate methods for time-critical geo-applications. With regard to GEOSS and INSPIRE, a secondary goal of this work is the possible integration of the developed methods in **spatial data infrastructures (SDIs)**. SDIs allow for providing geo-data as well as geo-spatial functionality within a specific network like the World Wide Web. By integrating geo-information fusion in SDIs, the interoperability increases dramatically as everyone is able to access and use the new geo-information as well as the fusion functionality itself.

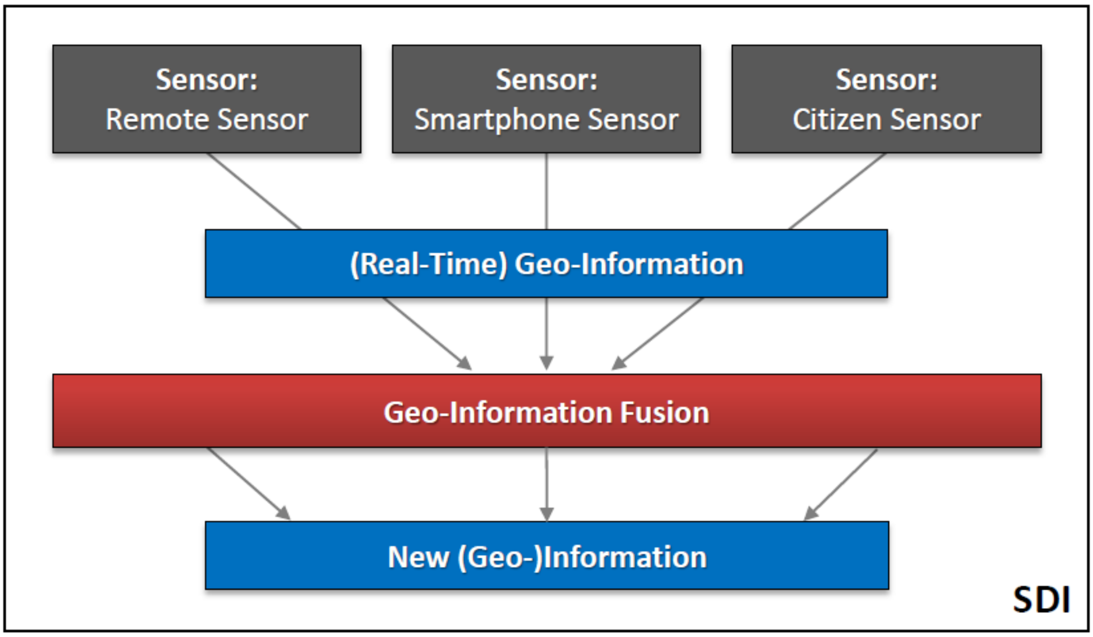


Figure 1. General concept of geo-information fusion.

Figure 1 illustrates the concept of geo-information fusion in the course of this thesis. Geo-information, whether it is actually real-time or not, is extracted from various sensor data, in this work remote sensors, smartphone sensors and citizen sensors. Afterwards, this information is combined in the "black box" called geo-information fusion and results in new information that might or might not be directly geo-related. In the course of this thesis, some facets of the aforementioned geo-information fusion "black box" are investigates, leading towards the full potential of the geo-information fusion concept.

1.2 Overall Approach

This dissertation addresses the lack of research regarding the fusion of geo-information by presenting three time-critical use cases from different facets of geo-information science, namely capturing, modelling and analysis. These topics are heavily related to the functional components model IMAP (input, management, analysis, presentation) of a GIS (de Lange 2013, p. 338) and are thus good representatives for GIS workflows and geo-applications. During the process of conception, implementation and evaluation of the use cases, challenges and benefits of integrating (real-time) geo-information are revealed. All presented approaches are generally based on the assumption that up-to-date geo-information is integrated constantly over time. As the use cases are prototypes of potential future applications, this can only be achieved by simulating the real-time information flow at this stage of research. However, the information itself is extracted from authentic data sets that are gathered under real circumstances and test sites of the respective use cases. Hence, all results and scientific findings can be applied for an actual integration in real time.

Use case #1 is about the **capturing** of new geo-information. For this purpose, an innovative acquisition approach for user-generated information named Geo-reCAPTCHA is introduced. Based on the model of the reCAPTCHA idea, it provides a test to differentiate between human and machine (e.g. for security issues like online form validation) and uses the effort of the user to generate new information (in this case geo-information). Fusion approaches are applied at two stages of the work-flow (Figure 2). First, the actual capturing by the user can be seen as a fusion process of remote sensors and citizen sensors (first red box in Figure 2). Second, the captured information itself is aggregated and combined to generate information that cannot be derived from single captures (second red box in Figure 2). To investigate this in detail, a Geo-reCAPTCHA prototype is implemented and used for an empirical user study.

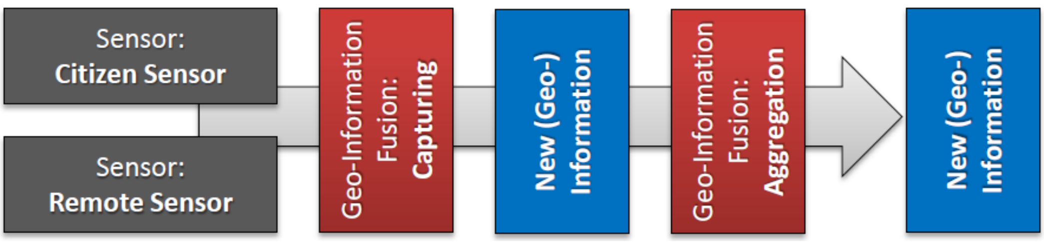


Figure 2. Overall methodology of the capturing use case.

Use case #2 deals with the **modelling** and prediction of spatial phenomena. The basis for this is an agent-based modelling approach for single person movement using remote sensing and smartphone sensor data. Therefore, test recordings and preliminary investigations regarding movement data recorded by smartphones are conducted. Based on these results, a model for predicting the movement of a single person is designed and implemented. The fusion approach is applied and implemented within the model itself by integrating smartphone and remote sensing data (Figure 3). Here, the smartphone orientation is used as an indicator for the movement direction of the agent. Information about the position of other people in the investigation area are derived from remote sensing data. Both pieces of information are not inferable from one of the sensors only. Thus, the effect of integrating both sensor sources is investigated. Furthermore, the real-time characteristic of geo-information is subject of research in this use case by comparing the modelling results using different geo-information integration frequencies.

Compared to the first use case, the new geo-information that results from the fusion process is the direct result of the modelling itself (red box in Figure 3). The information from both sensors is directly processed at certain points in the model. Consequently, the fusion is not providing new "raw" geo-information as it is the case in the first use case. The fusion rather is a part of the calculation of the new geo-information in this case.

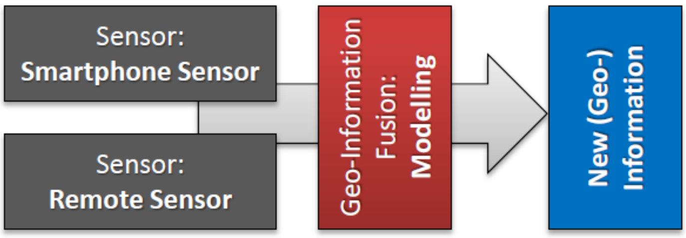


Figure 3. Schematic representation of the methodology of the modelling use case.

Use case #3 deals with navigation in dense human crowds during major events and is addressing the **analysis** potential of fused geo-information. The fusion approach in this use case is applied to create the data basis for an upcoming geo-spatial analysis (Figure 4). For this purpose, people density information is derived from remote sensing data using a texture-based classifier. In addition, smartphone movement data, especially the recorded movement speed, are converted to density information as well. Both information is combined to build a joint density map (first blue box in Figure 4). This map is then used as the basis for the actual analysis process of this use case, namely a least-cost routing calculation (orange box in Figure 4). In this case, the information derived from the sensors are the same so one could argue that the actual benefit of fusing the data is unnecessary. However, this use case is demonstrating how multiple sensor data might improve the data basis compared to the usage of only one data source.

Above that, this use case is the combination of the two aforementioned use cases. The fusion delivers new "raw" geo-information as it is the case for the first use case. Furthermore, this information is then integrated in a geo-spatial analysis. In particular, this use case is demonstrating the potential of the geo-information fusion for new applications.

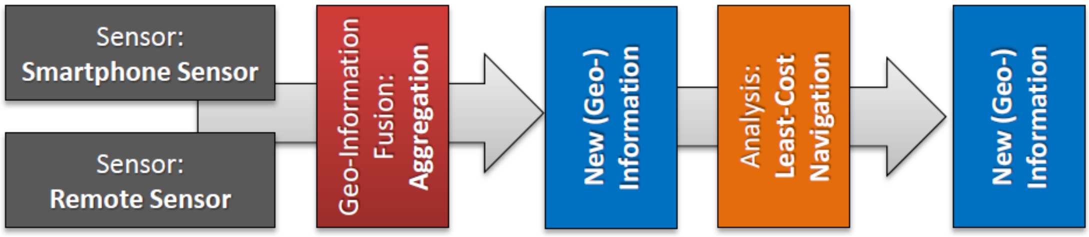


Figure 4. Schematic representation of the methodology of the analysis use case.

Concluding, a first approach for integrating a geo-information fusion process in an SDI is developed according to Figure 1. The conception and implementation is based on experiences gained from designing and implementing the presented use cases. On this occasion, the Information Fusion Service (IFS) is introduced and evaluated.

1.3 Selected Publications

The following peer-reviewed journal publications build the foundation of this dissertation. The written words of these papers are included in sections 3, 4 and 5 of this thesis along with unpublished research findings (see Table 1 for details). Footnotes highlight each literal and textual extraction at the beginning of a respective section:

1. **Hillen, F.**, Höfle, B., Ehlers, M., Reinartz, P., 2014. Information Fusion Infrastructure for Remote Sensing and In-Situ Sensor Data to Model People Dynamics. International Journal of Image and Data Fusion, 5(1), pp. 54–69.
2. **Hillen, F.**, Höfle, B., 2015. Geo-reCAPTCHA: Crowdsourcing large amounts of geographic information from earth observation data. International Journal of Applied Earth Observation and Geoinformation, 40, pp. 29–38.
3. **Hillen, F.**, Meynberg, O., Höfle, B., 2015. Routing in Dense Human Crowds Using Smartphone Movement Data and Optical Aerial Imagery. ISPRS International Journal of Geo-Information, 4(2), pp. 974-998.

Additionally, the following publications from conferences are included in this thesis as well:

4. **Hillen, F.**, Ehlers, M., Reinartz, P., Höfle, B., 2013. Fusion of Real-Time Remote Sensing Data and In-Situ Sensor Data to Increase Situational Awareness in Digital Earth Applications. In Proceedings of 35th International Symposium on Remote Sensing of Environment (ISRSE). pp. 1–6.
5. **Hillen, F.**, Höfle, B., 2014. Fast-Echtzeit vs. Echtzeit - die Auswirkungen von Echtzeit-Datenintegration am Beispiel einer agentenbasierten Modellierung im GIS. In Strobl, J. et al., eds. Angewandte Geoinformatik 2014. Wichmann, pp. 658–663.

Sections	Publications
3.1 - Introduction Use Case #1 **4.1** - Methodology Use Case #1 **5.1** - Results Use Case #1	Publication 2
3.2 - Introduction Use Case #2 **4.2** - Methodology Use Case #2 **5.2** - Results Use Case #2	Publications 1, 4 & 5
3.3 - Introduction Use Case #3 **4.3** - Methodology Use Case #3	Publication 3
5.3 - Results Use Case #3	Publication 3 & Unpublished
4.4 - Methodology SDI Integration	Publication 1 & Unpublished
5.4 - Results SDI Integration	Unpublished

Table 1. Overview of sections that contain parts that have partially or entirely been published in the respective publications.

1.4 Objectives and Research Questions

Currently, the wide range of earth observation data provided via platforms like GEOSS is not yet used and exploited appropriately from an application point of view. The benefits that arise from combining these diverse data is not revealed to developers and customers. Thus, this thesis addresses different time-critical use cases to demonstrate benefits and challenges of fusing (real-time) geo-information. Above that, a first advance to integrate geo-information fusion in SDIs to emphasise the interoperability within the context of GEOSS, INSPIRE or Digital Earth is conducted. In addition, the presented use cases themselves raise different problems and challenges that are addressed.

The primary research questions defined for this thesis are as follows:

1. How can time-critical geo-applications benefit from the combination of information from different geo-sensors, i.e. information that cannot be derived from only one geo-sensor?
2. Which challenges and obstacles accompany geo-information fusion regarding the integration in time-critical geo-applications?
3. To what degree does real-time geo-information increase the quality of the new information that is resulting from geo-information fusion?

4. How can geo-information fusion be used to increase the value and reliability of user-generated information from citizen sensors in particular?
5. How can the process of fusing real-time geo-information be integrated into an SDI?

The listed research questions are used to derive the following concrete objectives and tasks:

- To develop and implement different use cases showing the benefits of geo-information fusion for different aspects of geo-information science.
- To investigate and tackle the challenges that accompany the fusion of geo-information from different sources.
- To exploit the potential of citizen sensors in combination with information from other geo-sensors.
- To study the resulting differences of integrating real-time and near real-time geo-information in an exemplary modelling approach
- To design a concept of integrating geo-information fusion in SDIs that allows for a seamless integration in existing infrastructures (e.g. GEOSS, INSPIRE)
- To reveal new application possibilities that accompany the idea of geo-information fusion which might encourage and inspire developers to pick up some ideas and increase the awareness of geo-information fusion.

2 Definitions and Terminology

2.1 Programmes and Concepts of Geo-Information Acquisition

Geographic information is defined by Goodchild (1997) as the knowledge (e.g. derived from geo-data) about where something is located and what is to be found at a given location. As mentioned in the introduction, Sugumaran & Degroote (2010; pp. 3-5) state that "Geographic information is crucial to decision making by all manner of organizations" and that an "increased use of spatial information at all levels of government, business, and academics" is apparent. According to this, a lot of programmes and concepts have been developed and established in recent years to harvest geo-information and to provide it for the general public.

The Group on Earth Observations (GEO)[1] has been addressing the increasing need for comprehensive geographic information since its establishment in 2005. GEO consists of 97 member states and 87 participating organisations with the vision "to realize a future wherein decisions and actions for the benefit of humankind, are informed by coordinated, comprehensive and sustained Earth observations and information" (GEO 2015). For this purpose, GEO is building the Global Earth Observation System of Systems (GEOSS)[2] that will enable the access and use of world-wide Earth observation systems and resources especially for decision-makers. GEOSS relies on open exchange of data and tools (i.e. services or best practices) that can be accessed through the GEOSS Common Infrastructure (GCI). The GEOSS Data Collection of Open Resources for Everyone (GEOSS Data-CORE) records over 1.2 million data sets that consists of over 50 million measurements (e.g. satellite scene, gauge records, etc.) (Ochiai 2014). Despite this large number of data sets, Roglia et al. (2014) report on assessment surveys on GEOSS Data-CORE that "about three-quarters (76%) of the respondents [...] indicated that they were aware of the concept of GEOSS Data-CORE" and that "only 23% of the respondents that were aware of the GEOSS Data-CORE indicated that they were using it". Furthermore, it is stated that practical demonstrations on how to efficiently use the data might increase the acceptance.

In addition to the advances of GEOSS, other programmes and concepts are ubiquitous in geo-information science (GIScience) to provide and exchange geo-information. In Europe, the Directive 2007/2/EC to establish an Infrastructure for

[1] https://www.earthobservations.org
[2] http://www.earthobservations.org/geoss.php

Spatial Information in the European Community (INSPIRE) entered into force on 15th May 2007. Each member state has to implement its own infrastructure under common Implementing Rules (e.g. concerning metadata, services) by 2019 to provide spatial information for 34 data themes needed for environmental applications (European Commission 2015). Thus, INSPIRE will provide a lot of geo-information from municipal to country level Europe-wide.

Another programme that is coordinated and managed by the European Commission is the European Earth monitoring system Copernicus[3]. It consists of earth observation via satellite and airborne sensors as well as in situ sensors. The data are processed which provides "reliable and up-to-date information" via specific thematic services addressing the topics land, marine, atmosphere, climate change, emergency management and security (Copernicus 2015).

Compared to GEOSS, INSPIRE and Copernicus, the vision of the Digital Earth can be classified to a more conceptual level. Originally from a prepared speech by former US vice president Al Gore (1998), the idea grew into an independent research field (ISDE 2015). Gore envisioned a virtual globe that enables the access to all information (scientific and cultural) to understand the Earth via the Internet for every citizen free of charge. As the visualisation aspect of this vision is already fulfilled for the most parts by digital globes like Google Earth[4] or NASA World Wind[5], the information level is still under development with programmes like GEOSS and INSPIRE. A key for this latter aspect of the Digital Earth vision regarding exchange and interoperability of geographic information are Spatial Data Infrastructures (SDIs). An overview of current developments and standards is given in section 2.3.

Speaking about geo-information, a completely new source of geo-information has evolved in recent years. The dramatic rise of smartphones (Gartner 2015) has also increased the amount of sensor data that is used and shared for different applications. Health and fitness applications like the step counter Runtastic Pedometer[6] or security applications like the Life360 Family Locator[7] are examples of thousands of applications that use smartphone sensor information. Moreover, this information is not only used within the application but is often shared on social networks or other platforms. Thus, in the case of a running application, one receives geo-information consisting of the geo-location, sensor information like running speed and slope, and information about the health status of the user. Such detailed information cannot be derived from traditional in situ sensor system. Above that, the sensor density might become even higher considering the ongoing trend towards wearable sensors which "is expected to witness a significant growth" (PR Newswire 2015). Currently, wearable sensor are often narrowed to fitness

[3] http://www.copernicus.org/
[4] http://www.google.com/earth/
[5] http://worldwind.arc.nasa.gov/
[6] https://www.runtastic.com/de/apps/pedometer
[7] https://www.life360.com/family-locator/

bands, smart watches or similar but the development goes far beyond that towards a ubiquitous health monitoring with so called body sensor networks (Hung et al. 2015).

Summarising, one can state that concepts and programmes like GEOSS, INSPIRE, Copernicus and Digital Earth offer a flood of diverse geo data from various in situ as well as airborne and satellite sensors. Geo-information derived from this geo data and the combination of this information are not yet entirely exploited. Above that, this flood might even increase due to the fast rise of smartphone sensor and wearable sensors.

2.2 Geo-Information Fusion - Disambiguation

Early literature on information fusion can be found in the fields of robotics (Shafer et al. 1986), medical science (Lee & Leahy 1990) and remote sensing (Del Grande 1990; Ehlers 1991). Over the last decades, several modifications and specifications of the term "information fusion" have appeared in different scientific disciplines:

- Data Fusion (Waltz & Llinas 1990)
- Image Fusion (Klonus & Ehlers 2009)
- Sensor Fusion (Moravec 1988)
- Multi-Sensor Fusion (Schall et al. 2009; Ehlers et al. 2010)

Yet, the basic idea of combining data from multiple sources to generate enhanced data or information (e.g. about a measured object) is the same for all approaches. However, the data sources always deliver the same data type, for example rasterized images for the image fusion or scenes from different remote sensors for the multi-sensor fusion.

Regarding information fusion, the lowest common denominator of all data types (raster images, vector data, sensor measurements, etc.) is used, which is the derived information. Thus, it is possible to combine information from different data types, for example people density information derived from airborne remote sensors, video cameras and from smartphone measurements. In this work, the addition of the term "geo" is indicating the focus on geo-information and not on information in general. Concluding, the following definition for geo-information fusion is postulated:

Definition 1. Geo-Information Fusion

> The term "**geo-information fusion**" describes the process of combining geographical information (geo-information) delivered by different data sources to create (geo-)information that cannot be derived from the data sources individually.

2.3 Spatial Data Infrastructures (SDIs)

As the name implies, a spatial data infrastructure allows for sharing geo-spatial data within a specific network following the concept of service-oriented architectures. In most cases this infrastructure is the World Wide Web; however, it can for example also be the intranet of a company or a public administration. INSPIRE for example is aiming at a Europe-wide infrastructure consisting of many sub-infrastructures by the member states. In addition to the sharing of data, an SDI allows for the provision of geo-spatial functionality as well.

The Open Geospatial Consortium (OGC)[8] develops international interface standards for services that "geo-enable" the Web (OGC 2015) and thus build the basis for SDI developments. A short excerpt of existing OGC Web service standards that are relevant for geo-information fusion is provided in the following. On this occasion, the scope and range of application of the respective standard is explained. Moreover, the relevance of the standard regarding geo-information fusion is discussed briefly.

The first group of OGC standards that are relevant for geo-information fusion are the data providing Web services. The most common data services are the Web Map Service (WMS) (OGC 2006) to provide raster data and the Web Feature Service (WFS) (OGC 2005) to provide vector data. More specific are the Web Coverage Service (WCS) (OGC 2012a) for grid and coverage data and the Sensor Observation Service (SOS) (OGC 2012b) for sensor measurement data. All standards provide a specific set of operations that are accessible via HTTP to retrieve the data as well as metadata. Hence, the presented service standards allows for a simple integration of geo-data into SDIs.

The second group of relevant OGC standards are the processing services. They provide the possibility to e.g. extract geo-information from geo-data or conduct any kind of geo-spatial analysis. Alongside the specific processing service for the WCS, the Web Coverage Processing Service (WCPS) (OGC 2009), the Web Processing Service (WPS) (OGC 2007) is the most common standard in this group. As the name implies, the WPS allows for spatial processing of data over the Web. Thus, it offers the possibility to integrate any GIS or geo-related functionality into an SDI. The WPS is currently implemented in several software packages like the GeoServer[9] or as a standalone version like the PyWPS[10] or the 52° North WPS[11].

Despite being the exclusive standard of the OGC for Web processing of geo data, the WPS is not capable of handling data streams. The inputs and outputs of a WPS process are pre-defined and the processing starts as soon as all input data is completely available. However, geo-data acquired in real time are often delivered in continuous data streams. Thus, the real time aspect would disappear if the processing would a) need all data to even start the processing and b) need a certain time to process a large amount of

[8] http://www.opengeospatial.org/
[9] http://geoserver.org/
[10] http://pywps.wald.intevation.org/
[11] http://52north.org/communities/geoprocessing/wps/

data. This problem is addressed by the company 52° North by proposing the Streaming-based WPS (Carrillo 2012). The idea is based on typical multimedia streaming approaches implemented in YouTube or similar. Those approaches allow for consuming content without already downloading the whole data as the user only receives so called "chunks" of data (Timmerer & Müller 2010). For the Streaming-based WPS, the concept of the media playlist is adapted as the so called spatial-data-playlist. A playlist is continuously filled with links to new chunks of spatial data (e.g. sensor data delivered via SOS) and is processed step by step. The Streaming-based WPS can be classified in two ways, an Output Streaming WPS and a Full Streaming WPS. The Output Streaming WPS works as a typical WPS but streams the output in chunks as soon as parts of the data are processed. The Full Streaming WPS can read continuous data streams as input and is able to stream the preliminary output results as well. However, the idea of the Streaming-based WPS is still in its infancy and needs time for improvement and establishment. As most current processes available are still WPS-based and do not support data streams, the Streaming-based WPS cannot be used as the centre piece for an SDI conception. It is more reasonable to stick with the OGC standard regarding interoperability.

3 Use Cases and Related Work

In this section, the three time-critical geo-information fusion use cases from different facets of geo-information science are introduced. The first use case is presenting a system to **capture** new geo-information called Geo-reCAPTCHA. Agent-based **modelling** is the topic of the second use case dealing with single person movement estimation. Finally, the third use case addresses the **analysis** potential of fused geo-information on the example of least-cost navigation during major events. Related work and research in the corresponding field is provided for each use case.

3.1 Use Case #1: Geo-reCAPTCHA[12]

Almost every internet user has used it so far – unconsciously providing valuable information for the digitization of books: a reCAPTCHA (Figure 5). The basic idea of a CAPTCHA (von Ahn et al. 2003) is to provide a test that only a human can solve, and that is simultaneously almost unsolvable for a machine. Thus, CAPTCHAs are commonly used to protect login forms from hacking attempts or to prevent users from email spam as a part of contact forms. The most common type of CAPTCHA presents distorted text that has to be identified. However, other CAPTCHA types, e.g., image-based or audio-based, do exist as well.

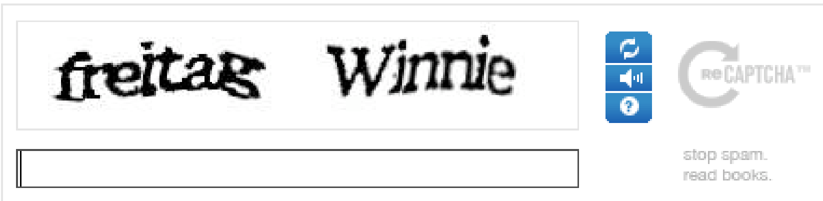


Figure 5. A typical reCAPTCHA presenting two words to be identified by the user. (Google 2015)

A reCAPTCHA (von Ahn et al. 2008) extends this idea and uses the effort of the user to solve this test for a greater good. It presents two words to the user (Figure 5), with one of the two words already known, which serves as a control word to identify an actual human user. The second word is unknown to the reCAPTCHA system itself, meaning that it cannot be automatically recognized with optical character recognition (OCR) software. As the user cannot differentiate between the control word and the unknown

12 This section has previously been published by Hillen & Höfle 2015. Additional paragraphs and formulations on geo-information fusion are added for this thesis. The research questions from subsection 3.1.3 are unpublished.

word, both words have to be identified. With this crowdsourcing method, thousands of books have been digitized in the past years, with an accuracy of 96.1% over 1 billion responses (von Ahn et al. 2008). Nowadays, reCAPTCHAs are found on 328,117 websites at the time of writing (builtWith 2015).

In this use case a novel enhancement of the reCAPTCHA idea is presented and is adapted to the geographic information domain. This system is termed "Geo-reCAPTCHA". Certainly, the system has to fulfil the same requirements as a typical reCAPTCHA, i.e., to provide a test that only humans can solve. Furthermore, Geo-reCAPTCHA is designed to create geographic information from earth observation data for subsequent applications. Such user-generated geographic information (UGGI) is already a crucial part of many recent applications in the field of geography and GIScience. In addition, several different concepts are ubiquitous in GIScience like volunteered geographic information (VGI), or citizens as sensors (Goodchild 2007), describing information captured from people. However, all these terms are united under the generic term UGGI, meaning all information captured directly (e.g., capturing of geometries by users) as well as indirectly (e.g., extracted from location-based social media data (Roick & Heuser 2013)). Prominent examples of applications depending on UGGI are OpenStreetMap[13] (OSM) or Wikimapia[14]. Two properties regarding UGGI have to be addressed in this context: (i) the users' heterogeneity and (ii) the reliability and quality of the information. The users' heterogeneity (i) for OSM is illustrated by Neis & Zipf (2012), showing that only 5% of the users are mapping frequently; whereas, 19% are non-recurring members. However, frequent users are more trained and are therefore supposed to generate more reliable information. Data errors, and abuse or vandalism, represent the major problems regarding the reliability and quality (ii) of UGGI (Neis et al. 2012). Geo-reCAPTCHA addresses both issues with redundancy of geographic information analogous to the idea of reCAPTCHA.

The first objective of this use case is to present a generic conceptual design for a Geo-reCAPTCHA system. Based on this, a Geo-reCAPTCHA infrastructure architecture is proposed, leading to a prototype implementation that allows capturing UGGI. This prototype implementation can be seen as a first geo-information fusion by combining aerial images and the effort of a human sensor. Based on the prototype, a proof-of-concept by means of an empirical user study is conducted in which capturing time and quality of the geographic information are investigated. The quality investigations in particular reveal the second opportunity for geo-information fusion in which information of multiple users is fused to new geo-information.

3.1.1 CAPTCHA and the reCAPTCHA Idea

The term CAPTCHA was introduced by von Ahn et al. (2003), and is an acronym for "Completely Automated Public Turing test to tell Computers and Humans Apart". However, CAPTCHA is a special form of a Reverse Turing Test, also known as Human

[13] http://www.openstreetmap.org
[14] http://wikimapia.org

Interactive Proof. It provides a test that can easily be solved by humans, in contrast to machines.

CAPTCHAs can be classified based on the medium used for the testing, such as texts, images or audio files. An overview of algorithms and methods for all classes of CAPTCHAs is given by Hidalgo & Alvarez (2011), and more recently by Roshanbin & Miller (2013). The most common CAPTCHA is the text-based CAPTCHA (e.g. "BaffleText" by Chew & Baird (2003)). This method presents a text fragment that is modified by distortions and disruptions. Those modifications make an automatic analysis by Optical Character Recognition (OCR) software more difficult. On the other hand, a human user can still read the text and easily pass the test. Another class of CAPTCHAs are the image-based CAPTCHAs. A recent approach is introduced by Kim et al. (2010) using rotated cut-outs of an image. The user has to find the correct orientation of the sub-images by rotating them in order to pass the test.

A rethinking of the CAPTCHA technology is made by von Ahn et al. (2008) by introducing the text-based reCAPTCHA (Figure 5). Instead of using one word for the test, reCAPTCHA presents two words to the user: one unknown word that cannot be identified with OCR software, and a control word for which the answer is known. By typing the control word correctly, the system identifies the user as a human and considers the unknown word as correct as well. Therefore, it is essential that the user cannot differentiate between the control word and the unknown word. The accuracy of the word identification increases depending on the amount of user results for a specific unknown word. The idea of reCAPTCHA is used to digitize words from old printings, for which automatic software has failed. With this approach over 440 million words were correctly deciphered in one year with an accuracy of 96.1% over 1.2 billion responses (von Ahn et al. 2008). However, these numbers are from the year 2008, in which reCAPTCHA was not as well known or commonplace as today. In comparison with 2008, when reCAPTCHA was deployed in ca. 40,000 Web sites (von Ahn et al. 2008), the number of Web sites with reCAPTCHA has risen to 328,117 (builtWith 2015) as of the day of writing. Concerning security, the hardest reCAPTCHA has recently been defeated with 99.8% accuracy by Google's own development team using neural networks (Goodfellow et al. 2013). Thus, they concluded that the security of using distorted text for a CAPTCHA test is "significantly diminished".

The geographic or spatial aspect regarding CAPTCHA systems has not played an important role. So far, localized CAPTCHAs are one basic approach. Fidas & Voyiatzis (2013) state that English words or the Latin alphabet are not suitable for a majority of internet users today. As a result, CAPTCHA systems with different languages or alphabets have been presented, like the system introduced by Banday & Shah (2011) for India in the Urdu language, using the IP address to geo-locate the user. Another example for this is the text-based CAPTCHA using Chinese characters proposed by Gustafson & Li (2013). GeoCAPTCHA described by Wei et al. (2012) is an actual image-based CAPTCHA that considers the geographical surrounding. This CAPTCHA scheme uses personalized contents in the form of rotated 3D street-view images. However, no current

CAPTCHA approach with a spatial component uses the idea of reCAPTCHA to produce user generated geographic information.

3.1.2 User-generated geographic information (UGGI)

The well-known OpenStreetMap (OSM) is one of the most popular projects of VGI acquisition and usage. OSM is a free map of the world created by over 1.7 million volunteers interested in mapping (OpenStreetMap 2015a). For many regions of the world, the data density of the map is remarkably high (Raifer 2014), with many different geographic features that can be tagged, like aerial ways, shop types, or tourist destinations (OpenStreetMap 2015b). However, the map is certainly not complete for all parts of the world, and is prone to errors and vandalism (Haklay et al. 2010; Neis et al. 2012). A different idea is pursued by Wikimapia to describe any place on Earth. Therefore, it offers the possibility to add information to a specific location in the form of rectangles or polygons with attached information (in the form of a Wiki). A related approach is adapted by Tomnod[15], which uses satellite images to solve current problems in specific campaigns, like the mapping of damage caused by the Oklahoma Tornado from 2013 (DigitalGlobe 2013), or finding missing Malaysian Airlines flight 370 (CNN 2014). For each campaign, a small set of tags is available to the user, who can freely navigate through the satellite imagery searching for relevant objects to tag. A similar concept is used by the Geo-Wiki project[16] to improve global land cover maps. For this purpose, volunteers classify land cover using high resolution imagery in Google Earth through different crowdsourcing campaigns run by the Geo-Wiki team (Fritz et al. 2009, 2012). However, all those platforms and projects are dependent on volunteers and their commitment and ambition to contribute.

For this reason, Geo-Wiki additionally uses simple user interfaces in the form of a game called Cropland Capture to attract more people (See et al. 2014). Using games as a possibility to generate geographic information has recently become very popular in science and economics (Matyas et al. 2012; Jordan et al. 2013), as it makes it easier to attract volunteers. The company Pallas Ludens[17], for example, offers the possibility to integrate annotation tasks in games to address millions of gamers.

A comprehensive overview of VGI developments and research is presented by Neis & Zielstra (2014). The reliability and credibility of VGI, with a focus on OSM, is in particular addressed in their work, as this has often been questioned in the past (e.g. Flanagin & Metzger 2008; Comber et al. 2013; Foody et al. 2013). Despite these issues, UGGI is integrated in many different applications. This can be in the form of background data for location-based apps on mobile devices like games (e.g. BucketMan[18]), or navigation (e.g. Locus Map Free[19]), as well as applications, in the context of Smart Cities

[15] http://www.tomnod.com
[16] http://geo-wiki.org
[17] http://pallas-ludens.com
[18] https://play.google.com/store/apps/details?id=de.web.butzbach.felix.bucketman
[19] https://play.google.com/store/apps/details?id=menion.android.locus

and Digital Earth, like CITI-SENSE[20] or WeSenseIt[21]. The possibility of generating a large amount of geographic information in a short period of time makes UGGI systems especially relevant and important, particularly for time-critical applications such as disaster response (Middleton et al. 2014), e.g. the rapid mapping activity presented by Reimer et al. (2014) for the crisis in the Philippines following typhoon Haiyan. Over 200 participants mapped valuable information for relief workers in two mapathons. Relevant user-generated information in the form of geolocated photos from the platforms Flickr and Instagram were provided as well.

3.1.3 Research Gap and Resulting Objectives

Up to now there is no approach among the geo-related CAPTCHA approaches that extends the reCAPTCHA idea and actually produces geographic information. In fact, only a few approaches take the user's geographic location into account at all. This gap between the need for complete and updated geographic information and the need for platforms to generate them should be filled. Therefore, a conceptual design for such a UGGI generating system is developed. The potential of geo-information fusion in the context of capturing new geo-information is analysed using the multiple results of the empirical user study.

The following main objectives are addressed in particular by means of this use case:

- To what degree can the concept of Geo-reCAPTCHA be used to generate new geo-information, i.e., how good is the quality of the resulting geo-information?
- How realistic is the actual usage of Geo-reCAPTCHA in practice, i.e., how much more effort does it take to solve a Geo-reCAPTCHA than a typical text-based reCAPTCHA?
- To what degree can the fusion of multiple user-generated geo-information increase the quality of a specific feature?

3.2 Use Case #2: Agent-based Modelling[22]

Today, a huge variety of geo-information is requested and required for various applications in real time. The term "real time" regarding airborne remote sensing data is seldom found in recent literature as such data typically require a particular time span to be available for further processing. This fact has two main reasons. First, the recording platforms like airplanes, unmanned aerial systems (UAS) or satellites so far have not been able to transmit data in real time to the application and users. Data recorded by a satellite can be transmitted only within a specific time frame to a defined ground station.

[20] http://www.citi-sense.eu
[21] http://www.wesenseit.com
[22] This section has previously been published by Hillen et al. 2014. Additional paragraphs and formulations on geo-information fusion are added for this thesis. Subsection 3.2.2 and 3.2.3 are expanded to provide more background information. The research questions from subsection 3.2.4 are unpublished.

Regarding airplanes and UAS, the data are typically read out after the aircraft finishes its flight. The second reason is the time consuming pre-processing steps like georeferencing and orthorectification which are required for further processing and information extraction.

In the course of the project VABENE of the Germany Aerospace Centre DLR, an airborne monitoring system has been developed that is able to pre-process remotely sensed images in real time by an on-board computing system and to directly transfer them to a ground station via a microwave data transfer system installed on the aircraft (Kurz et al. 2012). The term “real time” regarding remote sensing is not comparable to the common interpretation of “real time”, as daily or hourly applications are often referred to as “real time” or “near real time” by remote sensing scientist. The data delivered in the course of the project VABENE by the DLR redefines the understanding of “real time” for remote sensing applications (maximum data delivery time is here a few minutes) and therefore opens a completely new direction of research. The real time aspect of other types of geo-sensors has been ubiquitous for several years. In situ sensors are inherent parts of many time-critical systems and applications like early warning systems for tsunamis (Wächter et al. 2012) and weather predictions (Gendt et al. 2004). Geo-sensor networks and the so-called “Sensor Web” have recently been intensively investigated and are capable of providing various geospatial data over the internet. The Sensor Web was introduced by Delin (2002) and “is to sensors what the internet is to computers, with different platforms and operating systems communicating via a set of shared, robust protocols” (Delin 2002, p. 270). Such protocols and standards are defined by the Open Geospatial Consortium (OGC) under their Sensor Web Enablement (SWE) guideline (OGC 2013) that “refers to web accessible sensor networks and archived sensor data that can be discovered, accessed and, where applicable, controlled using open standard protocols and interfaces (APIs)” (Botts et al. 2008, p. 175).

Exploiting the real-time airborne remote sensing and the concept of the Sensor Web, this use case presents an agent-based modelling approach for single person movement that combines information from real-time remote sensing data and in situ sensor data, more precisely smartphone sensor data. The idea of this use case is based on security issues during major events to support avoiding tragedies like the Love Parade disaster 2010 in Duisburg, Germany (Diehl et al. 2010). During this music event 21 people suffocated and over 500 people were injured due to an unexpectedly high number of people streaming towards the same narrow spot which ended up in a mass panic.

Geo-information from both sources are fused within the modelling process to overcome the disadvantages of a single sensor type by making use of the advantages of the other type. Remote sensing data are normally provided for large geographic areas, especially for hard-to-reach regions (e.g., earthquake damaged or flooded areas (Brakenridge et al. 2003; Tralli et al. 2005; Dell’Acqua et al. 2011; Voigt et al. 2011)). Moreover, remote sensing data deliver no information on occluded areas, e.g., under bridges or in buildings, and always have a limited spatial and temporal resolution which varies depending on the sensor quality and the sensor carrier used. However, those particular optical remote sensing data sets are generally dependent on weather conditions during data acquisition. For example, regions which are covered by clouds can therefore not be mapped. In contrast, in situ sensors are generally independent of the weather conditions and can deliver data for areas hidden in the optical remote sensing image. However, geo-location of the recorded detailed information depends on the positional accuracy provided by the sensor systems via GPS/GNSS (Global Navigation Satellite System), DGPS and so forth. In addition, in situ sensor data might deliver information that cannot (or at least barely) be derived from optical remote sensing data, like temperature, soil moisture or orientation and moving directions of people and cars. A limiting factor is that in situ sensors generally deliver point information only, which reduces the coverage of the investigation area significantly. Besides, sensor systems installed on the ground are also vulnerable to vandalism and intentional destruction by persons and natural processes such as floods or avalanches as well as impact by animals.

3.2.1 Real-Time Remote Sensing: The DLR Project VABENE

VABENE stands for the German acronym for "Traffic Management during Major Events and Disasters" and is a project of the German Aerospace Centre DLR with the goal to develop efficient tools for agencies and organizations with security functions as well as traffic agencies in case of major events or disasters. The scientific focus is divided into three main areas: traffic research, information processing and data distribution concepts (Reinartz et al. 2011).

The airborne monitoring system with optical and radar sensors is an outstanding product of the VABENE sensor technology. Three digital high-resolution optical cameras record images with different viewing directions at a repetition rate of up to 3 images per second. These image data are then orthorectified in real time on graphics processing units (GPUs) using high precision navigational data together with a digital elevation model (DEM) and can be analysed using the on-board system. Another important part of the VABENE real-time system are the used data links. A commercial microwave data link (SRS 2015) is used as a basic data connection to the ground. Additionally, an optical data transfer system based on the work of Horwath & Fuchs (2009) was developed for transferring very large data volumes in real time via optical terminals on the airplane and ground stations.

Due to the on-board processing and analysis of the images in real time, the obtained information reflects the actual situation on the ground, including moving objects, which is very important for a large amount of real world use cases. This includes the integration of remote sensing data and derived information in real-time systems and spatial data infrastructures via the internet. So far, a number of algorithms for advanced traffic analysis as well as people detection and tracking have already been implemented (Rosenbaum et al. 2009; Sirmacek & Reinartz 2013).

3.2.2 Mobile In Situ Sensing via Smartphones

As the name implies, a mobile in situ sensor is not fixed in one location but is installed on, or within, a carrier with which it can measure specific phenomena for different geographic locations. Hence, any stationary sensor can be converted into a mobile sensor by simply combining it with a carrier object, which can be any moving object like a car, a boat, or a person.

For this use case, we will focus exclusively on smartphones as they combine all essential segments for real-time in situ sensing: mobility, location awareness, multiple built-in sensors as well as wireless connectivity to add additional sensors and to transfer the sensed data via the internet. A smartphone differs from a regular cellular telephone basically in its computational capability which makes a smartphone a combination of a mobile personal computer and a mobile phone. The majority of definitions for smartphones point out its extended functionality by built-in applications and its ability to access to the Internet (PCMag 2015). In 2014, worldwide sales of smartphones are recorded at 1.2 billion units (Gartner 2015), which represents two-thirds of global mobile phone sales (compared to 39.6% in the third quarter of 2012 (Gartner 2012)).

The variety of built-in sensors in smartphones has significantly increased: "Today, a smartphone or a tablet might integrate a MEMS microphone, an image sensor, a 3-axis accelerometer, a gyroscope, an atmosphere pressure sensor, a digital compass, an optical proximity sensor, an ambient light sensor, a humidity sensor and touch sensors" (Farnell 2013). Studies regarding accuracy and precision of smartphone sensors are rare so far and mostly focus on specific smartphone models with varying sensor products. An evaluation of accuracy of altitude data, images and 3D coordinates for photogrammetric coastal monitoring was conducted by Kim et al. (2013). The study showed standard deviations of 0.33° to 2.04° for the heading angle calculated by using the accelerometer and magnetometer. Wu et al. (2012) presented classification accuracies of physical activities for sanitary issues using smartphone motion sensors with satisfying results for activities like walking, jogging and sitting but less satisfying results regarding three-dimensional activities like vertical movements (upstairs and downstairs). Concerning external sensors connected with smartphones, many studies have been carried out for wired and wireless connections. Especially scientists in the field of health and medical innovations work on combining medical devices like ECG with smartphones via Bluetooth (Worringham et al. 2011). Smartphones in this connection offer a convenient way to add the geographic position of the user and transmit the data via high-speed mobile internet connection (like 3G or Long Term Evolution (LTE)). Thus, smartphone sensor data is highly suitable to be integrated in real-time applications.

In the past years, smartphone sensors have quite often been used in studies including participatory sensing (PS), a volunteered approach for sensing data with smartphones originally introduced by Burke et al. (2006). Early examples for PS are public health issues like air quality, urban planning with the monitoring of noise and ambient sounds, and natural resource management like gathering of semantic metadata by field scientists. Scientists recently used PS in diversified approaches varying from road surface monitoring

(Strazdins et al. 2011) to fuel-efficient navigation services (Ganti et al. 2010). Like in every research field dealing with geographic data, participatory sensing has its own privacy debate leading to various approaches to satisfy privacy needs (Christin et al. 2011; Groat et al. 2012).

3.2.3 Agent-based Modelling of People Movement

Agent-based modelling (ABM) describes the modelling of a system with entities called agents. Each agent reacts in consideration of its current situation and holds a set of predefined decision rules which lead to various behaviours of the agents. The neighbourhood around an agent, from which it can retrieve information, is limited and can change its values over time, although it cannot make decisions itself. The agents are capable of interacting among, and influencing the behaviour of each other which is defined in specific relationships. Furthermore, the agents generally learn from their experiences and are able to evolve which might result in unanticipated new behaviour (Bonabeau 2002; Johnston 2013, pp. 4-6). ABM offers the possibility to model real-world dynamics, especially the modelling of flows of humans, cars or any other individuals. However, “ABM is a mindset more than a technology” (Bonabeau 2002, p. 7280) which means that an intensive concept of designing a system from an individual perspective is more important than the actual technical implementation.

The history of agent-based modelling starts with cellular automaton by Stanislaw Ulam and John von Neumann in the 1940s (Wolfram 2002), which has a limited complexity in its decision rules and a defined rectangular grid that changes its values over time. One of the ABM’s pioneers is the social scientist Thomas Schelling who was the first to use ABM in his model of the formation of segregated neighbourhoods (Schelling 1971).

Nowadays, ABM is used in many areas of application, like evacuation management (Chen et al. 2006), traffic and customer flows (Baydar 2003; Lodhi et al. 2012), dynamics of the stock market (Ponta et al. 2012) as well as social simulations (Helbing 2012). The coupling of ABM with a GIS was identified as a “powerful tool for decision makers” by (Gimblett 2002, p. 14). It offers the possibility to work in a georeferenced environment and to link the behaviours and the impacts of the agents to a specific spatial location. Klügl & Rindsfüser (2007) declare that the pedestrian simulation “has the potential to become the great success story for the application of agent-based simulation” and consider ABM as “the best, if not the only modelling paradigm for reproducing the reaction of travellers to locally displayed or dynamic information”. Their results indicate that ABM has some disadvantages regarding the possibility to reproduce the results, as the models are not fully documentable, and because of sometimes high computational requirements.

Torrens et al. (2012) present a framework for simulating and evaluating individual pedestrian movements by examining various popular movement algorithms as motion controllers. Regarding the movement of crowds as a whole, many studies were performed concerning human behaviour during a panic and planned evacuation scenarios (Helbing et al. 2000; Braun et al. 2003; Zheng et al. 2009). The estimation of pedestrian movement based on smartphone data was mostly limited to the macroscopic level based on mobility patterns derived from antenna signals with corresponding coarse cluster sizes (Gonzalez et al. 2008; Song et al. 2010; de Montjoye et al. 2013). Mainly due to privacy issues, the microscopic level has not yet been fully studied.

3.2.4 Research Gap and Resulting Objectives

Due to the novel real-time characteristics of remote sensing data provided by the VABENE project, the whole analysis potential that comes with real-time remote sensing data has not been intensely investigated yet. Hence, the integration of remote sensing data in time-critical geo-applications was not an option thus far. This use case will (i) demonstrate geo-information fusion for a time-critical modelling application and will (ii) provide valuable information about the effect of fusing real-time geo-information.

The following main objectives are addressed in particular by means of this use case:

- How can geo-information fusion be applied within a time-critical modelling application and how do the results differ from modelling approaches with only one source of geo-information?
- What effect can be seen by fusing real-time geo-information, i.e., to what degree does the integration of real-time geo-information increase the quality of the modelling result?

3.3 Use Case #3: Least-Cost Navigation[23]

Major events, like music festivals or football games, attract tens of thousands of people. Unfortunately, accidents can happen every time despite high security preparation, and the consequences are often crucial due to the high number of visitors. In recent literature, crowd simulations that can be used for security issues during major events are typically not based on real-time sensed information but rely on empiric or physical heuristics. An overview of current methods and approaches for such crowd simulations (e.g., evacuations) is provided by Xu et al. (2014). Compared to that, in situ information has been a crucial part of navigation approaches in the field of robotics (Masehian & Katebi 2007). Use case #2, described in the previous section, focuses on fusing real-time in situ and remote measurements to create a more realistic estimation of people movement using agent-based modelling. Except for extracting only position information from optical remote sensing data as conducted in that use case, studies in the field of crowd monitoring present promising results in estimating crowd density and dynamics (Hinz 2009; Perko et al. 2013). The derived information can be utilized for a routing approach for major events.

[23] This section has previously been published by Hillen et al. 2015. Additional formulations on geo-information fusion and an additional figure are added for this thesis. The research questions from subsection 3.3.3 are unpublished.

However, event organizers and security authorities usually have very limited near real-time information about the location of visitors at the event site, despite the high penetration rate of smartphones in the general public (statista 2015). Terrestrial sensors, like security cameras, are often only available at the most important spots and only have a limited field of view. Recent airborne monitoring technology is able to provide additional high-resolution imagery in real time (Haarbrink & Koers 2006). Due to their mobility and large field of view, even large event sites can be captured in a couple of minutes. The increasing ground resolution of the captured images (in this case 9 cm; see Figure 6) allows for efficient detection of objects like cars and people (Schmidt & Hinz 2011).

Figure 6. Parts from aerial images with ground resolution of 9 cm; left: people during a music festival, right: cars and tents.

For this use case, real-time aerial images are combined with smartphone movement data and integrated into a routing tool for major events. It is designed to be used by the official authorities (i.e., police or ambulance) as well as the visitors themselves. It can be of great use for open-air music festivals, where large groups could gather spontaneously in less monitored locations, or for events in city centres (e.g., fairs), as they often take place in multiple locations. In the case of music festivals, for example, the motion of the crowd directly in front of a concert stage is hardly predictable during a live performance. Although the number of people in the crowd might be below the area's maximum capacity, the number of persons per square meter (crowd density) can quickly reach a critical level and lead to dangerous situations. If the crowd density rises above a certain threshold, the situation can become life-threatening and the authorities must intervene. But even in less dramatic scenarios, the perception of each person in these situations might be different. A person's physical condition, hydration level, degree of intoxication, or even the weather conditions at an event could all be factors that influence a person's desire to leave a crowded area in the fastest way possible. For this use case, it is assumed that the fastest way is synonymous with the route with the lowest crowd density.

For these critical and non-critical situations, a routing concept based on fusing 9-cm optical aerial images with movement data from smartphone users in near real time is proposed. The major aim is to provide an up-to-date crowd density map with a least-cost routing functionality for the event visitor as well as for rescue forces and security authorities.

In the following, two test scenarios are outlined in which the real-time routing approach is beneficial. The first scenario describes a tool to escape from emergency situations, whereas the second scenario presents a generic decision support application that can be used in multiple situations. The "give and take" principle is essential for all applications, meaning that both the event attendee and the organizer have to deliver information to receive a result. This concretely means for our scenarios that the event attendee has to send information about their current location and speed via smartphone and the organizer has to provide an aerial imaging system covering the event area. Only if information from both sides is available can the results be provided as desired. This means that on the one hand the user can fetch an overview map of the current crowd distribution and use the least-cost routing, and on the other hand the organizer can guarantee a high security standard and use the routing app for the event's security and rescue forces.

3.3.1 The Fastest Way Out of a Crowd

One application in which the real-time navigation can be used is during music festivals. The crowd in front of the music stages is often very dense. Combined with extreme weather conditions (e.g., high temperatures) and physical fatigue, this might result in dangerous situations. In such crowds there is no chance to get a full overview of the situation and to find the best way out, especially for persons with a low body height. Due to the lack of orientation, the person might go towards an even denser region within the crowd, not knowing that a free space might be very close by.

The presented routing approach can be integrated in an emergency app provided by the event organizer. The guests have to provide their current location and speed measured with their smartphone. In exchange for that, they are able to view an overview map with the current crowd distribution in the event area and are able to use the described emergency navigation (Figure 7). Additionally, the security and rescue forces of the event could directly receive the location of the visitor when the app is used. Thus, help can be on-site much earlier. The overview map has to be provided by the organizer by recording aerial imagery during the event (e.g., with helicopters, drones, or similar). It may even be possible for typical SLR cameras to be installed in high positions to cover special regions, like the space in front of the music stages, for example.

Figure 7. Schematic representation of an emergency smartphone app. The crowd density is visualized in the background. The fastest escape route is emphasized with a red arrow. (Hillen et al. 2015)

3.3.2 The Fastest Way towards a Point-of-Interest (POI)

The real-time routing approach can be adapted to any event that has appropriate image data available for the event site. In the following, this assumption is stressed for the example of football games. In this particular use case, dense crowds are gathering in short time frames (i.e., before or after the game as well as during the half-time break). A concrete example for this is reported by officials of the Borussia Park in Mönchengladbach (Germany). After the football games, the main way towards the parking spaces is commonly blocked by the police to escort the fans of the opposing team to their buses. In the meantime, many people have to wait while more and more people are streaming out of the stadium towards the parking spaces. The organizers try to avoid complications by opening gates that allow people to go the longer way around the stadium on the other side. In this situation, this way would be much faster compared to waiting in the dense crowd. However, the people that are streaming out of the stadium are often not aware of (i) the blockade by the police and (ii) the option to use an alternative way.

The presented routing approach could help to ease this situation by informing and navigating some visitors to the alternative route. Figure 8 illustrates the generic workflow in which the user has to provide their current location along with the target of routing. This information is sent to a web server where the actual calculation for the least-cost route is executed. The resulting route is afterwards visualized on the smartphone of the user, who constantly reports (automatically in the background of the app) his location and speed. For this example, it is essential to integrate the smartphone data of as many users as possible to avoid potential jams caused by the system itself. As soon as the alternative route is crowded as well, the system carefully has to decide which direction to choose. If the main way is open again and the crowd dissolves, the navigation system routes people along the typical way. Thus, potential mass panics or at least a tremendous gathering of people can be avoided.

In general, real-time navigation based on the presented routing approach could be used during any major event; for example to reach the nearest refreshment shop during a musical festival or city event. Even navigation through the city streets to a specific parking garage with an emphasis on avoiding large crowds (e.g., in front of stages or booths) can be useful. In any case, the advantages are on both sides, for the event organizers and the guests. The guests utilize the tool to avoid stress, overexcitement, and anger on the one hand, while on the other hand the organizers can ensure security during the event and are able to increase the event's attraction by providing a modern smartphone navigation app. In addition, security and rescue forces are able to utilize the app for their efforts and could reach the location of an emergency earlier.

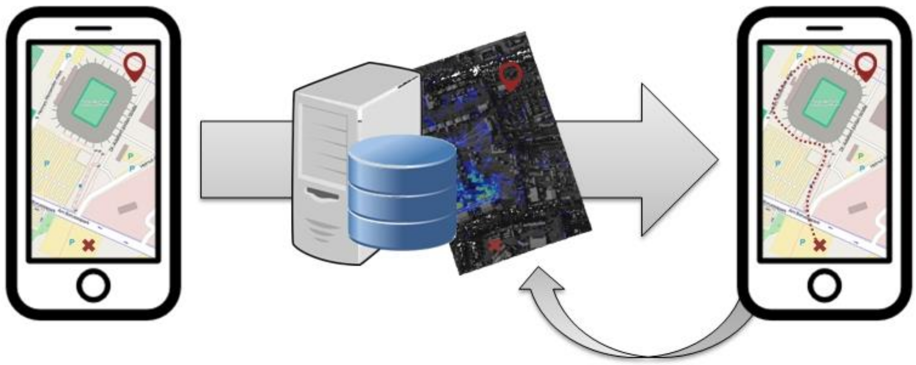


Figure 8. Conceptual design of a smartphone app for least-cost routing during or after a major event (in this case a football game). (Hillen et al. 2015)

3.3.3 Research Gap and Resulting Objectives

The research gap for this use case is closely connected to use case #2. Real-time remote sensing data can deliver information for a large investigation area that was not available in the past. Thus, analysis algorithms can be performed on a more precise data basis, and be constantly updated with real-time geo-information. This use case is demonstrating the benefit of geo-information fusion not as a part of the geo-application itself (as presented in use case #2) but as a preliminary step to feed geospatial algorithms.

The following main objective is addressed in particular by means of this use case:

- To what degree does fused real-time geo-information increase the quality of the results of geospatial algorithms?

4 Methodology

In this section, the methodology regarding the three previously presented use cases is described in detail. A brief overview of the methodical approaches for each use case and the SDI integration is illustrated in Figure 9.

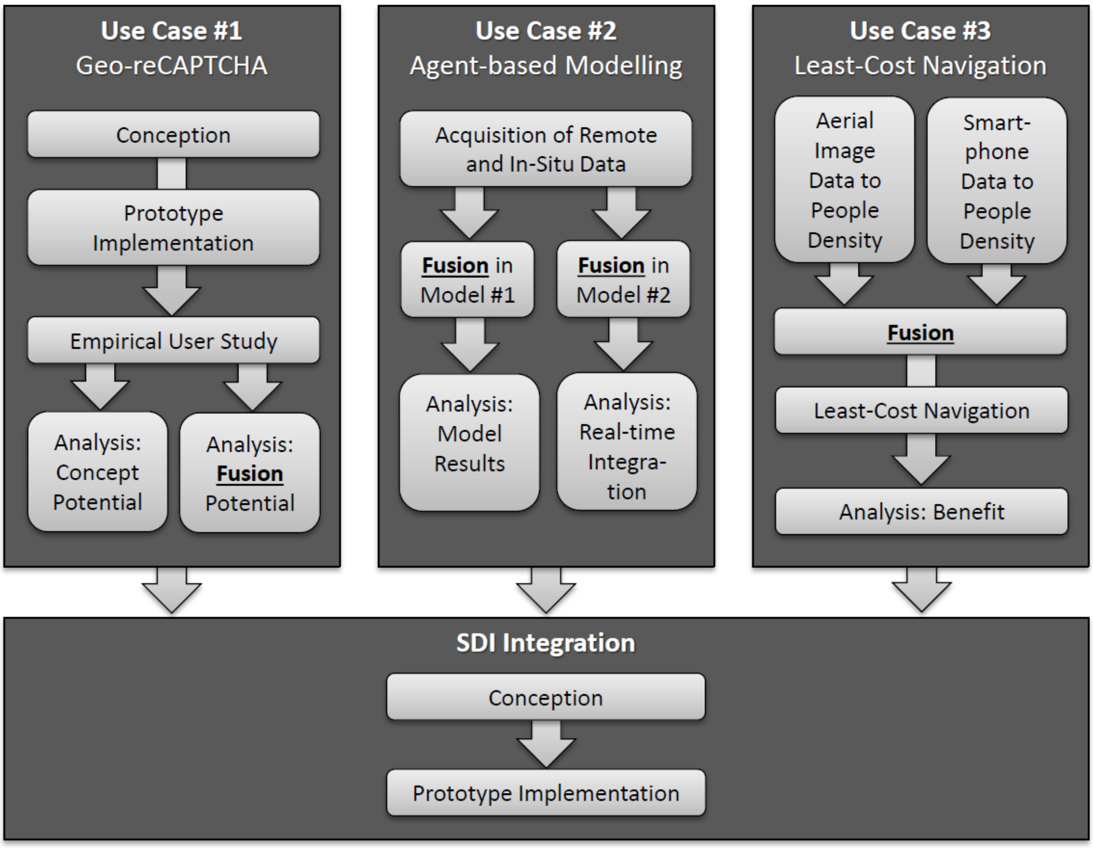


Figure 9. Methodical approaches of this work in a nutshell.

Concerning use case #1 (Geo-reCAPTCHA), a conceptual design is proposed based on the related works provided in section 3.1 that leads to a prototype implementation. This implementation is used to conduct an empirical user study with the goal to analyse the potential of Geo-reCAPTCHA in general and to investigate the benefits of fusing the results. For use case #2 (Agent-based Modelling), a data acquisition campaign under defined test conditions is conducted to gather suitable remote and in situ sensor data. The information from that data is integrated in the two models described in section 3.2. Model #1 allows for investigating the prediction quality of the model assumptions in general whereas model #2 is addressing the effect of real-time information integration. Regarding use case #3 (Least-Cost Navigation), information about the people density has to be calculated from the aerial images on the one hand and the smartphone sensor data on the other hand. This information is fused to a joint people density layer and builds the foundation for the least-cost navigation computation. Based on the comparison of the results using the fused and the non-fused density layer, the added value of geo-information fusion can be investigated. Having the methodology of the three use cases in mind, a first conceptual design for integrating geo-information fusion in a spatial data infrastructure is presented in the final subsection.

4.1 Use Case #1: Novel Acquisition Approach for User-Generated Information: Geo-reCAPTCHA[24]

Based on the review of the related works concerning CAPTCHA and reCAPTCHA as well as UGGI (see section 3.1), the technical requirements listed in Table 2, which have to, or should be, addressed in the system design, are concluded.

Table 2. List of technical requirements that have to, or should be, addressed in the UGGI generating system design. (Hillen & Höfle 2015)

No.	Technical Requirement
1	HAVE TO tell computers and humans apart (von Ahn et al. 2003)
2	HAVE TO be solvable in an acceptable amount of time (analogous to reCAPTCHA)
3	HAVE TO avoid the user distinguishing between control and unknown data
4	SHOULD use the same type of CAPTCHA for the control and the unknown data
5	SHOULD not exclude certain groups of people (regarding language, age, etc.)
6	SHOULD generate valuable geographic information (regarding reliability, quality, and quantity)

Based on the technical requirements (Table 2), a conceptual design for a UGGI generating system called "Geo-reCAPTCHA" is developed, which adapts the reCAPTCHA idea to the geo-domain. Furthermore, a web-based prototype is implemented, which is then used to conduct an empirical user study.

4.1.1 Conceptual Design of Geo-reCAPTCHA

The main idea of Geo-reCAPTCHA is to use human knowledge to solve the CAPTCHA, and to collect valuable geographic information at the same time. Such geographic information comprises the geometric representation of spatial features (e.g. the floor plan of a house, point location of a tree) and non-geometric, thematic, and semantic

[24] This section has previously been published by Hillen & Höfle 2015. Some changes and new figures are added in subsection 4.1.3.

information (e.g. type of land use, damage or no-damage). The type of geometry, however, is use case specific and is not relevant for the generic concept.

An overview of the essential steps for a Geo-reCAPTCHA is provided by the basic activity diagram in Figure 10. These four generic steps displayed in Figure 10 have to be addressed in every implementation of such a system. Subsequently, each step and the corresponding mandatory parameters are presented in detail.

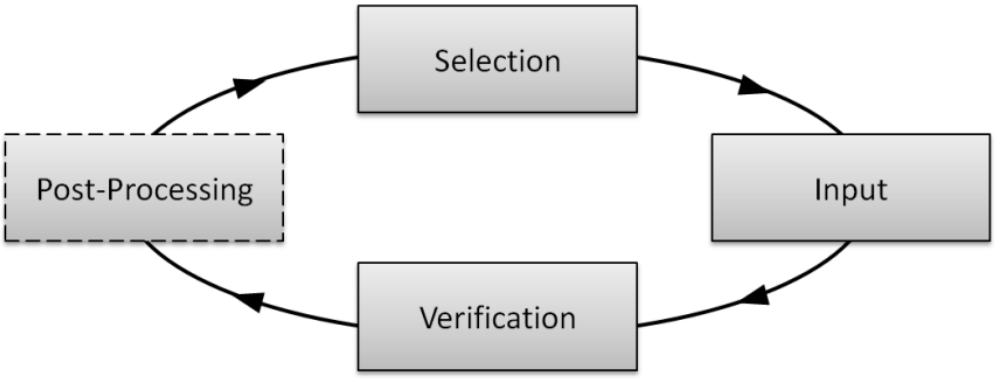


Figure 10. Geo-reCAPTCHA activity diagram consisting of the four main steps. (Hillen & Höfle 2015)

Selection

Each use case requires different basic data for the Geo-reCAPTCHA system (e.g. cadastre data, or remote sensing data for a specific geographic region). In the selection step, the system has to pick parts of the data (e.g. a small subset of the remote sensing data) that is used for the user input in the next step. Therefore, two main preliminary parameters have to be set. First, the known and the unknown data have to be defined. In this case, both parameters describe a data source (or a link to a data source) from which data are gathered or stored. This definition implies the spatial extent for the data capturing which can be different for the known and unknown data. The known data are used as the control data for the CAPTCHA whereas the unknown data are newly captured from the user. After the setting of both essential parameters, the selection step chooses a feature or a geographic extent from the two data sources and delivers the information to a client. In this process, it should be possible to define favoured regions (e.g. a specific city or a disaster region) from which features are selected more often in order to emphasize specific areas. Furthermore, additional information can be used to ensure that certain features are included in the data selection (e.g. compare with OSM data to make sure that a building is visible in an aerial image).

Input

A Geo-reCAPTCHA has to provide an input interface for the user. This interface can differ depending on the type of geographic information being captured. This information can be geometric (e.g. point, line, polygon, or point cloud) as well as non-geometric (e.g. context, topology, semantics). In the geometric case, the geometry class has to be defined.

The classes can be derived from the Open Geospatial Consortium (OGC) simple feature specification (OGC 2011). Although Geometry class is capable of being integrated in the concept, it is recommended that the class GeometryCollection be excluded to keep the system simple for the user. This means that only one feature at a time should be captured from the user. Thus, the system has a higher chance of achieving the technical requirement to be solvable in an acceptable amount of time (Table 2).

In the non-geometric case, it has to be defined whether i) a collection of given values is presented to the user or ii) the user can type free text. In the first case, the expected user input is known (e.g. taken from existing feature attributes of projects like OSM or GeoWiki) and thus the interpretational efforts during the post-processing are much less complex. The possibility to type free text in the second case has pros and cons. On the one hand, the results might be much more accurate due to the freedom of the user input and the fact that the user is not limited to pre-defined options. On the other hand, it may require significantly more effort to interpret the user input since the actual meaning has to be extracted and analysed. Furthermore, the interpretation of free text (automatic, semi-automatic, or manual) may result in a misinterpretation of the information.

Afterwards, corresponding capturing tools (e.g. a map representation with digitisation functionality) have to be provided for the user input. For this purpose, it is important that the user cannot distinguish between the input for the control data and for the unknown data, as defined in the technical requirements (Table 2). If this was not the case, the user could simply enter the control data to pass the CAPTCHA, but the unknown data would not be reliable. This is also the reason why one cannot simply mix up different types of CAPTCHA (according to the technical requirements) in a reCAPTCHA system (e.g. text-based CAPTCHA and a map input for unknown data) as the user is expected to avoid the input of the unknown data to save time.

Verification

The most important part of the system is the actual verification of whether the CAPTCHA is passed or not, i.e. whether the input was made by a human user or a machine. The verification has to be adapted to the type of information captured from the user, and has to compare the captured information with the control data. This testing is completely use case specific and can vary in its complexity. For example, it can be a rather complex comparison of two geometries (e.g. a floor plan of a house) to determine similarity, or a simple word check between the input of the user and a pre-defined set of correct values.

Post-processing

During the post-processing step the verified information of the user is analysed or combined with other data to generate an additional value or to solve a specific problem (for example, deriving one building outline out of all user digitization for one object). This step should be an integral part of a Geo-reCAPTCHA. Analogous to the verification step, the post-processing is use case specific as well. It can vary from simply storing every user input (e.g. for visualization purposes), to complex heuristics and analysis (e.g. comparing digitized building geometries with building data derived from remote sensing imagery for change detection approaches). Furthermore, additional external data sources can be included in the post-processing step (e.g. land cover classifications from remote sensing data).

4.1.2 Prototype Implementation

The four essential steps from the conceptual design are transferred into a Web infrastructure design. As a proof-of-concept, a Geo-reCAPTCHA prototype is implemented in which the user has to digitize the boundary of buildings from airborne imagery as illustrated in Figure 11. A generic overview of the infrastructure design for this prototype is illustrated in Figure 12. The essential parts are subsequently described in detail.

Figure 11. Prototype implementation of a Geo-reCAPTCHA client. Two map representations offer the possibility to digitize building boundaries in the form of polygons. The digitization in the left map is already completed (yellow polygon) whereas the digitization in the right map is currently in progress (blue sketch). (Hillen & Höfle 2015)

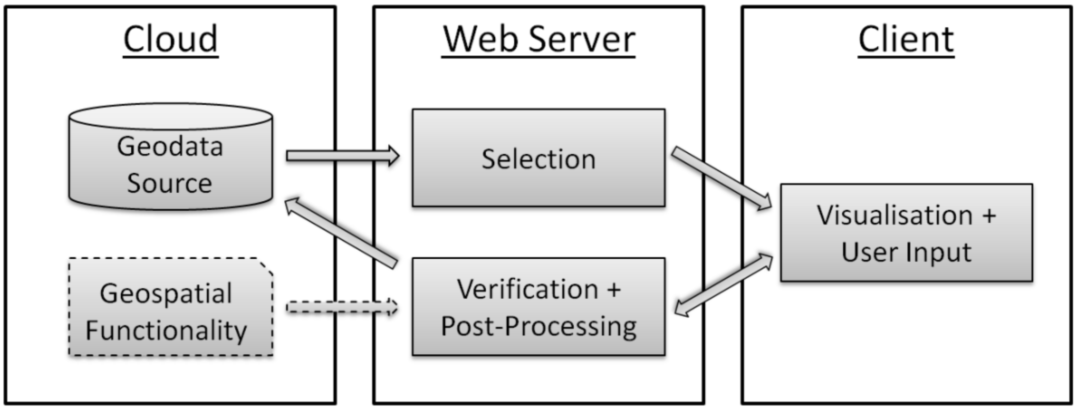


Figure 12. Infrastructure design for a web-based Geo-reCAPTCHA prototype consisting of a cloud component, a web server, and a client. (Hillen & Höfle 2015)

Web Server

The web server builds the centrepiece of the infrastructure design by managing all incoming requests of the client, building the bridge to the geo-data sources and holding the logic of the Geo-reCAPTCHA system in the form of selection, verification, and post-processing functionality. The initial point is the selection step in which the essential parameters "type", "unknown data" and "control data" have to be defined.

The information type defines whether the user has to digitize geometries or has to capture non-geometric information. The prototype implemented in this work will capture geometric information in the form of polygons. According to the information type, the control data and the unknown data have to be defined, e.g. by defining a region and a base layer from which the data are extracted. The selection process can now randomly fetch data from the given data sources or with emphasis on one or more defined favoured regions within the data. For our prototype, aerial images are provided by an OGC Web Map Service (WMS) for both control and unknown data.

The second part of the web server consists of the verification and the post-processing steps as outlined in the generic concept. The verification process is called by the client after the user inputs data. As it is defined in the conceptual design, it has to be decided whether the user input matches the control data or not. The presented Geo-reCAPTCHA prototype verifies the input using a simple algorithm that builds a buffer around the boundary of the control geometry and checks whether the boundary of the polygon digitized by the user lies completely within this buffer area.

If the user input for the control data is evaluated as correct, a message will be sent to the client to confirm the (successful) passing of the CAPTCHA. Simultaneously, the input of the unknown data is considered to be correct as well and can therefore be integrated into the post-processing procedure. The prototype currently has no automatic post-processing implemented as the interpretation is done manually in the course of the empirical user study.

Client

The client is the interface for the user with which input can be captured and transferred to the web server. In the prototype, the client is a typical website displayed within a standard browser. The website requests the relevant data for the Geo-reCAPTCHA from the web server and visualizes it for the user in two map representations (Figure 11). One map shows the selected data of the unknown data whereas the other map shows the control data. If a specific feature is pre-selected for capturing, it has to be marked somehow in the map to make sure that it can be correctly identified by the user. However, it has to be assured that the user cannot identify the map representation that displays the control data (technical requirements in Table 2).

Each of the two map representations has to provide a digitization tool (as implemented in the prototype in Figure 11) with which the user can capture the selected geometry type (e.g. a polygon or a linestring). The tool has to follow certain specifications: First, only the geometry type defined for the CAPTCHA is allowed in the digitization process. Switching between geometry types is not recommended. After the user finishes the digitization of the first geometry, the tool has to be disabled so that no further geometry can be captured from the user. No edit or delete functionality is provided to keep the system as simple as possible. However, the user can reload the map representation to receive new data from the server, and restart the digitization. For a non-geometric Geo-reCAPTCHA, additional input tools are needed like a selection box with pre-defined labels or a text field for free user input.

After both inputs of the user, the client automatically submits the result to the web server. Subsequently, the web server returns the result of the verification process. If the test is passed, the user can proceed. If the test is failed, the website will reload the test and request new data from the server.

Cloud

The cloud in this case describes any place, server, service, or resource in general, from the Web. This also includes local geo-databases as well as geospatial functions from a programming library installed on the Geo-reCAPTCHA web server itself. The cloud component of the infrastructure design specifies these resources to geo-data sources and the optional geospatial functionality.

4.1.3 Empirical User Study on Geo-reCAPTCHA

An empirical user study has been conducted to investigate how long the CAPTCHA approach within the Geo-reCAPTCHA prototype takes to be solved, and to derive the accuracy of the derived UGGI. In general, everyone aware of the user study was able to participate. However, specific advertisement was made among students and staff members of the Institute of Geoinformatics and Remote Sensing in Osnabrück (Germany) and the Institute of Geography in Heidelberg (Germany). Additionally, many participants are geography students consulted during a basic geography lecture at the University of Vienna (Austria). Thus, the following user groups are assumed to participate:

- Student of natural science
- Student of non-natural science
- Student of geography
- Student of geoinformatics or similar
- Geoinformatics expert
- None of the listed groups

In the experimental setup, the user is challenged to digitize the outlines of 15 consecutive arbitrary buildings within the map representation in a fast but convenient way. The study area contains different categories of building shapes (see Figure 13) varying from simple building shapes (Figure 13A; e.g. rectangular or mostly straight lines), complex shapes in which the building is composed of several parts (Figure 13B; e.g. several edges, attached garage) and buildings that are partly covered with trees (Figure 13C). This heterogeneous selection of building shapes will allow for identifying the limitations of building digitization with Geo-reCAPTCHA, such as best and worst-case buildings. Each digitization is recorded with a randomly generated user identifier to estimate the overall number of participants as it is not allowed to simply store the users' IP address. This identifier changes when the same user opens the site again which is why users are able to redo the study. Due to this fact, we cannot provide an exact number of participants but a number of digitization rounds with the same user identifier.

Figure 13. Three categories of building shapes. A: simple, mostly straight lines; B: complex, many edges, hard to distinguish from surrounding; C: complex, covered by trees.

The description of the test for the user was generically formulated to avoid influencing the user's behaviour during digitization. It was not mentioned in the task description that the user should be as fast or as accurate as possible. Before starting with the actual digitization, the user is requested to give basic information about age and user group (or rather experience level). Afterwards, a reduced version of the prototype with only one map representation is presented to the user (Figure 14).

Figure 14. Map representation of the conducted user study with the refresh button in the upper left and the amount of already digitised building below.

In this case, 25 pre-defined centre points for the map view are available to make sure that a building is visible for each digitization run. This leads to an extensive overlap of the

UGGI and allows for substantial statistical analysis of the accuracy of the captured geometries. The time from the first click in the map to the moment when the user finishes the digitization with a double-click is recorded and stored. The prototype implementation of the experiment does not permit editing or deleting of digitized features. However, the user has the option to withdraw the capture by reloading the map representation with new data and thus a new test. This function should be used if the user is not able to identify a building within the dataset. Each reloading process is recorded and stored in the database in order to investigate the reasons for reloading and withdrawing tests. The empirical experiment is finished for the users as soon as 15 buildings have been digitized. The structure of the gathered dataset is described in Table 3.

Table 3. List of data that are gathered in the empirical user study. (Hillen & Höfle 2015)

Name	Description
GEOMETRY	The geometry of the digitized building outline
TIME	The time for finishing the digitization (in s)
USER GROUP	The user group in the categories as mentioned above
AGE	The user's age in the categories: 18-24, 25-34, 35-44, 45-60, > 60, no age selected
TIMESTAMP	The timestamp of the digitization (date and time)
POINTID	The identification number of the different centres of the map view
USERID	The identification number which is created randomly for each user to identify digitization from the same user
COUNTER	The counter that represents the number of digitization done by the user

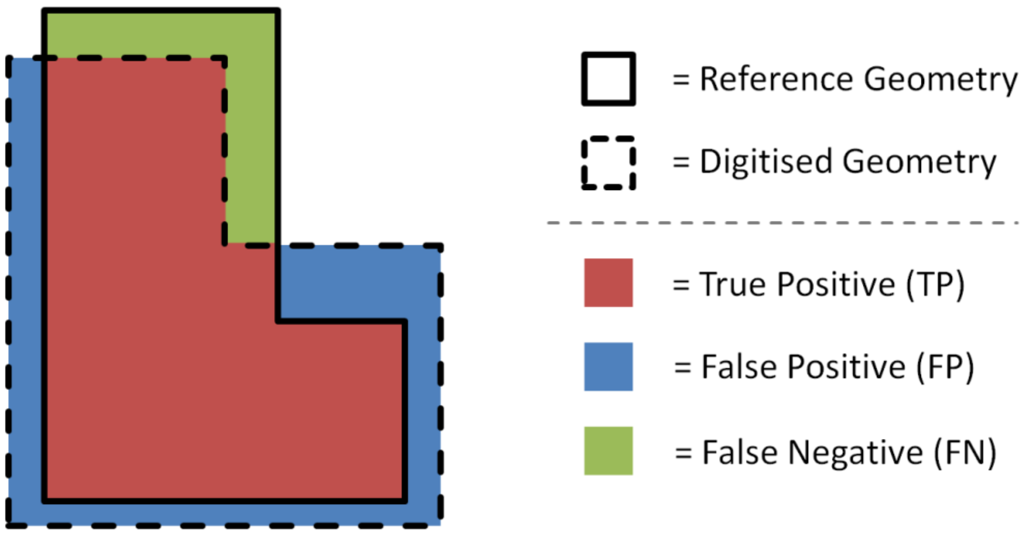


Figure 15. Three initial quality measures based on the overlapping and non-overlapping areas between the reference (solid polygon) and digitized (dashed polygon) geometries. (Hillen & Höfle 2015)

Furthermore, standard quality measures for building extraction are derived for each building (Rutzinger et al. 2009; Heipke et al. 1997). Each digitized geometry is compared to a reference with which the digitized geometry shares the most overlapping area. In a first step, three measures are derived based on the overlapping and non-overlapping areas between the reference (solid polygon) and the digitized (dashed polygon) geometries (Figure 15). The true positive (TP) area is the one that exists in both polygons (consensus), i.e. intersection area in GIS terminology. In contrast, the area that appears only in the digitized geometry is classified as false positive (FP). The area that is not digitized by the user but is actually part of the reference geometry is the false negative (FN) area. Consequently, the TP-rate (completeness), the precision (correctness), and the overall quality of the digitized geometry can be calculated with the following equations (Rutzinger et al. 2009):

$$TP\text{-}rate\ (completeness) = \frac{TP}{TP+FN} \tag{1}$$

$$precision\ (correctness) = \frac{TP}{TP+FP} \tag{2}$$

$$quality = \frac{TP}{TP+FP+FN} \tag{3}$$

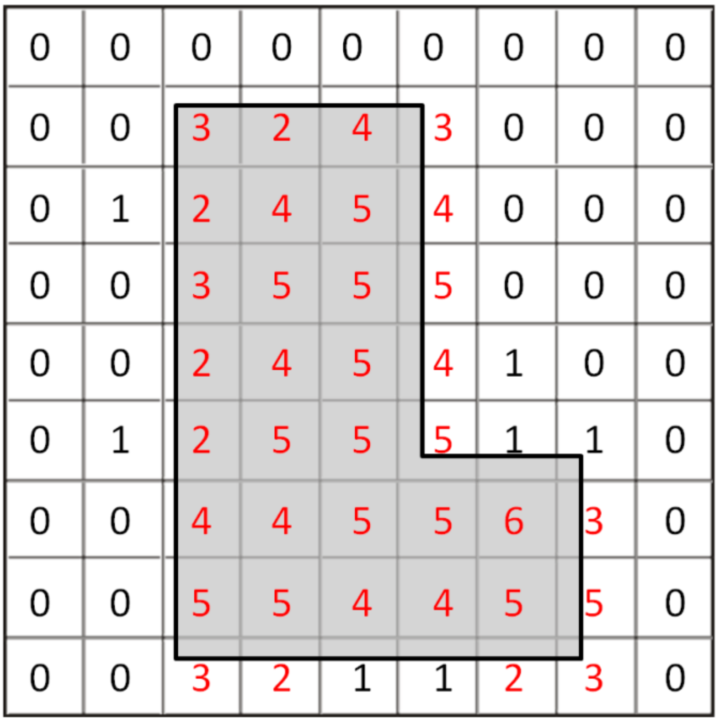


Figure 16. Reference polygon (grey) with overlaying raster grid. The raster is filled with the respective number of digitized polygons for each raster cell. Values above 1 are coloured red and are used for estimating the reference geometry. (Hillen & Höfle 2015)

Above that, it is analysed how many digitized geometries have to be fused to receive appropriate results that almost match the corresponding reference geometry. For this purpose, the idea of a raster-based quantitative analysis by Klonner et al. (2015) is adapted. The idea is to build a raster with a specific cell size and sum up the number of polygons within each cell. An estimation for an appropriate number of digitized geometries can be derived by comparing the boundary of the reference geometry with the raster grid (Figure 16). Thus, for a Geo-reCAPTCHA implementation a threshold for the transition from unknown to known data has to be set.

4.2 Use Case #2: Modelling People Movement based on Smartphone Sensors and Remote Sensing Imagery[25]

4.2.1 Data Acquisition and Experimental Setup

As a preliminary step, a simulated data acquisition campaign under defined conditions was planned and conducted. This enables full control over data recording, spatial coverage and temporal resolution, which is needed for a detailed interpretation of the derived results. The basic idea is to begin with a manual recording of image data series with a typical single-lens reflex (SLR) camera from a high building to simulate airborne imagery, before actually performing an expensive airborne campaign. The spire of the Marienkirche in Osnabrück (Germany) is chosen as an ideal recording platform as it is one of the highest buildings in the inner city of Osnabrück (Germany) with approximately 40 meters height. Above that, it holds an observation deck with an almost clear view over the ancient market place of Osnabrück.

Figure 17. Images from the observation deck of the Marienkirche in Osnabrück with different focal distances (left: 18mm; right: 48mm).

The SLR camera used for the test recordings is a Nikon D5100 with a 16.2 megapixel sensor equipped with an 18-55 mm lens. In a first step, images with different focal distances (18, 35, 48 and 55 mm) were taken to analyse the varying distortions after the georectification in a later step. Focal distances of 48 mm and 55mm are the ones closest

[25] The first subsection of this section has previously been published by Hillen et al. 2014, except for two new figures and some additional paragraphs. The text of subsection 4.2.2 is basically unpublished, however, the idea of model #1 is published in the aforementioned paper. The idea of model #2 is part of a German conference paper by Hillen & Höfle 2014.

to typical airborne image recording systems (right in Figure 17) whereas a focal distance of 18 mm increases the recorded area significantly (left in Figure 17).

The relatively low height of the recording platform (compared to aircraft) results in an oblique view. This requires a precise rectification of the images based on very accurate and reliable ground control points. The TOPCON real-time kinematic (RTK) differential GPS (dGPS) system is used for collecting control points. As the camera position is fixed, the acquisition of ground control points has to be done only once and allows for an automatic processing of image series.

Figure 18 shows two georeferenced images with different focal distances, 18 mm on the left and 48 mm on the right. The images are not orthorectified as the heights of different objects are not included resulting in an oblique view of buildings and objects in the recorded area. For this use case, the images with a focal distance of 18 mm are used due to the significant increase of the study area. Above that, no clear differences regarding the distortion after rectification can be seen for the varying focal distances (Figure 18). Due to the low recording height, both focal distances provide a highly sufficient image resolution.

Figure 18. Georectified images from the observation deck of the Marienkirche in Osnabrück with different focal distances (left: 18 mm [zoomed in]; right: 48 mm). (Hillen et al. 2014)

The in situ sensor data are recorded from test persons on the ground equipped with Samsung Galaxy S3 smartphones and Garmin GPSMap 60CSx hand-held GPS devices. The Samsung Galaxy S3 has a large number of built-in sensors like a 3-axis accelerometer, a 3-axis magnetic field sensor, an orientation sensor, a gyroscope sensor and a GPS receiver (Samsung 2013). The Garmin hand-held GPS device serves as a second provider of the current position of the test person to validate the smartphone location recording. The sensors of the Samsung Galaxy S3 can be accessed via Android programming interfaces (Android 2013). Hence, an Android App was implemented to store the sensor data and the geographic location in a specific frequency which matches the recording frequency of the SLR camera (in this case: 1 Hz). As a forecast for a later integration in SDIs, it offers the possibility to directly integrate the recorded data into a Web database by choosing "online" as storage type. However, mobile internet connectivity is often prone to errors and blackouts in particular which is why the app also offers local data storage.

In a first step, all data sources are used to evaluate the quality of the measurements as it is expected to be poor due to the urban surroundings (houses, high steeple, etc.). This step is of high importance regarding the integration of the data in an agent-based model. If the data is not providing the information needed for the modelling, it is more or less useless.

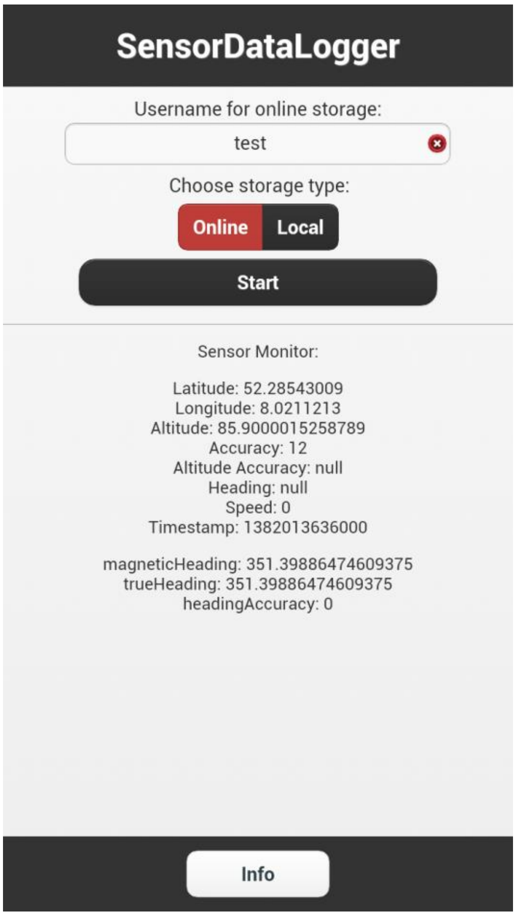


Figure 19. Implemented Android app to read and store the smartphone sensor data.

For the actual test recordings, the image and in situ data have to be recorded simultaneously. Therefore, the internal clocks of the SLR camera, the smartphones and the Garmin GPS devices have to be synchronized. This allows for an easier post-processing and data calibration. Eventually, the actual positions of the test persons are gathered for each image of the image time series manually. The moving directions are derived from the connection of two consecutive points. Additionally, obstacles are provided using respective cadastre data.

4.2.2 Combining Remote and In Situ Sensor Information with Agent-Based Modelling

In the following, an agent-based model is designed with the goal to estimate the movement of a single person as well as possible. In this first step, the remote sensing data serves as an evaluation source because the actual walking path of the person is recorded with the image series. Thus, every modelling result can be compared to the derived locations from the image series. In a second step, information from the remote sensing data is directly included in a second agent-based model. This creates a more realistic information basis and thus allows for a more realistic estimation. The modelling is performed with the open-source software Agent Analyst[26] that can be integrated in the desktop GIS ArcMap.

Model #1: Modelling exclusively based on in situ measurements

This model consists of one agent that is the test person equipped with a smartphone (red star in Figure 20). The start point of the agent is set during the model initialization using the first image of the recording series with the recording time as an accessible parameter to match the location with the smartphone data. Also derived from the first image of the recording series are the positions of the other pedestrians in the scene (people icons in Figure 20). The green points symbolise the actual walking path of the test person derived from the image series from beginning to end. Thus, this path can be seen as the main evaluation criteria. The absolute positions of the smartphone measurements are illustrated as blue rectangles. However, only the headings derived from the internal smartphone sensors are included in the model to calculate the new locations of the test person for each time step. The walking speed of the test person is extracted from the smartphone sensor data for each time step as well. The destination of the agent (chequered flag in Figure 20) is pre-defined. This represents the actual behaviour of individuals during major events to reach a specific goal like the festival area, the soccer stadium or other fixed places. The basic assumption of the model is that the agent wants to reach the end point on the shortest path. Hence, the direct heading to the destination is used as the main moving direction. Additionally, the heading extracted from the smartphone data is included as well. Both headings are recalculated at each time step and the mean value is then used to estimate the next step of the agent.

[26] http://resources.arcgis.com/en/help/agent-analyst/

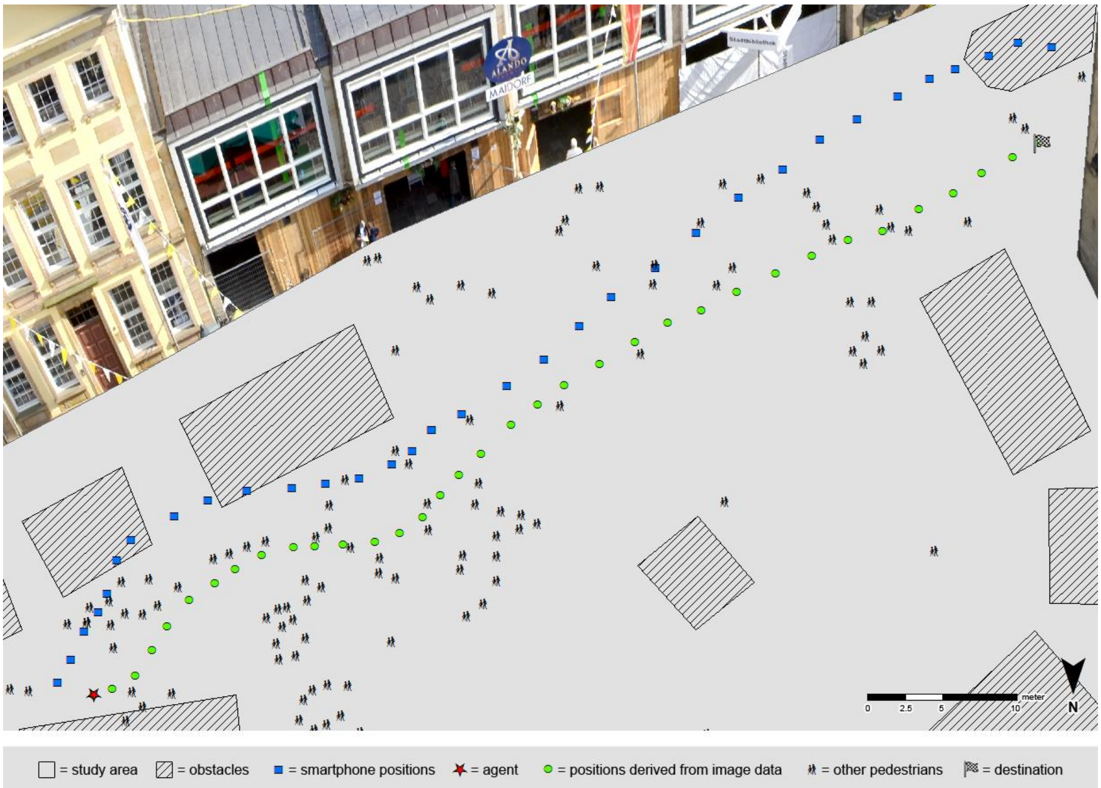


Figure 20. Starting position of the agent-based model. (Hillen et al. 2014)

With the given moving speed and heading, the only missing factor for this model are the other pedestrians which might get in the way of the agent. To avoid colliding with the other pedestrians, the model defines a "comfort zone" of 50 cm for the agent. If another pedestrian is within this range on the actual path, the agent will change his moving direction as long as no other pedestrian is in his way. The model stops as soon as the agent reaches the goal with the next step.

Model #2: Fusing information from remote and in situ measurements

This second model consists of two types of agents. The first agent is the same agent introduced in model #1 which is the test person (red star in Figure 20). All model assumptions defined for this agent remain unchanged. Thus, the modelling results of model #1 and #2 can be compared in general due to the same preconditions. The second type of agent defined in this model is the other pedestrians (people icons) in the scene which are derived from the remote sensing data. Unlike model #1, the other pedestrians are capable to change their position which is certainly increasing the realism of the estimation. However, it also increases the model complexity and includes sources of errors and uncertainties as each individual in the scene is reacting differently. These uncertainties are eliminated by exclusively using the people's position derived from the image data, meaning that the movement of the other pedestrians is not estimated, but represents the real position during the test recordings. For the first experiment, the position information for the pedestrians is updated every 5 seconds.

The sketched scenario is a time-critical application in which the movement of the other people in the scene has a significant influence on the movement direction of the test person and thus the whole walking path of the agent. This influence needs further investigation, especially with emphasis on the (near) real-time integration rate of 5 seconds. Without these continuous updates of data, no realistic modelling would be possible. The other people would either stay at their initial positions (model #1) or might be modelled as well and would thus not sufficiently represent reality. Only with the integration of up-to-date information is a realistic foundation for the modelling established.

To study the influence of the integration rate, experiments are conducted in which the position information about the other pedestrians is integrated with higher frequencies (1 and 2 seconds) and with lower frequencies (10 and 15 seconds). Afterwards, the resulting movement paths can be analysed and compared among each other. The distance of the respective paths to the actual walking path of the test person, which is derived from the image data, is calculated and provides evidence for similarity or dissimilarity. Thus, the quality of the modelling can be interpreted visually as well as statistically.

4.3 Use Case #3: Least-Cost Navigation Approach for Major Events[27]

For this use case, real-time aerial images are combined with smartphone movement data and integrated into a routing tool for major events. The routing approach is based on fusing 9-cm optical aerial images with movement data from smartphone users in near real time. The major goal is to provide an up-to-date crowd density map with a least-cost routing functionality for event visitors as well as for rescue forces and security authorities.

4.3.1 Crowd Density from Aerial Images

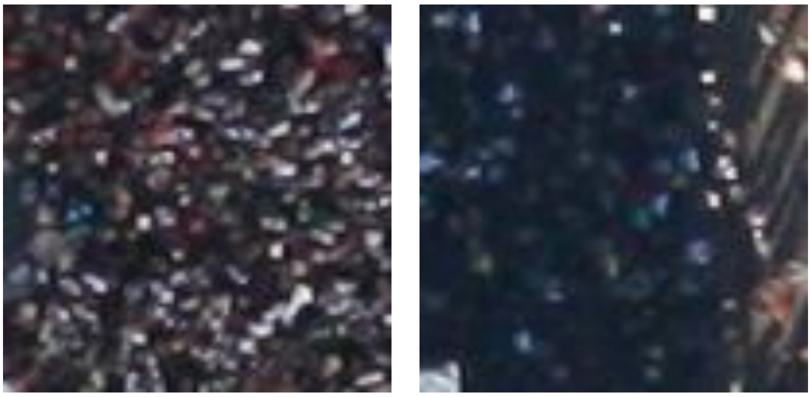
In the following, the process to automatically compute a density map of a crowd from aerial images ("crowd detector") is described. This map builds the basis for a location-based individual routing application using a raster-based least-cost path calculation.

Before the crowd density map can be computed, it is necessary to describe the features of the aerial camera system. The routing system is supposed to work at large festivals with an event area of several square kilometres. Despite this large area, the density map must cover all crowded places and must be updated regularly. Thus, one major requirement for the generation of an up-to-date routing recommendation is the timely delivery of the density map to the server. To achieve this, a processing system with aerial cameras and an integrated data link must transmit the images to the receiving station on the ground. The processing includes a georeferencing and orthorectification step, which is not mandatory for the crowd detection itself, but for the fusion of image and trajectory

[27] This section has previously been published by Hillen et al. 2015. Parts of subsections 4.3.2 and 4.3.3 are swapped and additional details are added for the information fusion in subsection 4.3.3.

data (Section 4.3.3). Kurz et al. (2012) describe a system with on-board orthophoto generation and a bidirectional air-to-ground data transmission. Their system works well for the routing system presented in this use case, although the installation of the processing system could be located on the ground as well.

The aforementioned requirements of large coverage and short update intervals of the density map lead to a trade-off between the field of view of the cameras and the spatial resolution. Hence, for this use case, the method described by Meynberg & Kuschk (2013) is used, which is able to detect crowds in aerial images with a resolution of approximately 9 cm. At this resolution, a single person appears as a small blob of roughly 5 × 5 pixels. In very crowded scenes these blobs are hardly discernible due to occlusion and changing lighting conditions. In this case, they instead form a heterogeneous texture without any orientation or regular pattern structure (Figure 21a). Moreover, the appearance of these textures distinctly changes depending on background pixels and lighting conditions (Figure 21b).



(a) **(b)**

Figure 21. Example of two 100 × 100 pixel image patches containing human crowds (9-cm resolution). The major challenges are varying lighting conditions, varying backgrounds, and mutual occlusions. (**a**) High crowd density, many occlusions; (**b**) low contrast. (Hillen et al. 2015)

To overcome these problems the crowd detection tool chain proposed by Meynberg & Kuschk (2013) is used. The approach convolves image patches of a constant size with a Gabor filter bank and uses a concatenation of filter responses as the input feature vector for a support vector machine (SVM). Readers are referred to Meynberg & Kuschk (2013) for development details. In the context of this use case, the term "crowd texture" is used to describe an image region where people stand very close to each other and form one coherent structure. The term "crowd patch" is defined as a patch containing this crowd texture. In the following, the main processing steps to estimate the person density in aerial images are summarized for which no further a priori knowledge is required.

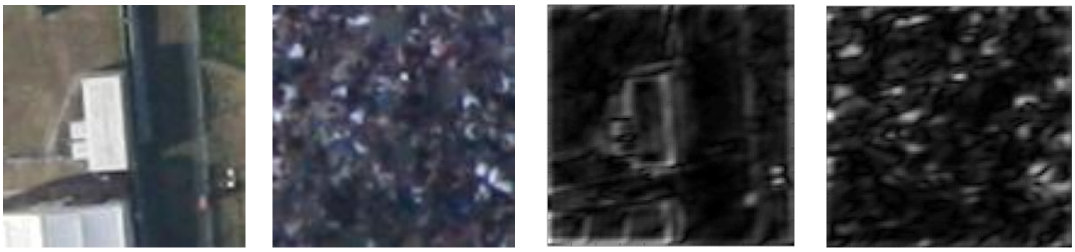
Step 1: Detecting Interest Points

The purpose of this step is two-fold. First, it detects corners and saves the coordinates as possible locations of a person, which are the basis for the density estimation described in step 4, and second, it significantly reduces the search space for the filtering in step 2. The search space reduction is motivated by the fact that during a flight campaign a large number of images are being taken, each image having a resolution of around 18 megapixels. With the original images as the input, the outputs of this step are possible pixel locations where a high number of people are located. Due to the computationally expensive feature extraction and classification steps, the search space should be limited to image regions in which a high number of people is likely to occur. As mentioned earlier, a person appears like a small blob or corner with a size of roughly 5 × 5 pixels in 9-cm resolution aerial images. Therefore, a corner detector by Rosten & Drummond (2006) is first applied to the whole image, which reduces the locations of possible crowd textures from theoretically all pixel positions to only those positions that are detected as a corner, and hence have the necessary condition to be considered for further processing. In this way, the number of filter operations that are performed according to step 2 can be reduced by a factor of 1000 (depending on image content) to allow for usage in time-critical scenarios.

Step 2: Finding a Feature Vector Representation for Crowd Image Patches

The input of this step is an array of all possible pixel locations of crowd textures. The resulting output is a set of feature vectors that discriminate well between image patches with crowds and image patches without crowds. In the following, it is described in detail how such feature vectors are created.

Every image patch I_k is convolved with a bank of Gabor filters. These filters are particularly appropriate for texture representation, first introduced by Manjunath & Ma (1996), as they encode both orientation and scale of edges in a low-dimensional feature vector. Image patches with regular building structures (Figure 22a) result in a strong response at certain orientation angles (Figure 22c). In contrast to that, a crowd patch (Figure 22b) gives a high response in every direction (Figure 22d), because the people do not form any regular pattern. In this way, it is possible to construct effective, discriminating feature vectors for the binary classification task that follows.



(a) (b) (c) (d)

Figure 22. Two original images (**a**) and (**b**) with their respective response images (**c**) and (**d**) after convolving both with a Gabor filter. Subfigure (c) shows the response of the regular structure in the original image (a), while (d) shows the response of the unstructured crowd in the original image (b). (Hillen et al. 2015)

Let $I \in \mathbb{R}^{M \times N}$ be an image patch at a candidate pixel position (x,y). Its Gabor wavelet transform is thus defined as

$$W_{s,k}(x,y) = I(x,y) * g_{s,k} = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} I(i - \frac{M}{2}, j - \frac{N}{2}) \times g_{s,k}(i,j) \quad (4)$$

where $g_{s,k}$ is one Gabor filter function where s and k determine the scale and the orientation angle of the filter, respectively. Next, for each combination $W_{s,k}(x,y)$ the mean $\mu_{s,k}$ and variance $\sigma_{s,k}$ are computed and stacked into the final feature vector $f(I) \in \mathbb{R}^{2SK}$:

$$f(I) = [\mu_{(0,0)}, \sigma_{(0,0)}, \mu_{(0,1)}, \cdots \mu_{(S-1,K-1)}, \sigma_{(S-1,K-1)}] \quad (5)$$

with K being the number of orientations and S being the number of scales of the filter bank.

Step 3: Classification with Non-Linear Support Vector Machine

The set of all feature vectors $f(I)$ is then passed as a matrix to an SVM with a radial basis function kernel. Its return value is a vector of scores that determines if an image patch has been classified as a crowd patch or not.

Step 4: Crowd Detection: From Binary Classification to Continuous Density Estimation

At this point, the list of possible person locations (step 1) and the classification result (step 3) can be combined. From now on, only those possible person locations that lie within a positively classified image patch are considered and are used to compute a probability density function with a Gaussian kernel over the image domain. In this way, the crowd density estimation can be expressed as an intensity value. This value can be assigned to every pixel of the original image and not only to a finite and very sparse set of detected corners. To this end, the assigned value is not calibrated with a verified crowd density that can hardly be measured in a real-world scenario; however, it is still sufficient to serve as a two-dimensional cost function in this context.

4.3.2 Crowd Density from Smartphone Data

The preliminary step for working with smartphone sensor data is the implementation of an app to record specific internal sensor data via the Android API[28]. For this work, the current geographic location of the smartphone user and the corresponding movement direction along with the estimated movement speed are derived from different smartphone sensors like the acceleration sensor, compass, and GPS/GNSS. Based on previous investigations, it is claimed that the position accuracy of GPS/GNSS is sufficient

[28] https://developer.android.com/about/versions/android-4.4.html

especially for events in rural areas but also for events in small and medium-sized cities (Hillen et al. 2014). In Figure 23 an exemplary dataset of recorded smartphone movement data (geographic location plus corresponding moving direction) of three different smartphone users is visualized.

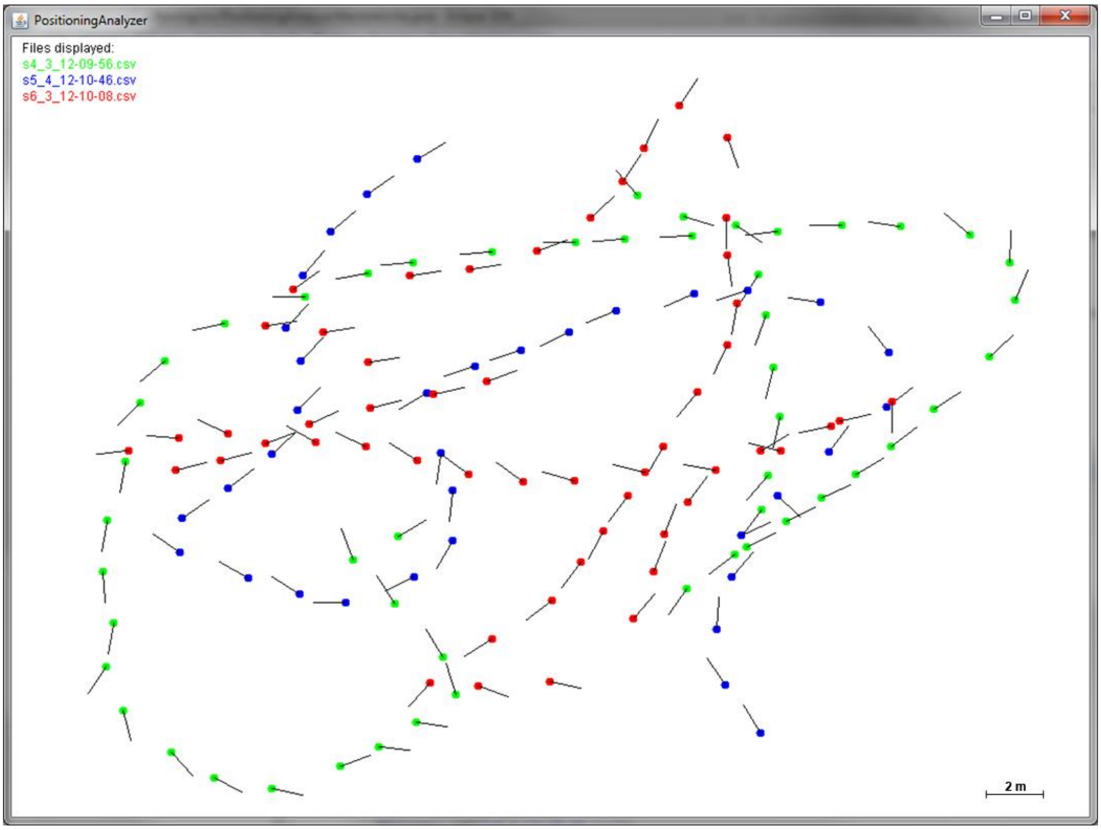


Figure 23. Visualization of movement data from three different smartphone users (green, blue, and red) derived from the internal sensor data via the Android API. The dots symbolize the GPS/GNSS location of the smartphone user. The lines oriented according to the corresponding movement direction of the user. (Hillen et al. 2015)

The movement speed of the user at the specific geographic location is used to re-evaluate the image-based crowd density estimation. It is assumed that high movement speed is an indicator for a low crowd density whereas a slow movement speed suggests a high crowd density. Rastogi et al. (2011) conducted a comprehensive comparison of pedestrian walking speeds based on literature from 1967 to 2007. The values of average speed for adults vary from 1.32 m/s to 1.51 m/s. Furthermore, every study revealed significantly lower walking speeds for elderly people (generally over an age of 65 (Gates et al. 2006)) with 0.97 m/s to 1.34 m/s. In addition, Carey (2005) found that pedestrians in groups tend to be slower (1.54 m/s alone compared to 1.41 m/s in groups for younger pedestrians). Thus, varying circumstances have to be considered regarding the analysis of movement speed. It is especially important for major events that it is determined whether the user is only moving slowly because of a specific reason (e.g., to look for shirts at the merchandising booth or to buy something to drink), or if the user actually has to move slowly because of high crowd density. This might result in the misinterpretation of high crowd density for less crowded regions.

The smartphone app transfers the raw movement data into a spatial PostgreSQL/PostGIS database on a web server using a mobile Internet connection. Afterwards, the dataset is integrated in a GeoServer in order to be accessible via Web Map Service (WMS) and Web Feature Service (WFS) interfaces by the Open Geospatial Consortium (OGC). Thus, the data can be integrated in any processing chain or application over the Web. Above that, the data can be directly processed in the database or can be integrated in OGC Web Processing Service (WPS) processes, which is of high importance regarding the following conversion from movement speed to crowd density information.

Weidmann (1992) investigated the relation between the local speed and the local density of people and formalized it as:

$$v_i = v_{F,f} \times \left[1 - e^{\left(-\gamma \cdot \left\{\frac{1}{D} - \frac{1}{D_{max}}\right\}\right)}\right] \quad (6)$$

where v_i is the speed at a certain density, $v_{F,f}$ is the maximum speed at full freedom (1.34 m/s), D is the crowd density in people per m^2 (p/m^2), D_{max} is the crowd density at which no movement is possible anymore (5.4 p/m^2) and γ is an empirically derived fit parameter (1.913 p/m^2). Wirz et al. (2013) conducted an empirical study based on smartphone measurements to verify this relation. Based on Equation (6), the crowd density can be estimated from the smartphone data using

$$D = -\frac{1.913}{\ln(1.34 - v_i) - 0.646929} \quad (7)$$

for each local speed v_i recorded with the smartphone.

4.3.3 Information Fusion

The image-based crowd density estimation (section 4.3.1) and the density information derived from smartphone movement data (section 4.3.2) are afterwards combined to create a joint cost layer for the least-cost navigation. For this purpose, the geographic information system GRASS GIS[29] is used. GRASS GIS is highly suitable for this work as it is a) raster-based and b) supported by the Python implementation of the OGC WPS standard named pyWPS (see section 2.3). This allows for future Web-based real-time processing of the aerial image and smartphone data.

The density layer derived from the aerial image data serves as a base layer for the raster-based least-cost routing process. For this purpose, the layer is reclassified to a range between 0.43 (no density) and 7.1 (high density). Fruin (1981) identified these values of (a) 0.43 p/m^2 and (b) 7.1 p/m^2 as the crowd densities with (a) a normal walking speed and (b) no movement at all. Above that, Fruin (1981) investigated a reduced walking speed at

[29] http://grass.osgeo.org

2.0 p/m², involuntary contact between people at 3.57 p/m², and potential dangerous crowd forces starting at 5.55 p/m², which are important thresholds for further evaluation of the crowd density information.

The smartphone-based density information is imported into GRASS GIS as well and is converted from vector to raster format in order to be combinable with the information derived from the image data. For this, the point (now the respective pixel) of the smartphone measurement is expanded so that it delivers information for the area surrounding the smartphone user as well. Thus, the people density calculated with Equation (7) is adopted for the local neighbourhood of the test person as well. This is more realistic instead of using only the point measurement for the density enhancement. Otherwise, the density at the pixels next to the measurement would be totally different.

Based on the complemented density information, a cost layer can be calculated using the GRASS GIS function *r.cost*. The initial point for this calculation is the current geographic location of the user. The cumulative cost of moving from this point to each cell is calculated and stored in the resulting cost layer. Finally, the least-cost path between an arbitrary point and the current location of the user can be calculated using the function *r.drain*.

4.4 SDI Integration: Web-based Geo-Information Fusion Infrastructure[30]

In this section, a concept for integrating geo-information fusion in an SDI is proposed. Based on the experiences made in the presented use cases, one could imagine an information fusion infrastructure that mainly depends on OGC standards as introduced by Hillen et al. 2013 (Figure 24). Multi-source sensor data (orange) is provided via OGC standards like the WMS, WFS, WCS or SOS. The data are then integrated in a new service called Information Fusion Service (IFS; dashed rectangle) which consists of information extraction processes (i), information fusion process (ii) and an information database (iii). The idea is that information is extracted with a WPS processes (i) from the raw sensor data which is then forwarded to another WPS process (ii) that stores the information in a database (iii) and handles the communication with the application.

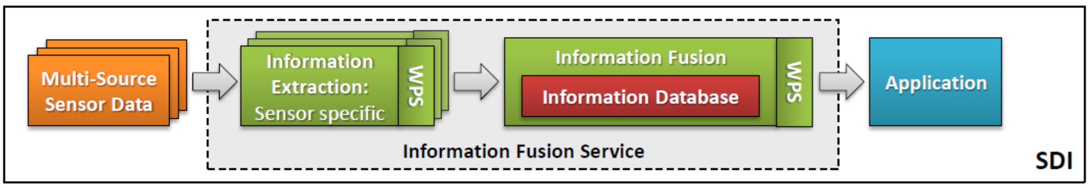


Figure 24. Information fusion infrastructure to fuse multi-source sensor data in a spatial data infrastructure (SDI). (Hillen et al. 2014)

[30] The infrastructure approach described in the first paragraph of this section has previously been published by Hillen et al. 2014 as referenced in the text. The new approach is a further development based on the first approach and is unpublished so far.

However, this concept has some shortcomings that need to be addressed and that led to a new conceptual design. WPS processes are generally designed to solve specific problems. In case of the concept by Hillen et al. 2013, the information fusion process acts as a controller with a static data base for which the WPS process has to run in an infinite loop. Furthermore, a WPS process generally has a defined set of input data that are required to start the process in the first place. This implies that it is not intended to add unlimited new input data while the process runs.

These shortcomings are addressed in a conceptual design illustrated in Figure 25. The centre piece of this infrastructure is the IFS controller (dark grey) that replaces the information fusion process from the concept of Hillen et al. 2013. The data sources (orange) can be registered on the IFS Controller in form of OGC Web services (WMS, WFS, SOS, etc.). Furthermore, corresponding information extraction processes (green) in form of WPS processes can be attached. These processes are sensor specific algorithms to extract relevant information from a given dataset. New processes can be implemented depending on the current use case (for example deriving water surfaces from radar satellite imagery or extracting traffic flow information from vehicle sensor data). As WPS processes are not capable of integrating continuous data streams, the IFS Controller triggers the processes with new data in a given frequency. By doing so, the streaming functionality is simulated by the IFS Controller.

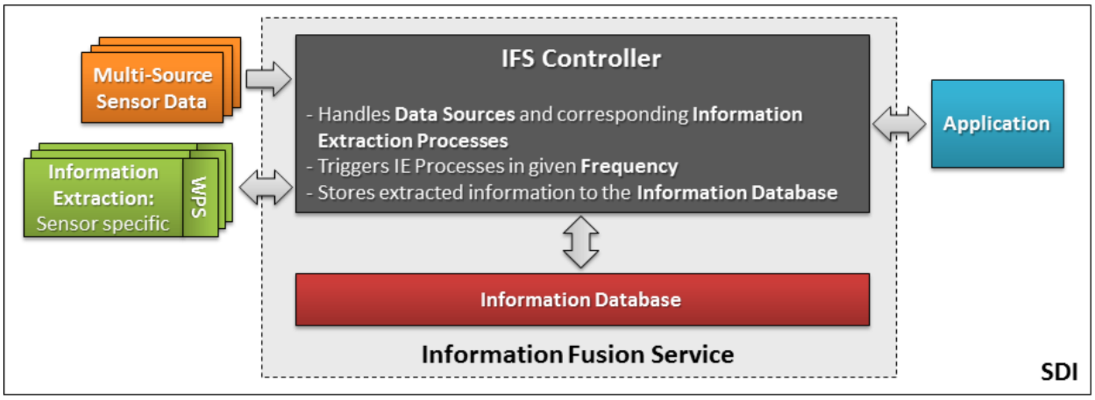


Figure 25. Web-based information fusion infrastructure to fuse information from multi-source sensor data for integration in an application.

The derived information is afterwards stored by the IFS Controller to the information database (red) analogous to the concept of Hillen et al. 2013. The database can be implemented as an integrative part of the IFS Controller or as a standalone component inside the IFS. This allows for scaling the complexity of the IFS as it is not reasonable for example to integrate a heavyweight database system for a lightweight use case or application.

The incoming information might vary depending on the frequency of the sensor itself, the complexity of the information extraction process or the rate of transmission of the sensor. By caching these information into the database, the IFS is able to synchronize the information in time. Furthermore, data gaps and missing information can be identified and addressed. Without this functionality the information extracted from the sensor data would be sent to the application without any order or previous matching which is highly error-prone. Additionally, the information database allows for a retrospective data retrieval that is needed for some applications (e.g. agent-based modelling for people movement that is based on the 5 or 10 last positions).

With all information stored in the information database, the IFS Controller provides an interface for integrating this information in an application. Depending on the use case and the complexity of information, it might be reasonable to exploit the existing interfaces, e.g. of the WFS. In this case, especially the integrated OGC Filter Encoding (OGC 2010b) allows for advanced data querying (e.g. for retrospective data retrieval). However, own interface definitions might be necessary in case of complex information that cannot be represented with an existing OGC standard or special needs by the respective application itself. Obviously, the IFS Controller cannot be implemented according to any existing OGC standard.

5 Results and Discussion

In this section, the results of the three use cases are presented and discussed. The research objectives that are posed during the use case introduction in section 3 are evaluated according to the respective results. Above that, implementation details for realising a geo-information fusion within a spatial data infrastructure with regard to the presented concept from section 4.4 are provided. Figure 26 is illustrating the overall methodical approach as presented in Figure 9 with emphasis on the aspects that are examined in this section (highlighted in red).

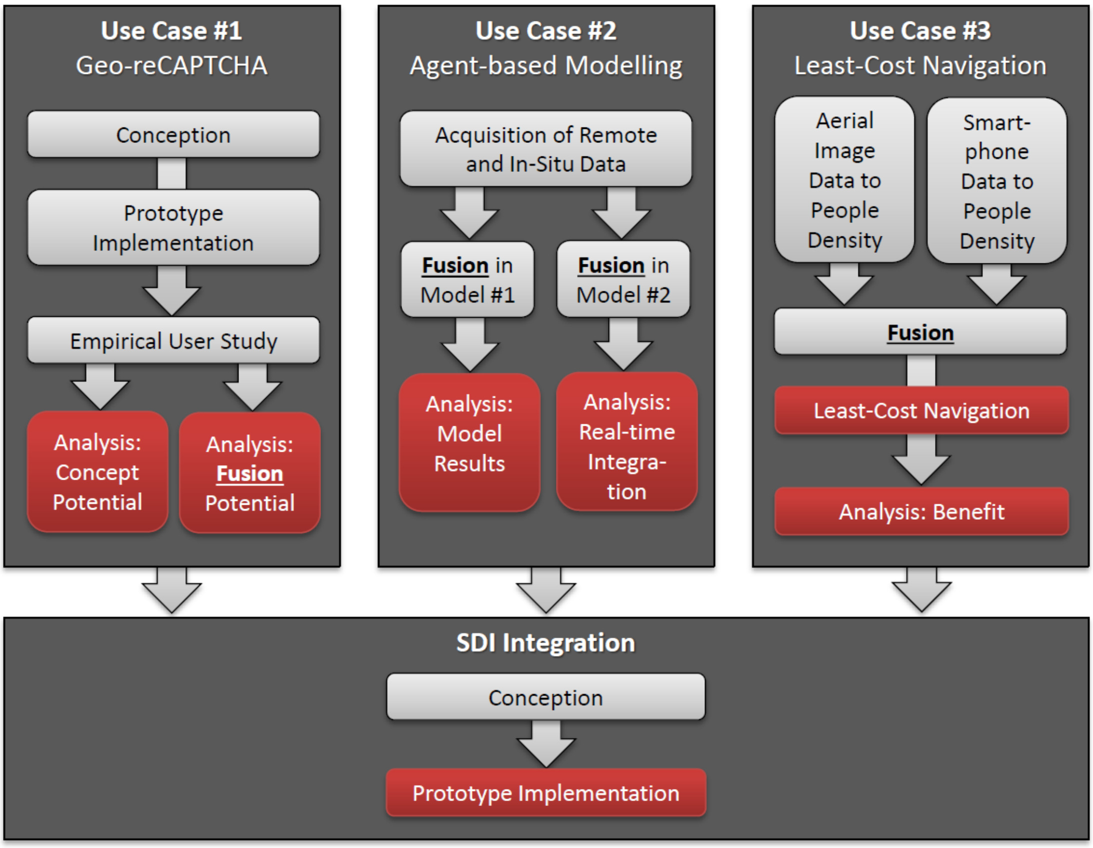


Figure 26. Methodical approaches of this work in a nutshell according to Figure 9 with emphasis on relevant aspects for this section (red).

5.1 Use Case #1: Fusing User-Generated Data? Results of the User Study on Geo-reCAPTCHA[31]

The conceptual design was implemented in a prototype, which was used for a proof-of-concept in the form of an empirical user study. Within the two weeks of the empirical user study, 2260 geometries were digitized in 189 total digitisation rounds. As users could also digitize multiple times, the number of unique users might be lower than the number of digitisations. The distribution of the digitisations among user groups and age groups of the users is presented in Table 4. According to the user selection, most geometries are digitized by students of geography with 950 (42.0%) followed by geoinformatics experts (531 geometries (23.5%)) and students of geoinformatics or similar (428 geometries (18.9%)). As the study was promoted in a basic lecture in geography, it can be assumed that most of the students of geography do not have much expertise regarding geoinformatics. Furthermore, most geometries are digitized from users with an age from 25 to 34 years with 1285 geometries (56.9%) as well as 18 to 24 years with 700 geometries (31.0%). People with an age of 45 and above are not well represented in this user study (60 geometries, 2.6%). The options "None of the listed groups" for the user group and "No age selected" for the age were the default values for the selection boxes in the user study.

Table 4. Distribution of digitisations among the categories user group and age of the participants of the empirical user study. (Hillen & Höfle 2015)

		Age					
		18 - 24	25 - 34	35 - 44	> 45	No age selected	**Total**
User Group	Student of natural science	1	90	0	0	0	**91** 4.03%
	Student of non-natural science	30	30	0	0	0	**60** 2.65%
	Student of geography	499	451	0	0	0	**950** 42.03%
	Student of geoinformatics or similar	142	259	27	0	0	**428** 18.94%
	Geoinformatics expert	13	363	125	30	0	**531** 23.49%
	None of the listed groups	15	92	15	30	48	**200** 8.85%
	Total	**700** 30.97%	**1285** 56.86%	**167** 7.39%	**60** 2.65%	**48** 2.12%	**2260** 100.00%

[31] This section has previously been published by Hillen & Höfle 2015. Additional unpublished paragraphs on geo-information fusion are added at the end of 5.1.2. The research questions from subsection 5.1.3 are unpublished.

5.1.1 Concept Potential: Time and Quality

In a first step, the time for digitising an arbitrary building in comparison with the derived quality is analysed. The recorded time is almost normally distributed with an average of 11.3 s and a standard deviation of 74.5 s over all 2260 digitized geometries for 68 different building objects. The high standard deviation is caused by three very long digitisation times (way above 60 s) with a maximum of 3527 s (almost 59 min). Removing those three datasets, the average digitisation time changes to 9.6 s with a standard deviation of 6.9 s. The following analysis will be based on the cleaned datasets.

Table 5. Descriptive statistics of all digitisations regarding the digitisation time (in seconds) of one building divided by user groups. (changed after Hillen & Höfle 2015)

		Digitisation time for one building [s]			
User group	**N**	**Min**	**Max**	**Mean**	**Std. dev.**
Student of natural science	91	2.8	39.0	11.4	6.7
Student of non-natural science	60	3.2	49.4	12.1	9.6
Student of geography	949	2.1	44.2	8.6	5.8
Student of geoinformatics or similar	426	2.2	57.0	10.4	8.0
Geoinformatics expert	531	2.3	59.9	9.5	6.9
None of the listed groups	200	1.4	56.1	11.5	7.4

Table 6. Descriptive statistics of all digitisations regarding the quality (in %) of one building divided by user groups. (changed after Hillen & Höfle 2015)

		Quality of one building [%]			
User group	**N**	**Min**	**Max**	**Mean**	**Std. dev.**
Student of natural science	91	0	97.0	79.6	24.2
Student of non-natural science	60	0	95.5	79.5	22.4
Student of geography	949	0	97.6	82.4	20.5
Student of geoinformatics or similar	426	0	98.3	83.3	18.3
Geoinformatics expert	531	0	97.9	83.9	18.2
None of the listed groups	200	0	96.9	76.8	28.1

Furthermore, time and quality are analysed in detail to determine differences between user groups and groups of age. Table 5 and Table 6 present the results for the corresponding user groups. Students of geography are digitising one second faster in the mean (8.6 s) than the geoinformatics experts (9.5 s), which are the second fastest group. The quality of the experts, however, is slightly higher in the mean (83.9% compared to 82.4%) with a lower standard deviation (18.2% to 20.5%). It can be seen that the groups with geography or geoinformatics background (students of geography, students of geoinformatics or similar and geoinformatics experts) do record the lowest values regarding digitisation time and the highest average qualities of building polygons.

The results for the different age groups can be seen in Table 7 and Table 8. Participants with an age between 18 and 34 are generally slightly faster (9.2 s to 9.6 s in the mean) than older participants (10.2 s to 13.5 s in the mean). Regarding the quality of the digitisation, the differences are much smaller between these age groups. The highest quality is recorded for the 18-year to 24-year old users with 83.5%. The 35-year to 44-year old users, however, record only a slightly lower quality of 81.5%. Overall, performing an analysis of variance (ANOVA) and a t-test, the user and age groups do show significant differences regarding digitisation time and quality.

Table 7. Descriptive statistics of all digitisations regarding the digitisation time (in seconds) of one building divided by age groups. (changed after Hillen & Höfle 2015)

		Digitisation time for one building [s]			
Age group	**N**	**Min**	**Max**	**Mean**	**Std. dev.**
No age selected	48	1.4	35.5	11.3	7.3
18 – 24	699	2.3	56.1	9.6	6.6
25 – 34	1283	2.1	57.0	9.2	6.9
35 – 44	167	3.8	59.9	11.1	7.6
> 45	60	5.1	32.7	12.7	6.9

Table 8. Descriptive statistics of all digitisations regarding the quality (in %) of one building divided by age groups. (changed after Hillen & Höfle 2015)

		Quality of one building [%]			
Age group	**N**	**Min**	**Max**	**Mean**	**Std. dev.**
No age selected	48	0	94.1	59.9	33.5
18 – 24	699	0	97.7	83.5	19.1
25 – 34	1283	0	98.3	82.6	20.2
35 – 44	167	0	97.2	81.5	20.2
> 45	60	0	97.2	78.9	27.6

The presented results provide insights into the fulfilling of the two main Geo-reCAPTCHA requirements (Table 2). First, it is shown that a map-based CAPTCHA can be solved in an overall mean of 9.6 s. Thus, a total time for a Geo-reCAPTCHA of 19.2 s can be expected as the Geo-reCAPTCHA approach requires two digitisations (for the control and the unknown data). Von Ahn et al. (2008) proved that, on average, the time required to solve a conventional CAPTCHA is 13.51 s and 13.06 s for a reCAPTCHA.

Therefore, a Geo-reCAPTCHA does need more time to be solved than a reCAPTCHA. Nevertheless, regarding the effort of other CAPTCHAs like image-based CAPTCHAs, the expected time can be considered acceptable as it is less than 50% slower than traditional reCAPTCHA. Furthermore, the results of this user study show that Geo-reCAPTCHA can be solved successfully by any of our user groups.

Moreover, the main Geo-reCAPTCHA requirements ask for the creation of reusable information. An overall quality for a single building of 82.2% on average suggests that this requirement is fulfilled in the specific use case of building digitisation. However, a detailed analysis of the digitisation quality is needed. Additionally, quantitative statements regarding the amount of digitisations that are required for a successful derivation of a valid geometry from Geo-reCAPTCHA have to be determined.

5.1.2 Fusion Potential: Combining Multiple Object Digitisations

Using the calculated accuracy parameters, the building objects can be described based on a single user digitisation and also the full track of all digitisations available for each object.

Table 9. Descriptive statistics of the three accuracy parameters TP-rate, precision, and quality (equations 1-3) for all digitized geometries (all values in %). (Hillen & Höfle 2015)

Accuracy parameter	Min	Max	Mean	Median	Std. dev.
TP-rate (completeness)	20.4	100.0	88.8	95.06	8.7
Precision (correctness)	22.1	100.0	88.1	95.10	9.2
Quality	20.4	98.3	82.2	88.84	10.7

The three accuracy parameters (equations 1-3) are calculated for each single building digitisation individually. The accuracy statistics of all building digitisations is summarised in Table 9. Overall, an average quality of 82.2% with a standard deviation of 10.7% is measured. The mean values for the completeness and the correctness are quite similar with 88.8% and 88.1%, respectively. The maximum values of those two parameters are recorded with 100%. However, this is not surprising as digitisations that are fitting the building footprint or are larger will result in a completeness of 100%, whereas digitisations that are completely inside of the reference geometry (and thus smaller) will deliver a correctness of 100% and completeness values lower than 100%. The mean quality of digitisations is 88.1% for all digitisations with completeness above the median value (95.06%). This indicates that those buildings are digitized very well but presumably slightly larger than the actual building footprint. Likewise, the mean quality of digitisations reaches 89.9% for all digitisations with correctness above the median value (95.10%). Thus, the majority of buildings were captured very well. Here, the quality value of 89.9% indicates that those buildings were digitized slightly smaller than the reference building footprint.

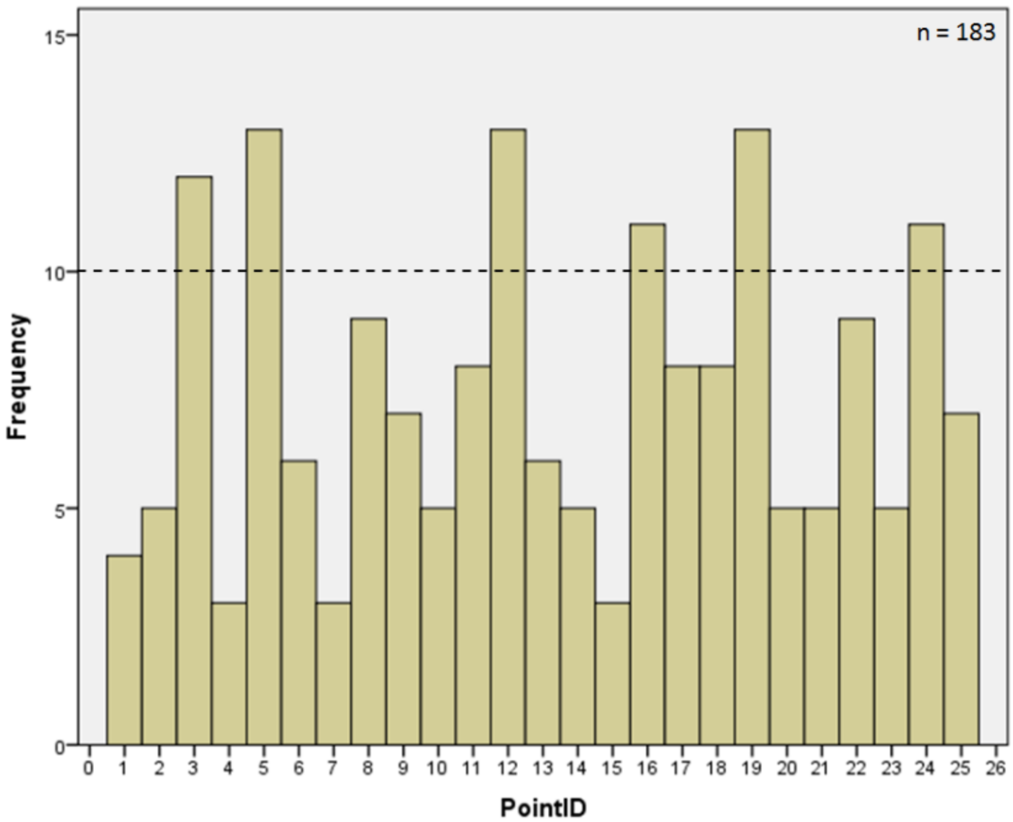


Figure 27. Distribution of map view reloads for each map centre point. (Hillen & Höfle 2015)

Figure 27 shows the distribution of map view reloads during the user study with relation to the respective centre points. It can be seen that some map views (i.e. centred on a certain building) are skipped more often than others. This can be seen as an indicator for problems by the user with the digitisation of certain buildings. Figure 28 is illustrating the map view (left) and corresponding geometries (right: red = reference; blue = user digitisations) of two exemplary building shapes from the user study.

One of the lowest mean qualities for a building (53.6%) is found in the map view with the PointID 12 (Figure 28A). The structure of the main building (darker grey in the middle) is basically rectangular and is thus representing a rather simple building shape. However, it is not obvious which of the parts seen in the image is actually a part of the building itself. One might identify the lighter grey extensions of the building as a garage or similar. Hence, some users skipped those parts in their digitisations while others include them. Most digitisations in this case are focused on the main building (darker grey), which results in a poor digitisation quality because the reference shape for this building (red in Figure 28A) includes the extensions (lighter grey).

The building shape (PointID 6) with one of the highest average qualities (92.7%) is shown in Figure 28B. The building has a simple structure that can easily be distinguished from its surroundings. However, the user digitisations (blue geometries) reveal some drastic visual errors. For example, one can clearly see a spike in upper right and a high distance to the reference polygon for some digitisations in the upper left.

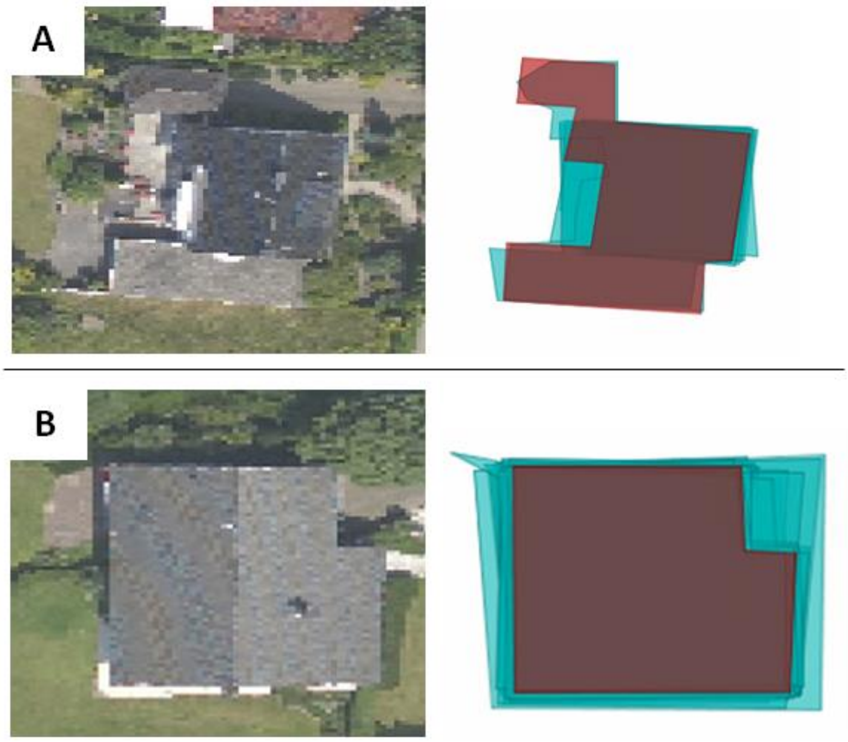


Figure 28. Map view on the left and corresponding geometries on the right (reference: red / user digitisations: blue) of the building with the lowest overall average quality (53.56%) within the map view of PointID 12 (A) and the building with the highest overall average quality (92.73%) within the map view of PointID 6 (B). (Hillen & Höfle 2015)

In the following the potential of the geo-information fusion is analysed based on the quantitative analysis by Klonner et al. (2015) presented in section 4.1.3. For this purpose, it is investigated if an additional value can be derived from fusing the individual user digitisations. The two buildings presented in Figure 28 serve as example for this analysis.

Figure 29 and Figure 30 illustrate the raster-based cumulated geometries (user digitisations) of the two buildings. The value of each raster cell is representing the number of geometries within the respective cell in classes from 0 (green) to "above 10" (red). It can be seen that even a low number of fused digitized user geometries deliver a good estimation for the actual building, especially compared to some individual unsatisfactory digitisations. Figure 29 emphasizes the problem of neighbouring buildings that can or cannot be recognized as a part of the main building by the user. However, the main building itself can be derived from the fused geometries despite the low overall quality (compared to the reference geometry) of the digitisations for this building.

The same applies for the building visualised in Figure 30. As mentioned above, certain user digitisations record a high error regarding the distance to the reference geometry. Those errors can still be seen in Figure 30 with up to seven digitisations outside of the reference geometry. However, the building shape is very well represented by the class "above 10".

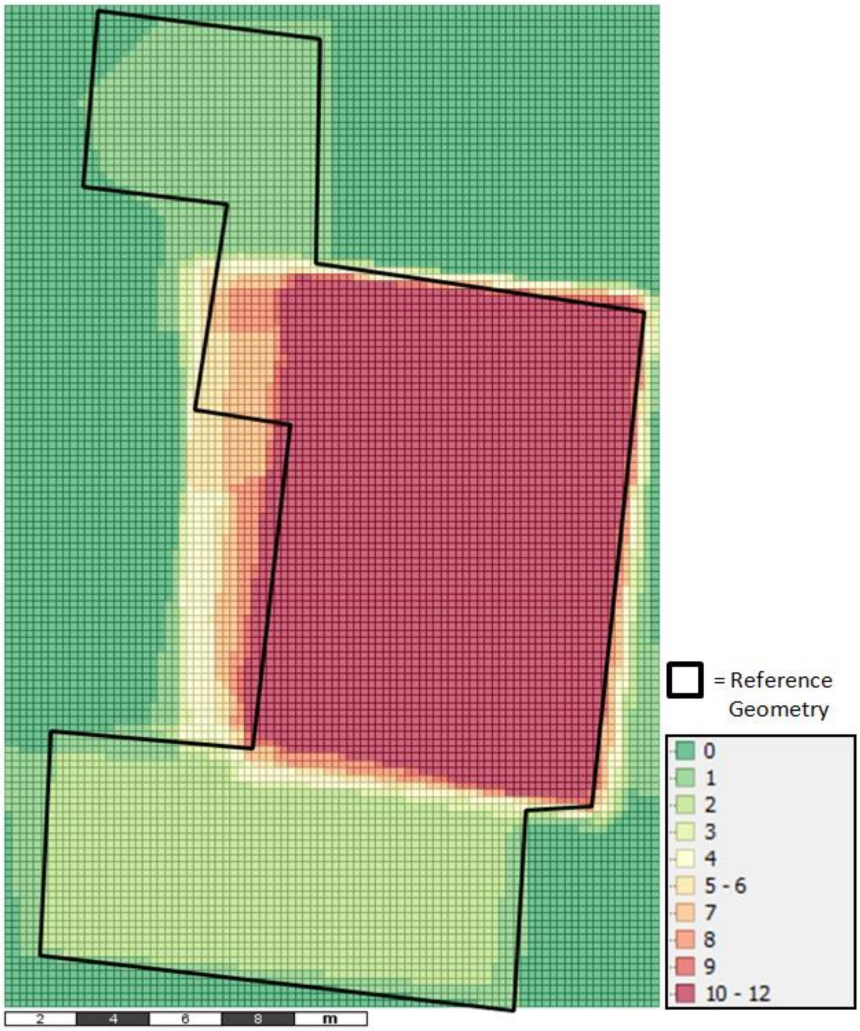


Figure 29. Number of overlapping geometries on an 18.0 m x 27.6 m raster with a cell size of 0.2 m for the building with the lowest overall quality (53.56%). (Hillen & Höfle 2015)

Thus, it can be stated that if all digitisations are fused to one geometry, the quality of the information will be better than the single information provided by the individual digitisation. However, at a certain point, the gain of quality is not significant as the overall quality is already high. Therefore, a threshold for the number of digitized geometries for one building can be defined, at which point the building is approximated accurately. This threshold has to be adapted depending on i) the geometries that are captured from Geo-reCAPTCHA (e.g. point or polygon) and ii) the method that is used to combine the geometries (e.g. centre point of a point collection, intersection of a polygon collection).

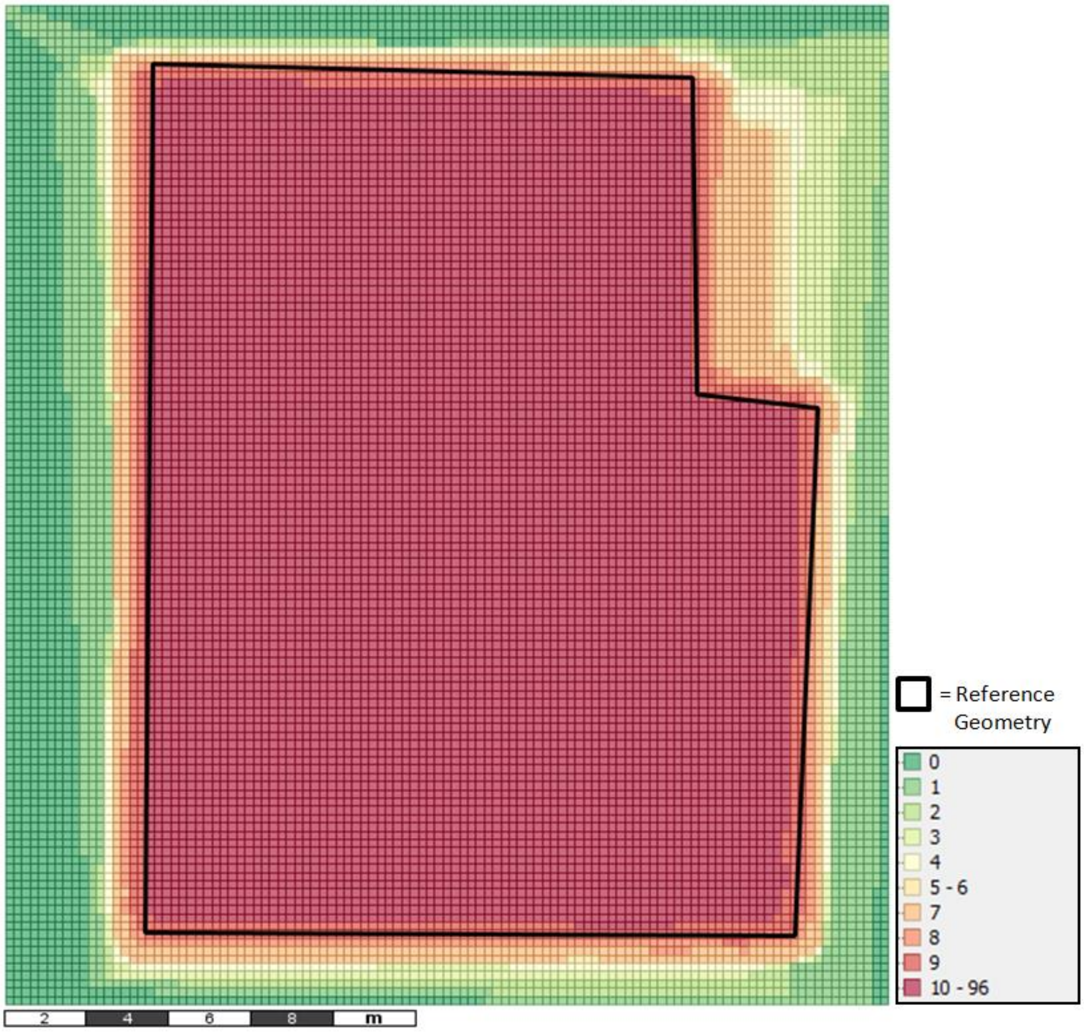


Figure 30. Number of overlapping geometries on a 21.4 m x 24.2 m raster with a cell size of 0.2 m for the building with the highest overall quality (92.73%). (Hillen & Höfle 2015)

5.1.3 Research Objectives

Regarding the research objectives that are posed in section 3.1 one can state that the reCAPTCHA idea is successfully adapted to the geo domain with the concept of Geo-reCAPTCHA. New geographic information can be created in an acceptable amount of time and with a good quality. Thus, Geo-reCAPTCHA is another approach that fits in the gap between the need for complete and updated geographic information and the need for platforms to generate this information. The following main objectives for this use case can now be addressed:

- **To what degree can the concept of Geo-reCAPTCHA be used to generate new geo-information, i.e., how good is the quality of the resulting geo-information?**

  Overall, an average quality of 82.2% with a standard deviation of 10.7% is measured during the course of the user study concerning the digitisation of building geometries. It is found that younger age groups are able to provide a slightly higher quality. The same applies for groups that are supposed to be more familiar with digitisation in general which are the geo-related groups (i.e. students of geography, students of geoinformatics or similar, geoinformatics experts). Furthermore, it can be stated that the digitisation of buildings with a simple shape (i.e. a simple geometry, fewer edges, straight lines, no extensions) records a higher quality (e.g. 92.7%). Thus, one can summarise that the Geo-reCAPTCHA concept can be used to generate geo-information with a good quality for this specific use case. In general, it can be assumed that the concept can be adapted to provide any kind of geo-information in the context of another use case.

- **How realistic is the actual usage of Geo-reCAPTCHA in practice, i.e., how much more effort does it take to solve a Geo-reCAPTCHA than a typical text-based reCAPTCHA?**

  The average time to solve a conventional reCAPTCHA is recorded by von Ahn et al. (2008) with 13.06 s. The user study reveals an overall digitisation time of 9.6 s (standard deviation of 6.9 s) for one digitisation. This means that the total time to solve a Geo-reCAPTCHA can be estimated with 19.2 s as it requires two digitisation (for control and unknown data). Once again, the younger user group is slightly faster. The same applies for students of geography and geoinformatics experts. However, the difference between students of geoinformatics or similar and the other user groups is not as significant compared to the difference in quality. Hence, the results of the user study show that there is a slight difference between user and age groups but this does not affect the usage of Geo-reCAPTCHA significantly. Concluding, one can say that solving a Geo-reCAPTCHA needs more time than solving a conventional reCAPTCHA. Nevertheless, the effort can be considered acceptable as it is less than 50% slower than a traditional reCAPTCHA and that it could be used in practice.

- **To what degree can the fusion of multiple user-generated geo-information increase the quality of a specific feature?**

  The presented raster-based approach showed that the fusion significantly increases the quality of geo-information. However, a universal statement about this is not resilient and reliable. The building in Figure 29 for example is reduced to the main building after the geo-information fusion. The accuracy however might be even lower as it differs from the reference geometry. This means, that conclusions about the quality are certainly dependent on the use case and the corresponding needs. But generally speaking, it can be claimed that geo-information fusion can be used to sharpen the geo-information to the specific requirements and can thus increase the quality of the geo-information for the respective application.

5.2 Use Case #2: Genuine Added Value via Real-Time Geo-Information Fusion? People Movement and Possibilities for Micro-Navigation during Major Events[32]

The in situ sensor data for this study are mainly based on the built-in smartphone sensors. The presented Android app therefore stores the following sensor data into CSV (comma-separated values) files or an online database respectively:

- Date and time
- GPS position as geographic coordinates (lat, lon) as well as the altitude (above sea level) and the estimated GPS accuracy in meters
- Speed of movement in m/s
- Bearing / Orientation in degrees
- Inner orientation (azimuth, pitch and roll) in degrees
- Acceleration (x, y and z) in m/s^2
- For future use: atmospheric pressure in hPa (millibar) and the volume level

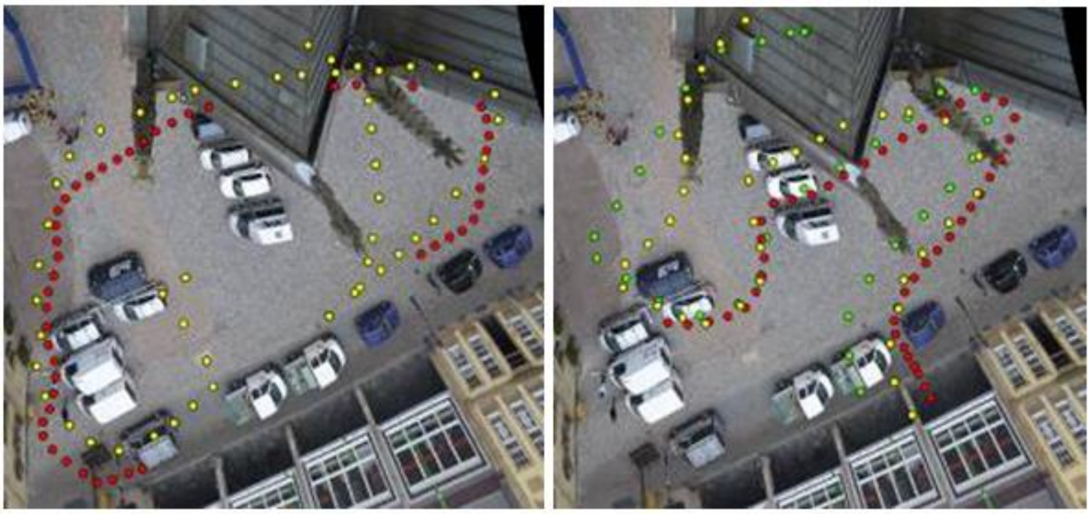


Figure 31. Recorded smartphone positions (yellow) and the actual positions derived from the image series data (red) for test person 1 (left) and test person 2 (right). Additionally, the test recording of test person 2 was enhanced with a Garmin hand-held GPS (green). (Hillen et al. 2014)

Beyond that, the recorded position data are visualized in a GIS to compare different measurements. Figure 31 presents the recorded Smartphone positions (yellow) and the actual positions derived from the image series (red) for test person 1 (left) and test person 2 (right). Despite the different starting points of the recordings one can see that the recorded tracks are roughly similar to each other. However, it is obvious that the

[32] This first part and subsection 5.2.1 have previously been published by Hillen et al. 2014, enhanced with additional paragraphs and intermediate results in subsection 5.2.1. Subsection 5.2.2 is translated from a German conference paper by Hillen & Höfle 2014. The research questions from subsection 5.2.3 are unpublished.

smartphone positions vary in their accuracy. This fact is supported by the positions of the Garmin hand-held GPS of test person 2 (Figure 31: right, green), which are supposed to be more accurate than the positions from the GPS device of the smartphone. However, varying differences to the actual positions (red) can clearly be identified. Hence, the deviation is not only a result of the potential lower quality of the smartphone GPS receiver but is apparently also due to the conditions of the study area itself which is in fact surrounded by higher buildings. These buildings occlude large parts of the sky and thus reduce the number of satellites for precise positioning via GPS. Taking this into account, the results of both the smartphone and the Garmin hand-held are reasonable. However, they are not suitable for a highly accurate single-person tracking.

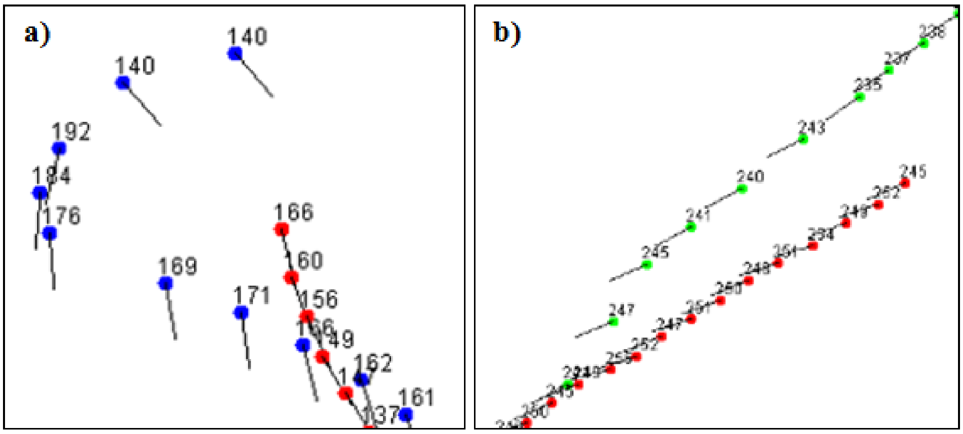


Figure 32. Positions and their respective headings of (a) test person 2 (blue: smartphone; red: extracted manually from images) and (b) test person 3 (green: smartphone; red: extracted manually from images). (Hillen et al. 2014)

Figure 32 presents a subset of the test recordings of test person 2 (a) and test person 3 (b). The smartphone positions are visualized in blue or green respectively whereas the actual positions derived from the image series are coloured red. In addition, the moving directions for each position are displayed with a straight line towards this direction and the number value next to the respective position. For the actual positions (red), the moving directions are calculated as the direct connection between two subsequent points. The moving directions of the smartphone positions (blue and green) are provided by the internal sensors.

In the subset of the test recordings of test person 2 (Figure 32a), one can clearly see that the GPS positions are not very accurate. The poor GPS quality at the beginning might be due to the fact that the test person starts the recording in front of the Marienkirche (high building). However, the headings of the initial seven points are similar to the headings derived from the image data. The mean value of those seven headings differs only one degree from the first heading of the image derived positions. It can be seen that the GPS accuracy does not significantly influence the accuracy of the heading as it is apparently measured with different internal sensor systems. The subset of the test recordings of test person 3, illustrated in Figure 32b, supports this observation. The difference between the headings is recorded with up to a maximum of 10 degrees whereas the absolute geographic positions indicate higher variations. Therefore, it can be assumed that the in situ measured headings are quite sufficient for modelling people dynamics in combination with information derived from image series data.

Regarding the actual integration of real-time smartphone sensor data, the experiment reveals that the data volume of the recorded data is very low. Even with a low mobile internet bandwidth the data can be transmitted to a webserver without creating an overflow or reaching the limit of the data connection.

5.2.1 Modelling Results

In the following, the results of the agent-based modelling to estimate the movement of a single person are presented. The models are implemented with Agent Analyst in ArcMap. Model #1 is mostly based on the smartphone in situ measurements, more specific the movement directions of the respective test person (agent). In contrast, model #2 is based on information from both, remote sensing and smartphone sensor data, which is supposed to create a more realistic estimation.

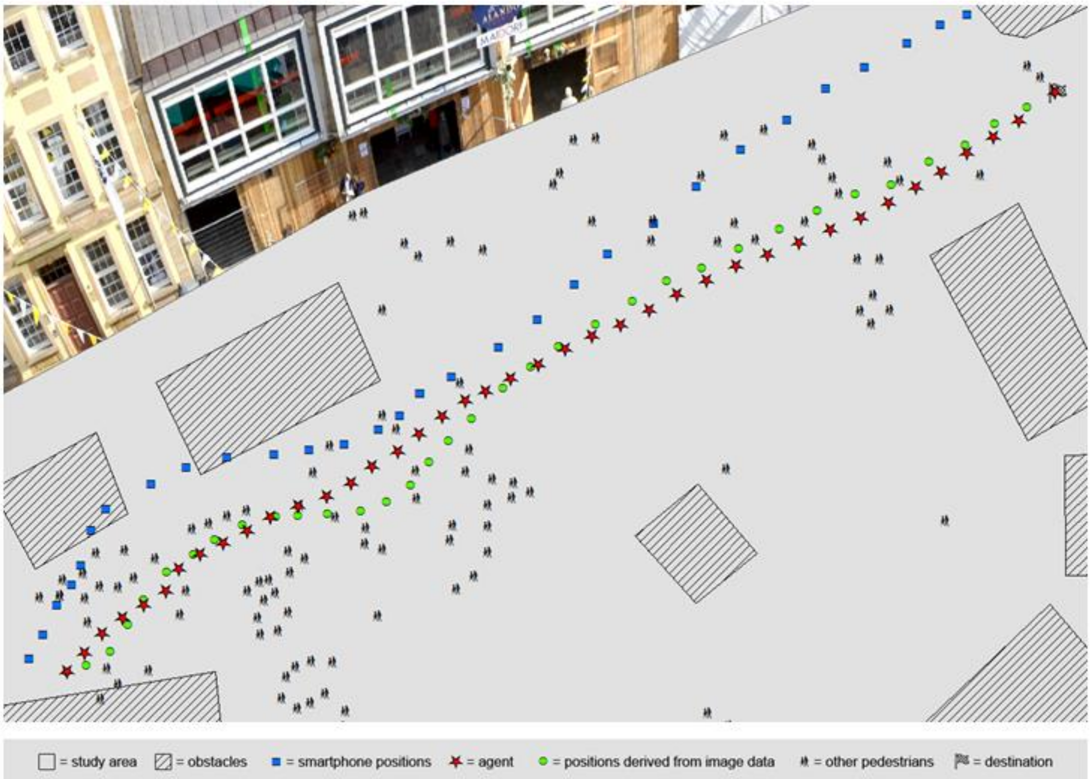


Figure 33. Result of the agent-based model #1.

The estimation of agent-based model #1 is illustrated in Figure 33. The calculated walking path (red stars) obviously differs from the actual walking path (green circles) which is derived from the image series. The agent basically walks straight towards the destination as it is programmed in his behaviour. Only slight variances can be seen which are mostly due to influence of the smartphone movement directions (blue squares). One obvious correction is performed by the agent at the beginning of the modelling. A person stands in the way of the agent and thus the next step is corrected to avoid a collision according to the defined "comfort zone" of the agent. In conclusion, one can state that the general track of the test person (green) is for some parts well represented by the modelling result whereas other parts are not well estimated.

The estimation of agent-based model #2 is illustrated in Figure 34. Compared to model #1, the other pedestrians are modelled as agents as well and their positions can be updated recurrently. For this first test, the positions of the pedestrians are updated every 5 seconds. One can see slight differences in the estimations, e.g. some obvious correction to avoid pedestrians that are not represented in model #1 due to the static pedestrian information. However, the differences are not as significant as expected which questions the actual benefit of additional information and to update this information frequently. The importance of this is investigated in the following subsection.

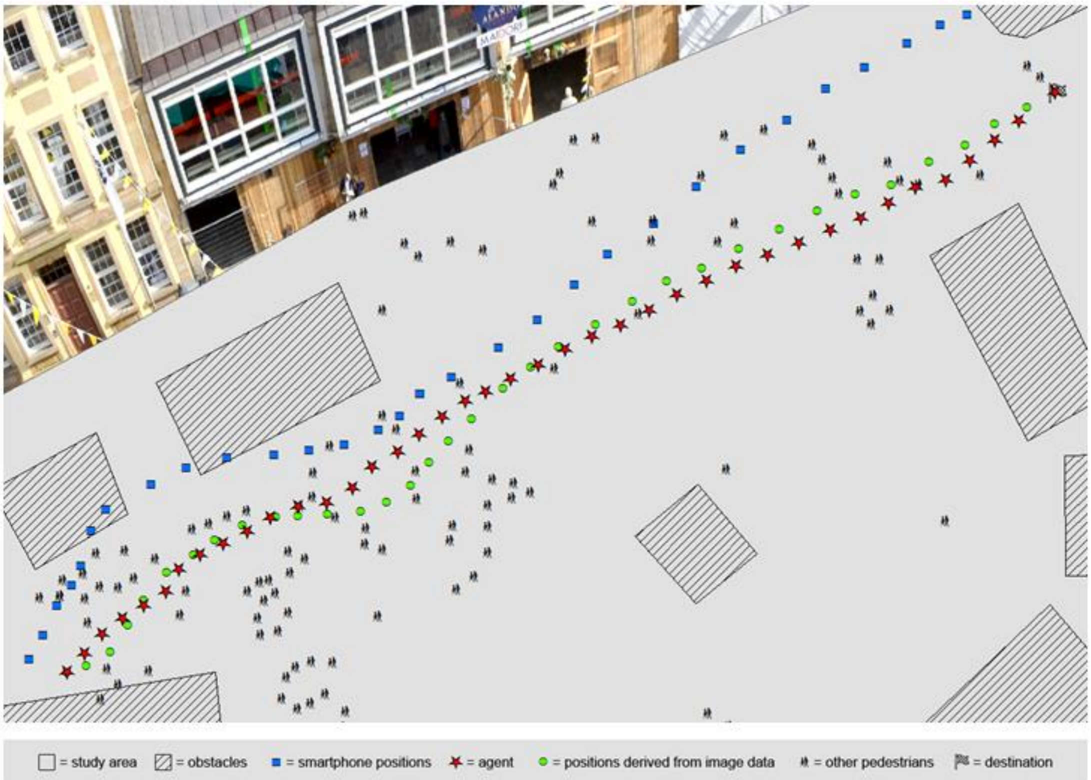


Figure 34. Result of the agent-based model #2. (Hillen et al. 2014)

5.2.2 The Importance of Real-Time Information

Concerning the focus of this work, the capability of real-time information integration has to be studied. Therefore, the adaption of the modelling process to the continuous stream of new pedestrian information is investigated in detail.

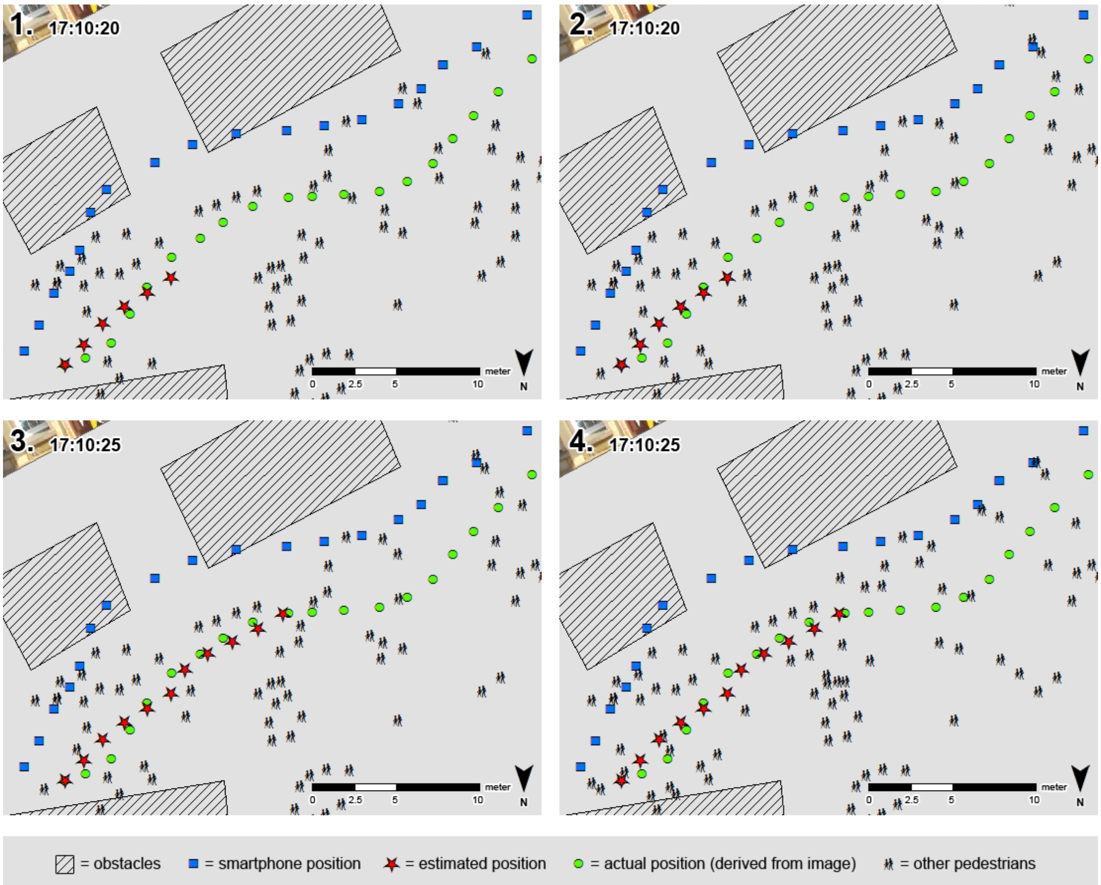


Figure 35. Subsets of the agent-based modelling result at different timestamps before (left: 1. and 3.) and after new pedestrian information is loaded (right: 2. and 4.). (Hillen et al. 2014)

Figure 35 presents four subsets of the modelling result of model #2 at two different points in time (17:10:20 and 17:10:25 CEST). The subsets 1 and 3 represent the modelling state right before the new pedestrian information is loaded whereas the subsets 2 and 4 illustrate the subsequently changed information basis. In the transition from subset 1 to subset 2 one can identify a newly emerged pedestrian right in front of the agent that would be within the "comfort zone" of the agent in the next step. Subset 3 shows the adaption of the agent to avoid a possible collision with the pedestrian at this point by correcting the next step on the moving path. The situation at 17:10:25 CEST in subset 3 would change the walking direction of the agent significantly compared to the actual walking path derived from the image data. The agent is supposed to head towards the obstacles in the top of the image to avoid the group of pedestrians right before him. The question why the test person walked through this group is answered after the reload of new pedestrian information shown in subset 4. The new information reveals that the group dissolved itself in the meantime so that the agent can stay on his path. This situation could not be solved and would have led to wrong estimations without the reload of the new pedestrian information.

The importance of a continuous information stream of new pedestrian positions is illustrated in Figure 36. Subset 1 shows the modelling situation at 17:10:50 CEST before new pedestrian data are loaded. At this point in time, the agent has no chance to reach his destination (chequered flag) without breaking the "comfort zone" constraint. This situation differs from the actual walking path (green circles) of the test person because he headed straight towards the destination. After loading the new pedestrian information (subset 2) no pedestrians are present between the agent and the destination. The modelling can be continued and leads to the result visualized in subset 3.

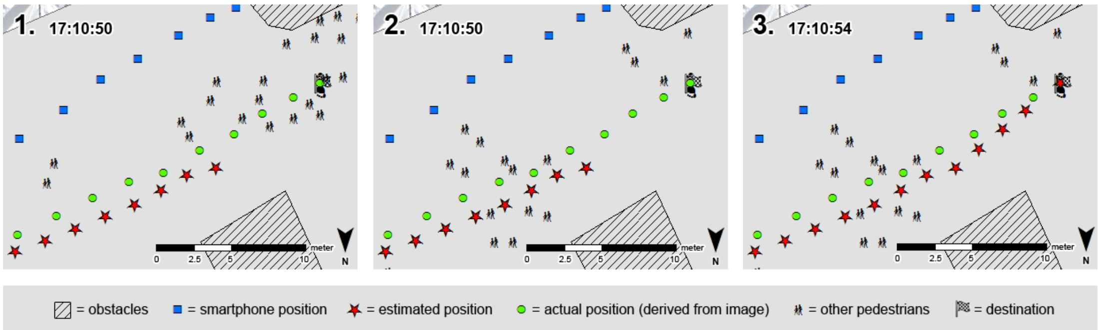


Figure 36. Subsets of the agent-based modelling result at different points in time showing the importance of continuously reloading new pedestrian information. (Hillen et al. 2014)

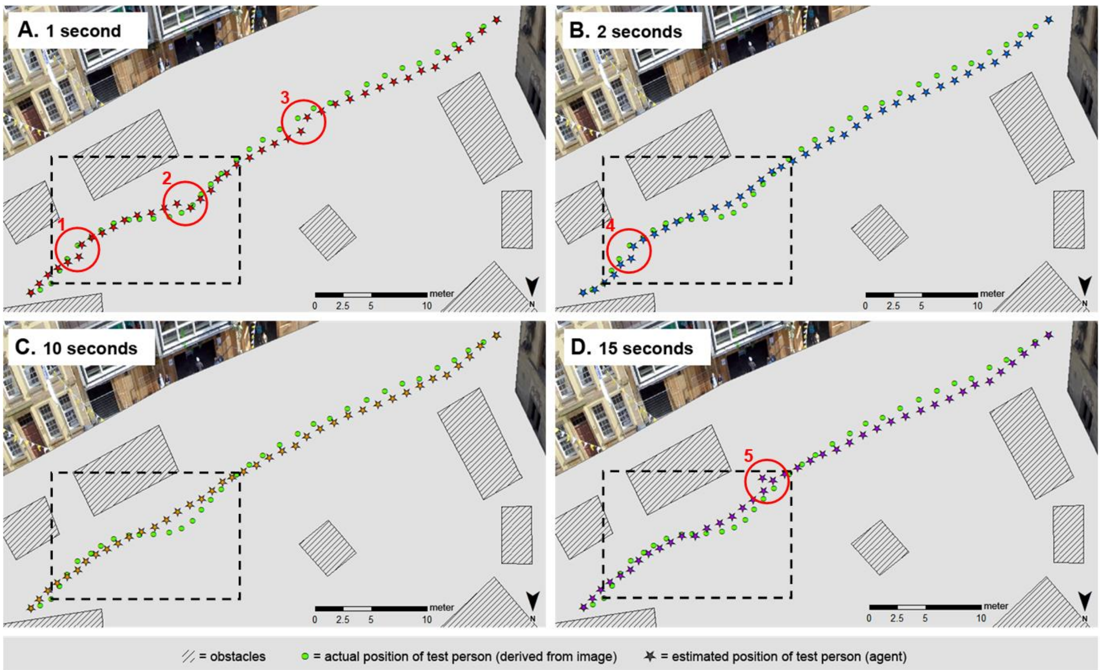


Figure 37. Modelling results with varying updating frequencies of the pedestrian information. A: 1 second, B: 2 seconds, C: 10 seconds, D: 15 seconds. The focus region is illustrated with a dashed rectangle. Hotspots are marked with red circles. (Hillen & Höfle 2014, translated)

Different updating frequencies lead to varying modelling results regarding the fit with the actual walking path of the test person. Figure 37 illustrates the modelling results with the tested frequencies of 1 second (A), 2 seconds (B), 10 seconds (C) and 15 seconds (D). The starting point of the agent is located in the lower left and the goal in the upper right corner of the respective image. The green circles represent the actual position of the test person which are derived from the images. The star symbols with different colours are representing the estimated positions of the test person (respectively the agent) calculated by the model.

The modelling results with an updating frequency of the position of the pedestrians in the scene of 1 second and 2 seconds show a good visual match between the estimated and the actual walking path of the test person. This can be seen in particular in the twisting walking path at the beginning of the modelling (dashed rectangle in Figure 37). In this area the test person has to avoid the most pedestrians. However, a much more homogeneous path can be exhibited for the modelling result with an updating frequency of 2 seconds compared to the path with an updating frequency of 1 second (see hotspots 1, 2 and 3 in Figure 37). These sudden steps can be explained by other pedestrians that cross the way of the test person. Using an updating frequency of 2 seconds, the chances are higher that some pedestrians are skipped. The position of the pedestrian is then updated after the agent moved on and is thus not affecting the walking path. One concurrent jump in the modelling can be seen in hotspots 1 and 4 in Figure 37. Hence, the modelling path with an updating frequency of 2 seconds seems to be smoother. However, the statistics reveal that the result of model A (1 second) is slightly better than the result of model B (2 seconds). Regarding the distance between estimated and actual walking path, model A records an arithmetic mean of 0.49 m (standard deviation 0.24 m) whereas the path of model B has a mean difference of 0.52 m (standard deviation 0.26 m).

In contrast to that, the modelling results with an updating frequency of 10 and 15 seconds are not matching the actual walking path well. A conspicuous straight walking path can be investigated in the focus region at the beginning of the modelling (dashed rectangle in Figure 37). This is assumed to be caused by the low dynamic of the other pedestrians due to the low updating frequency.

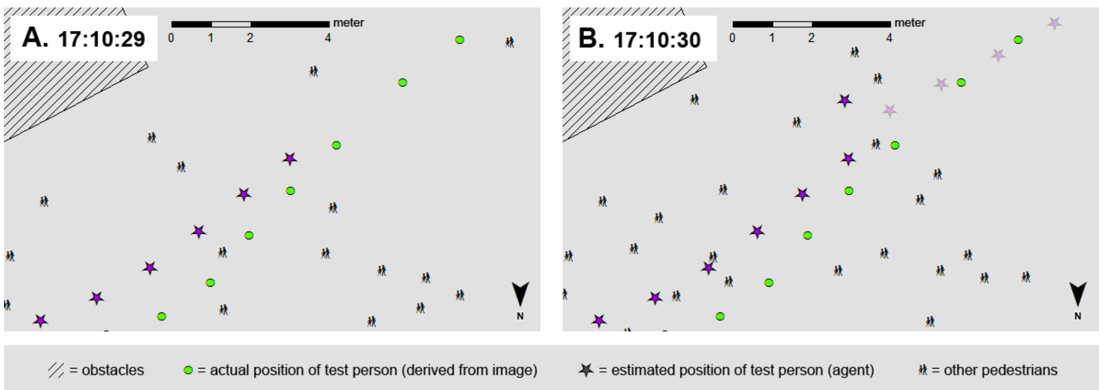


Figure 38. Extract of modelling results with an updating frequency of 15 seconds for the points of time 17:10:29 (A) and 17:10:30 (B) displaying the changes for the pedestrian positions after loading new information. The upcoming modelling results in B are illustrated with a lower opacity. (Hillen & Höfle 2014, translated)

The modelling results indicate that lower updating frequencies in this case are more prone to errors based on (i) obstacles that are not recognized at all and (ii) obstacles that appear suddenly. The latter aspect can be clearly seen in the modelling results in the hotspot 5 of model D (Figure 37). Figure 38 is focussing on this part of the modelling result with an updating frequency of 15 seconds at the time 17:10:29 (A), right before updating the pedestrian information, and 17:10:30 (B), after the update of pedestrian information.

One can easily identify a drastic change for the position of the other pedestrians between the two subfigures because of the low updating frequency of 15 seconds. With this new information, a pedestrian suddenly appears right in front of the agent. This was not foreseeable by the model and thus the agent has to react and change the current walking direction to avoid a collision. However, this correction is not reasonable with respect to the actual walking path of the test person. Similar corrections can be found within the results of model A and B (Figure 37) with updating frequencies of 1 seconds and 2 seconds respectively (see hotspots 1, 2, 3 and 4). These cases however are caused by the high updating frequency of the information and are positive corrections. Meaning that the estimated walking path is reasonably corrected towards the actual walking path of the test person instead of increasing the difference.

5.2.3 Research Objectives

The potential for information from real-time remote sensing data as provided by the VABENE project can be seen as very high as it was no option for time-critical geo-applications so far. This use case demonstrates another time-critical application for geo-information fusion. Above that, it has been shown that the real-time integration of geo-information provides valuable information and in this case modelling results that cannot be derived from a single sensor (model #1). The following main objectives for this use case can now be addressed:

- **How can geo-information fusion be applied within a time-critical modelling application and how do the results differ from modelling approaches with only one source of geo-information?**

  Geo-information fusion was applied as a part of model #2 that combines in situ smartphone measurements of the movement direction with remotely sensed information about the position of other pedestrians to estimate a single person movement through a crowd. The integration of geo-information fusion in model #2 has not shown an increase concerning the calculation time of the estimation compared to model #1. However, the results of model #1 and model #2 are not significantly different in the first place. Even so, it has been shown in this investigation that model #2 can increase the quality of the estimations if real-time information about the other pedestrians are integrated. This means that the added information in model #2 (two information sources instead of only one) increases the precision of the estimation.

- **What effect can be seen by fusing real-time geo-information, i.e., to what degree does the integration of real-time geo-information increase the quality of the modelling result?**

The integration of real-time geo-information increases the quality significantly. Different update frequency for the integration of information has been tested. The modelling results with lower frequencies (10 and 15 seconds) are more smoothed and are not representing the actual walking path of the test person. The higher frequencies (1 and 2 seconds) however show more sudden steps in the modelling results. Those steps are corrections due to the new information and are generally increasing the quality of the estimation instead of decreasing it. Thus, one can state that the more up-to-date the information available for the model is, the more realistic is the estimation resulting from the model.

5.3 Use Case #3: Multiple Sensors for the Same Information. Least-Cost Navigation on People Density Data[33]

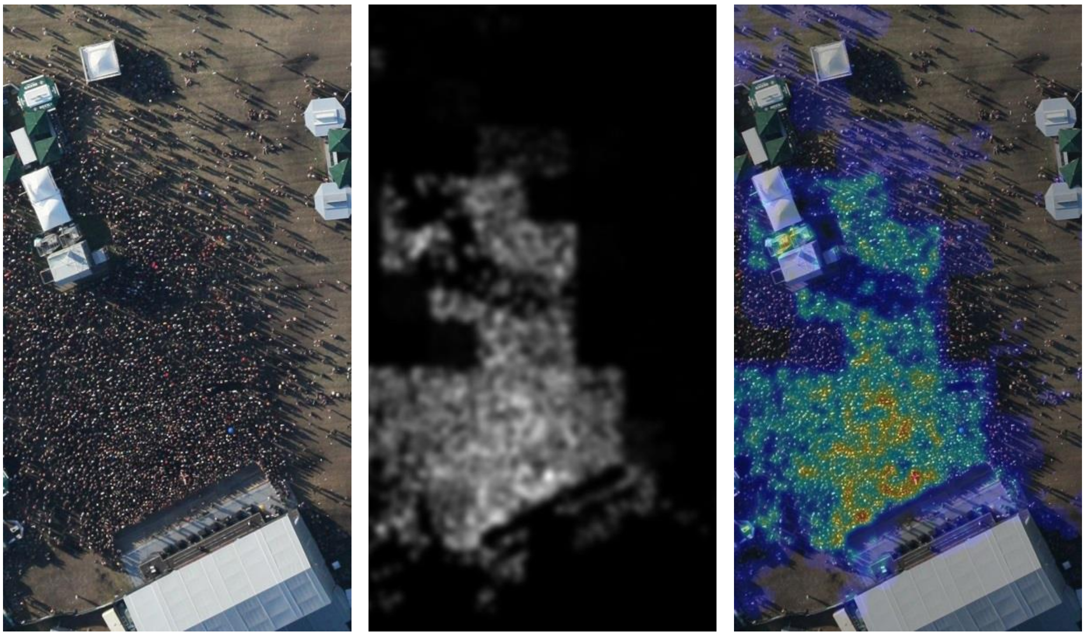
A prototype implementation based on non real-time data is conducted as a generic proof of concept for the integration of the two data sources: remote sensing and smartphone data. The test data for the implementation are recorded during the music festival Wacken in 2013 (Figure 39). One can clearly see crowds standing in front of the stages. The focus region for this use case is the area in front of the two main stages of the festival (red rectangle in Figure 39). The crowd density is estimated from the remote sensing data and is supplemented by estimation based on movement information from smartphones. Finally, the calculation of a least-cost path is performed on the combined information using GRASS GIS.

Figure 39. Recording area during the music festival Wacken in 2013. The stages are at the bottom, the focus area is marked with the red rectangle.

[33] This first subsection has previously been published by Hillen et al. 2015. Subsection 5.3.2 has been significantly extended by implementation details and unpublished intermediate results. The research questions from subsection 5.3.3 are unpublished.

5.3.1 Crowd Density Estimation in Aerial Images - Implementation Details

The density estimation step requires panchromatic aerial images with a spatial resolution of ca. 9 to 20 cm. As the fusion with location data requires georeferenced and orthorectified images, a real-time orthorectification module processes every aerial image before the crowd density estimation is initiated. For this time-critical use case a fast GPU-supported orthorectification and georeferencing implementation (Kurz et al. 2012) is used, which processes a typical 18-megapixel image in under 200 ms. It uses an interior parameter set determined prior to a flight campaign by a self-calibrating bundle adjustment. The system is equipped with an IGI AEROcontrol GPS/IMU unit[34], which records the external orientation parameters for every image with a sufficient angular accuracy. In this way, no ground control points are needed, which is of high importance for this time-critical use case. Moreover, the projection step uses a digital elevation model of the Shuttle Radar Topographic Mission (SRTM[35]) to derive 3D world coordinates from the image coordinates. It has a resolution of 25 m and a 16-bit quantization.



(**a**) (**b**) (**c**)

Figure 40. Image (a) shows a subset of an unprocessed aerial image from a music festival with a dense crowd standing in front of a stage. Image (b) is the computed crowd density layer as a gray value image (black = low density, white = high density). For illustration purposes we created a composite image (**c**), where the density is laid onto the original image (blue = low density, red = high density). (Hillen et al. 2015)

The actual crowd density estimation, consisting of the four steps described in the methodology, takes the orthorectified image as an input (Figure 40a), computes filter

[34] http://www.igi.eu/aerocontrol.html
[35] http://srtm.usgs.gov/

responses of patches at promising locations, and classifies the filter responses into the two classes "crowd" and "no-crowd". Based on supervised learning, the classification step with a support vector machine needs initial training. For this purpose, the SVM is trained with roughly 10,000 image patches, each has a size of 64 by 64 pixels. For the training, one patch is convolved with 24 Gabor filters consisting of S = 4 scales and K = 6 orientations (see methodology for details). Each filter has a width of 48 pixels. The resulting 24 mean values and 24 variances of each filter response are then used as the final 48-dimensional feature vector, representing one image patch and being the input for the training of the support vector machine. The computationally intense training can certainly be done offline.

During the event, under real-time conditions, the filtering is performed in parallel on several patches using C++ with OpenMP[36]. The efficient libSVM library[37] is then able to produce the results almost immediately. Finally, the succeeding Gaussian filtering produces a greyscale 8-bit image of the same size as the original input image, where an intensity value of zero (black) corresponds to a very low crowd density and a value of 255 (white) corresponds to the highest measured crowd density (Figure 40b). Figure 40c illustrates the calculated density information from low (blue) to high (red) with the orthorectified image in the background. This image provides the basis for the least-cost path calculation in GRASS GIS.

5.3.2 Calculating the Least-Cost Path using GRASS GIS

The previously calculated crowd density layer and the smartphone information are imported into GRASS GIS to perform the least-cost path calculation. Figure 41 is illustrating the experimental setup in GRASS GIS with the crowd density layer and two defined points (left image).

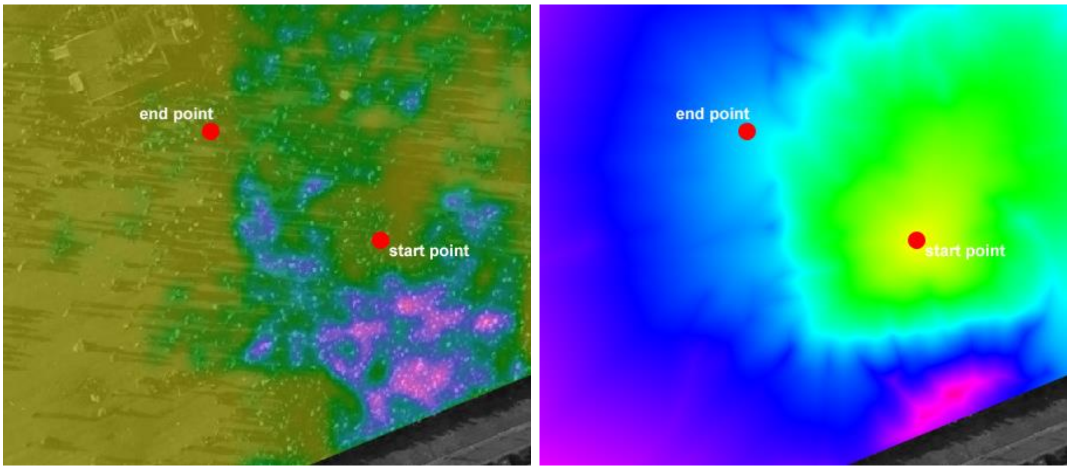


Figure 41. Start point of the least-cost path in the crowd and end point outside of the crowd. Left image: people density layer (yellow = low density, purple = high density). Right image: cost layer calculated based on start point.

[36] http://openmp.org/wp/

[37] https://www.csie.ntu.edu.tw/~cjlin/libsvm/

For this use case, the starting point (i.e. the current location of a fictive user) is located in front of the stages at the edge of a highly crowded area. In a first step, a cumulative cost layer is created based on the current location of the user using the GRASS GIS function r.cost (Figure 41, right). The cumulative costs can then be used to navigate to a defined point or to navigate towards a less dense area out of the crowd depending on the application. For the latter case, a point within a less dense area has to be identified using, for example, a nearest point functionality. In this case, an end point is pre-defined outside the crowded area. Knowing the start and end point, the least-cost path can be calculated using the GRASS GIS function r.drain.

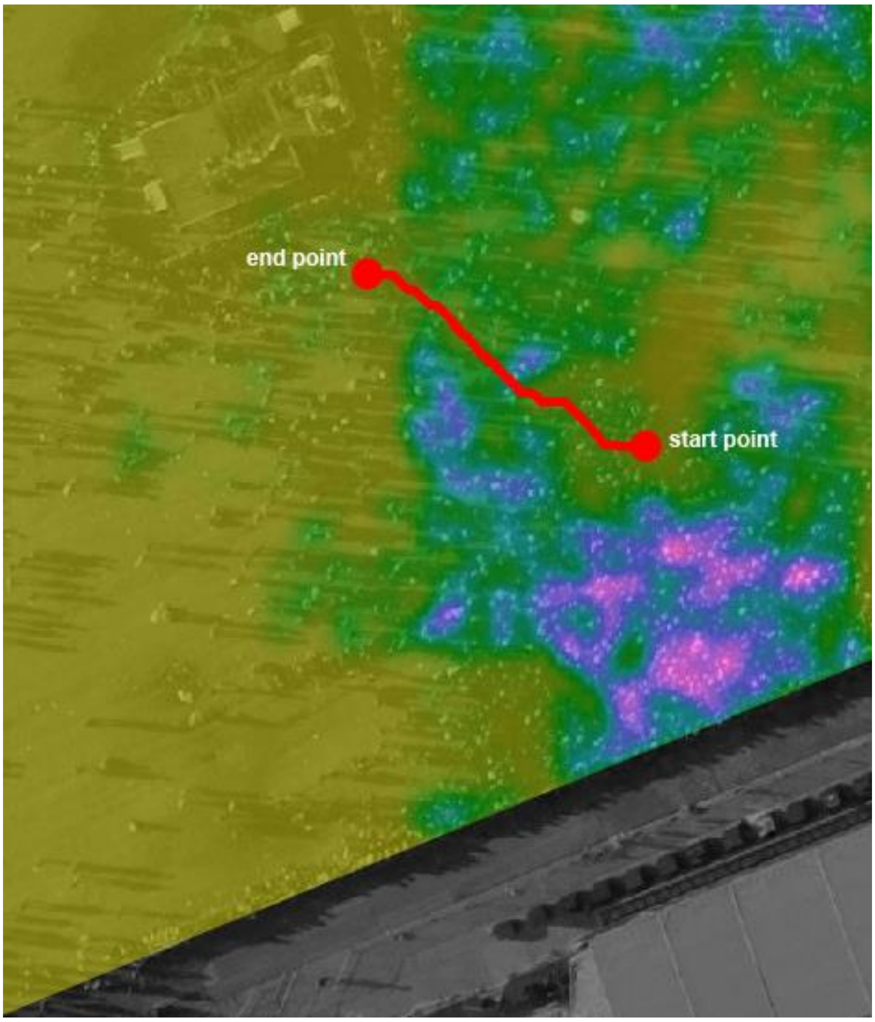


Figure 42. Resulting least-cost path (red line) from a start to an end point based on the cost layer derived from the aerial image. (Hillen et al. 2015)

Figure 42 is illustrating the result of the least-cost path calculation based on the crowd density layer derived from the aerial image. The background consists of a transparent representation of this crowd density layer (low density (yellow) to high density (purple)) over the corresponding aerial image. One main stage of the music festival is located in the lower right of the image. Start point and end point are visualised with red points. The red line is the path from start to end point with the lowest cost (compare with right image in

Figure 41) according to the people density. One can see that the path is basically following the yellow area between the people.

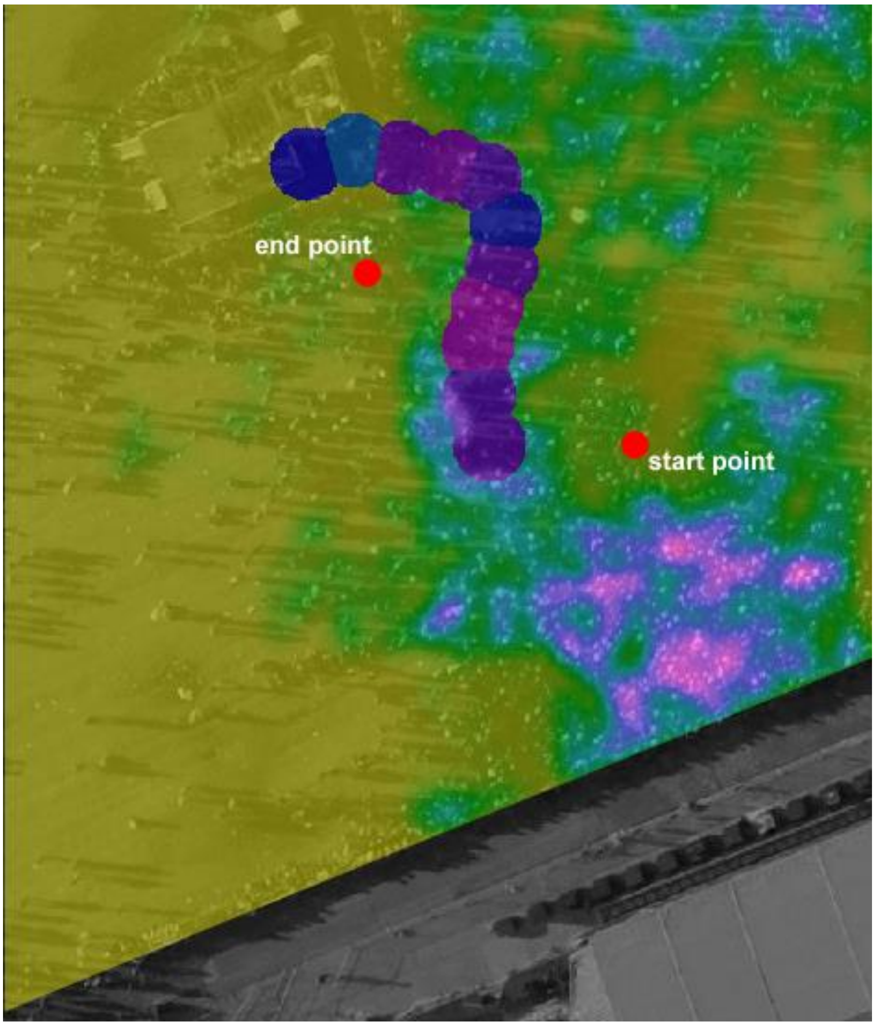


Figure 43. Crowd densities derived from smartphone data fused with the density layer derived from aerial images.

Yet, the calculation is based on the crowd density information derived from the aerial images only. However, the effect of integrating the crowd density derived from the smartphone movement data should be investigated. Hence, the densities derived from the smartphone data are fused with the density layer derived from the aerial images (Figure 43).

As the aerial information might be obsolete (because the overflight was some time ago), the smartphone data indicate a high crowd density where the original least-cost path is located (compare with Figure 42). The structure of the smartphone density as seen in Figure 43 significantly differs from the density information derived from the aerial image. This is due to the methodology with which the density information is calculated from the smartphone data. The density is calculated based on the recorded movement speed for each geographic location measured by the smartphone. Afterwards, this density value is expanded to the local neighbourhood of the smartphone user which results in the circular shape of the density information. The value range is the same for both information sets, however, the density information from the smartphone seems to be more bulky and prominent.

Subsequently, an updated least-cost path can be calculated on a new cost layer (r.cost) based on the fused density information. Figure 44 shows the result with the updated least-cost path. It can be seen that the route for the user has changed significantly compared to the result shown in Figure 42 because of the added density information derived from smartphone movement data. Instead of moving away from the dense crowd, which is the typical behaviour (e.g. in a stress situations), the new calculation suggests that the user move sideways straight through a medium-dense crowd to reach a free space much better.

Summarising one can state that the fusion of geo-information is capable of providing a more accurate and up-to-date information base for existing geospatial functionality. This is of particular importance for time-critical applications or applications that have to rely on real-time information like presented in this use case implementation.

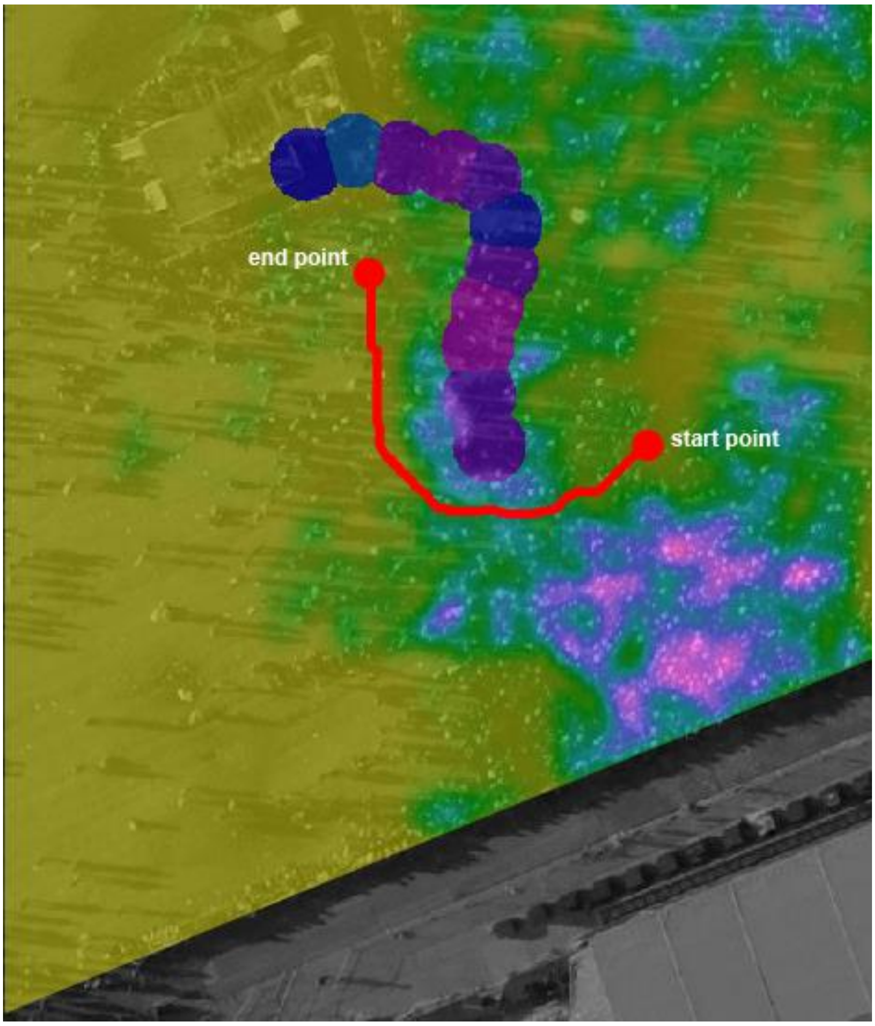


Figure 44. Resulting least-cost path (red line) based on the cost layer derived from the aerial image and the additional cost information (circles) derived from smartphone sensor information. (Hillen et al. 2015)

5.3.3 Research Gap and Resulting Objectives

As stated for use case #2, the potential for real-time remote sensing data (e.g. by using the VABENE system) in combination with other data sources is tremendous. Geo-information fusion offers the possibility to exploit the potential even further by integrating other valuable information sources (in this case smartphone movement speed). This use case has shown that geo-information fusion is not only useful as part of a geo-related algorithm or application, but it can significantly increase the reliability and credibility of information used for traditional geospatial algorithms especially for time-critical applications. The following main objective for this use case can now be addressed:

- **To what degree does fused real-time geo-information increase the quality of the results of geospatial algorithms?**

  The quality of a geospatial algorithm (e.g. least-cost navigation in this case) remains the same as the logic itself is not affected by geo-information fusion. However, geo-information fusion increases the quality of the input information for geospatial algorithms which results in a higher quality regarding reliability and credibility for the specific application. This is of particular importance for time-critical applications where up-to-date and precise information are crucial. This means that aerial images recorded for example four minutes ago might be too old for a specific application like the application described in this use case. Least-cost navigations based on this "old" information are not reliable at all. With geo-information fusion, the old aerial information can be updated selectively with newer information from other sources like smartphones in this case. This can be repeated until new extensive information is provided via aerial images. Thus, for time-critical applications the results of a geospatial algorithm are in general better, i.e. in this case more up-to-date, using fused input information instead of outdated information. But also for non time-critical applications, geo-information fusion can increase the informational content of the input by combining multiple data sources.

5.4 SDI Integration: Seamless Integration in existing Structures? The Geo-Information Fusion Infrastructure

In this section, details of the prototype implementation of the information fusion service are provided with emphasis on the IFS Controller that cannot be implemented according to any existing OGC standard. However, for the actual infrastructure prototype itself, several OGC Web services need to be available. Therefore, the GeoServer and the PyWPS are installed on a webserver. The GeoServer provides data via WMS or WFS standards whereas the PyWPS performs spatial processing for the information extraction.

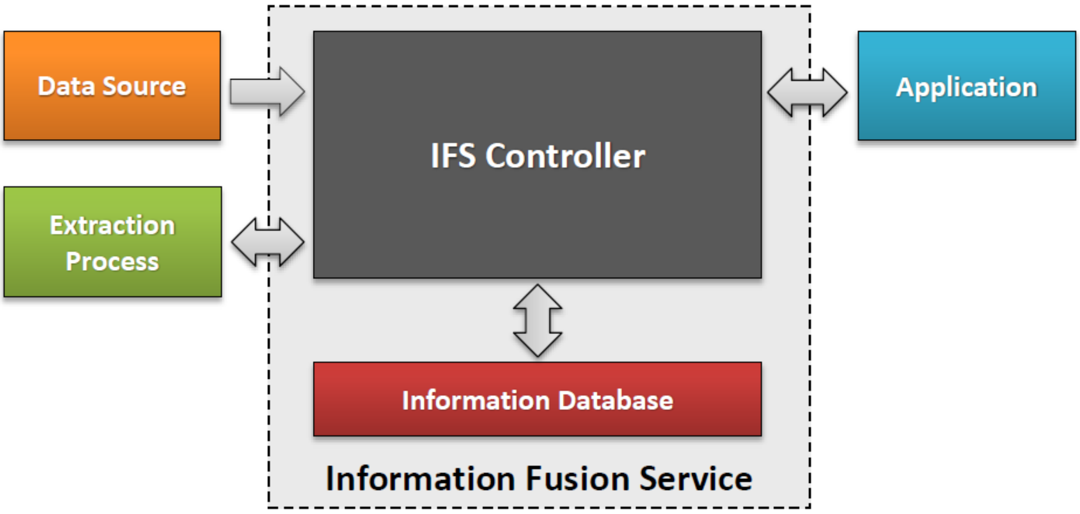


Figure 45. IFS controller and related components as part of the web-based geo-information fusion infrastructure.

Figure 45 is illustrating the tasks of the IFS Controller. It has to handle the data sources (orange) that are registered with the corresponding information extraction processes (green). These processes are triggered in a given frequency and the received information is stored in the information database (red). This database can be queried by any kind of application (blue) via simple interfaces of the IFS Controller.

The programming language Python is used for implementing the IFS Controller. This decision is made because of the high performance regarding Web applications as well as the easy expandability with spatial libraries. The basic interaction possibilities with the IFS Controller are illustrated in Figure 46. The user of the IFS can add new entries to the IFS Controller, consisting of information about the data source as well as the resource and frequency of the processing. After the user initialises the start of the IFS, new data is retrieved and processed in the given frequency for each entry. In this case, the resulting information is stored within the IFS Controller itself and can be retrieved by any application. However, it is certainly possible to store the information in a spatial database management system like PostgreSQL[38]/PostGIS[39] or SQLite[40]/SpatiaLite[41].

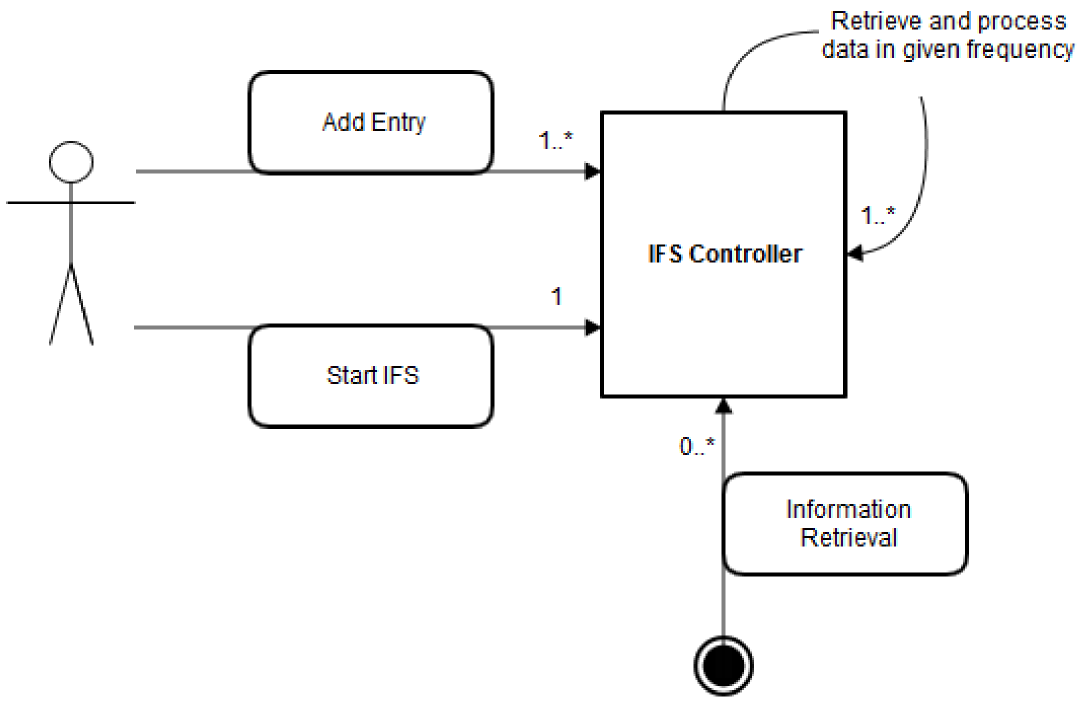


Figure 46. Activity diagram showing the basic workflow of interaction possibilities with the IFS Controller.

Figure 47 shows implementation details of the IFS Controller and the corresponding Entry data structure in form of a UML class diagram. The Entry class consists of the attributes *description*, *dataSourceHost*, *dataSourcePath*, *processHost*, *processPath*, *processExecute* and *frequency*. The respective host and path attributes store the corresponding parts of the URL for the data source (e.g. WMS or WFS) and the processing resource (e.g. WPS). The *processExecute* attribute defines the process identifier or rather the name of the WPS process that extracts the information from the corresponding data. The interval between upcoming processing runs is defined in the *frequency* attribute. Moreover, the Entry class has get and set methods for each attribute.

The IFS Controller class has two main attributes: *entries* and *information*. The *entries* attribute stores a list or an array of Entry objects and represents all data sources that will be processed during the information fusion. This attribute can be accessed with the *getAllEntries*, *getEntry*, *addEntry* and *deleteEntry* methods. The resulting information of the respective processing of the entries are integrated in the information database. In this prototype implementation, this database is kept lightweight as an integrative part of the IFS Controller in the form of a single semicolon-separated text string. This string is stored

[38] http://www.postgresql.org/
[39] http://postgis.net/
[40] https://www.sqlite.org/
[41] https://www.gaia-gis.it/fossil/libspatialite/index

in the attribute *information* and can be accessed with the public method *getInformation*, which consequently builds the interface to the applications.

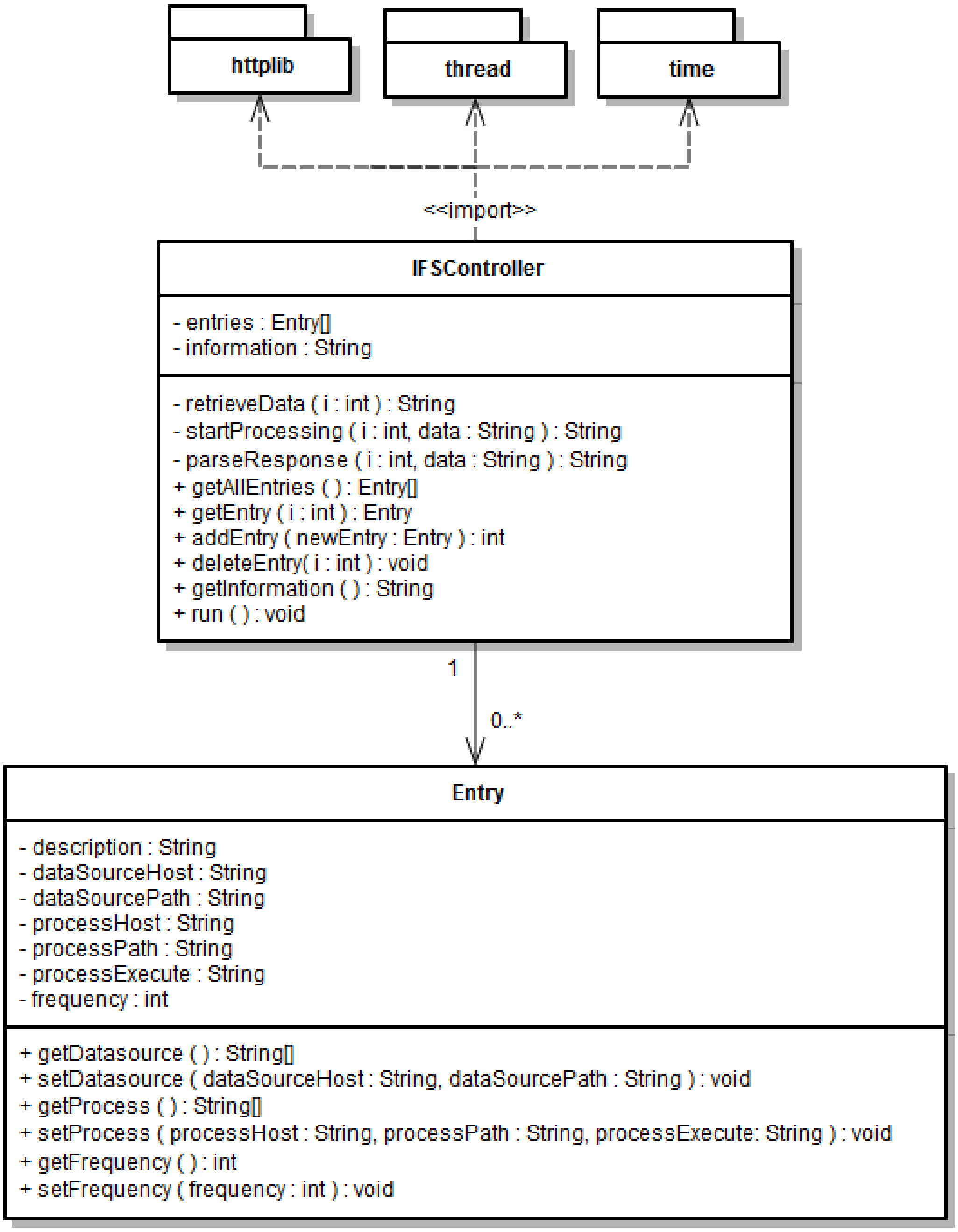


Figure 47. UML class diagram describing the IFSController class and the corresponding Entry data structure.

The *run* method initialises the controller and starts the data retrieval and processing of the stored entries. For this purpose, the private methods *retrieveData* and *startProcessing* are used. Each second the *run* method checks whether an entry has to be processed depending on the corresponding *frequency* attribute. If that is the case, a new thread is started to retrieve new data from the data source (*retrieveData*) and to start the WPS process (*startProcessing*) afterwards. The Python library httplib[42] is used to perform HTTP requests via HTTP-GET for the data sources and HTTP-POST for the WPS. Afterwards, the response of the information extraction process is parsed to gather the information and store it to the *information* attribute. It is important to outsource the three latter steps of data retrieval, processing and parsing into a joint thread to avoid accumulation of processing steps. This might be caused by connectivity problems as well as performance issues during the processing. The accumulation of waiting processes would lead to a domino effect that might result in i) skipping some processing interval in the best case or ii) in an overflow error that will crash the IFS Controller in the worst case. Thus, it is important to allow the processing sequence to run parallel using threads.

The IFSController runs until it is shut down manually. In this stage of development the prototype might run into a memory error at some point as no limitations are set for the *information* attribute. In the future it would be useful to integrate an expiration date for i) the stored information or b) the runtime of the controller. Alternatively, a maximum runtime parameter could help to avoid such errors as well. Moreover, the integration of an actual database system would reduce the potential for errors.

[42] https://docs.python.org/2/library/httplib.html

6 Conclusions

This thesis addressed the lack of research regarding the fusion of geo-information by presenting three time-critical use cases from different facets of geo-information science, namely capturing, modelling and analysis. During the process of conception, implementation and evaluation of the use cases, challenges and benefits of fusing (real-time) geo-information are revealed. The results and scientific findings of the use cases are concluded in the following.

Use Case #1: Geo-reCAPTCHA[43]

In this use case, a concept for adapting the reCAPTCHA idea to gather user-generated geographic information from earth observation data is presented. Therefore, the reCAPTCHA concept was extended to provide geographic information instead of text to the user. Digitisation tools allow for capturing new geometries or semantic information about a geographical feature.

The performed Geo-reCAPTCHA empirical user study on building geometry mapping revealed a digitisation time per building object of 9.6 s (average over 2257 geometries) which results in an average total solving time for a Geo-reCAPTCHA of 19.2 s. Furthermore, an average quality of single digitized building polygons of 82.2% was achieved. A detailed analysis shows that the differentiation between the main building and additional buildings is one of the main reasons for poor digitisations. However, the fusion of all single building digitisations allows for an appropriate estimation of the actual building despite the poor quality of some digitisations. This underlines the real benefit of geo-information fusion for this use case as it is able to generate new and valuable geo-information from a heterogeneous set of unreliable geo-information.

In conclusion, the technical requirements, which are extracted from an extensive review of the related works (see Table 2), are addressed in the Geo-reCAPTCHA system design. Thus, Geo-reCAPTCHA offers an appropriate alternative to reCAPTCHA regarding CAPTCHA security as well as the resulting data quality. In the future, this might lead to the integration of Geo-reCAPTCHA in many websites and thus the creation of lots of valuable and reliable geo-information that can also be used for time-critical geo-applications. It has been shown with this use case that geo-information fusion has high potential, especially for heterogeneous user-generated geo-information that is often unreliable individually. Geo-information fusion can have a high impact on user-generated

[43] Most parts of this conclusion have previously been published by Hillen & Höfle 2015.

geo-information in general as it is able to increase the information quality as it has been proven with this use case.

Use Case #2: Agent-based Modelling

For this use case, an agent-based model is developed and implemented that is able to predict the movement of a single person within a crowd based on information derived from aerial images and smartphone sensor data. An offline experiment to gather real information has been conducted with a test person in the inner city of Osnabrueck. Even though the GPS accuracy of the smartphone in the urban study area turned out to be low, the measured moving directions are found to be sufficient for modelling single-person movement.

Two agent-based models have been designed and implemented. The first to evaluate the feasibility of modelling the movement of the test person in general based on information from smartphone sensor data only. The second model expands its model assumptions and integrates information from the aerial images to detect the other pedestrians with the study area and to react to their respective positions. The information from the two data sources are fused within the model itself.

The results of both models are compared with the actual movement path of the test person that has been derived from the aerial images as an evaluation data source. The evaluation reveals that model #2 is predicting the walking path of the test person better than model #1. This means that the fusion of geo-information from the two sources has increased the quality of the modelling results.

In a second evaluation, the influence of real-time information on the modelling results has been investigated. For this purpose, different integration frequencies (1, 2, 10 and 15 seconds) have been implemented for model #2. The results are compared among each other on the one hand and with the actual movement path of the test person on the other hand. It can be seen that lower integration frequencies lead to a smoothing of the model prediction, which might be interpreted as a better result. However, the analysis has revealed that the low frequency is also causing random errors because of sudden appearance of other pedestrians as well as the skipping of some path corrections because of outdated information. However, the results for the higher frequencies have shown a more disturbed path. This is mainly due to the high actuality of the information and the need to react to the new setting. Above that, it can be summarised that up-to-date or real-time information is useful and might provide better results for time-critical applications.

In conclusion, the use case has shown that it is possible to model a single person's movement through a crowd in general using agent-based modelling. Geo-information fusion can increase the quality of the model predictions by fusing multiple information right within the model. Furthermore, geo-information fusion opens up new vistas and possibilities for future applications regarding the ubiquity of real-time remote sensing for example. Time critical approaches relying on real-time remote sensing had not been addressed in the past due to the missing technology. Nowadays, projects like VABENE allow such applications to become reality and significantly increase the need for and the role of geo-information fusion.

Use Case #3: Least-Cost Navigation[44]

In this use case, a least-cost navigation based on the fusion of information from real-time aerial image data and smartphone sensor data is proposed. The image data are used to estimate an extensive crowd density map. For this purpose, a patch-based approach with a Gabor filter bank for texture classification in combination with an interest point detector and a smoothing function is applied. The GPS location information and the current movement speed of a user are gathered with a smartphone app. The real-time in situ crowd density is estimated based on this smartphone information and allows for enhancement of the overall density information. Finally, a least-cost routing is performed based on the fused crowd density information using GRASS GIS.

Two time-critical applications for the integration of the least-cost navigation approach are introduced as the fundament of this use case. The emergency application can support people that quickly want to escape from a dense crowd (e.g. during a music festival). Above that, the routing approach in general can help in various situations, for example after a football game where certain routes are blocked by the police. To date, these applications are difficult to realise as it is too expensive to record comprehensive aerial images. However, considering the ongoing rise of unmanned aerial systems (UAS) in the private sector, both applications might find consideration in the near future. The fundamental research and a first approach towards these application has been made with this use case.

Overall it can be stated that the advantages of our approach are twofold, both for the event organizers and the event attendee. The guests can use the real-time tool to avoid stress, overexcitement, or anger, whereas the organizers can raise the security level of the event and increase its attraction at the same time by providing a modern smartphone navigation app. In addition, security and rescue forces are able to utilize the app for their efforts and could reach the location of an emergency faster.

Regarding geo-information fusion, it has been shown that the fusion is able to decisively change the quality and reliability of traditional geospatial algorithms and methods utilized for time-critical applications like the one presented here. Instead of being integrated in the algorithm or method itself, it ensures a high actuality of the input information which eventually increase the quality of the result in terms of time-critical approaches.

[44] Most parts of this conclusion have previously been published by Hillen et al. 2015.

Overall objectives and research questions

As proclaimed in the introduction of this thesis, the wide range of earth observation data provided e.g. by GEOSS or Copernicus is not yet used and exploited appropriately from an application point of view and the benefits that arise from combining these diverse data is not revealed to developers and customers. This thesis has presented three different time-critical use cases to demonstrate those benefits and challenges coming along with (real-time) geo-information fusion. Furthermore, a first concept and prototype implementations for integrating geo-information fusion in SDIs have been conducted.

In section 1.4, the following research questions were proclaimed that can now be addressed based on the findings of this thesis:

1. **How can time-critical geo-applications benefit from the combination of information from different geo-sensors, i.e. information that cannot be derived from only one geo-sensor?**
2. **Which challenges and obstacles accompany geo-information fusion regarding the integration in time-critical geo-applications?**
3. **To what degree does real-time geo-information increase the quality of the new information that is resulting from geo-information fusion?**
4. **How can geo-information fusion be used to increase the value and reliability of user-generated information from citizen sensors in particular?**
5. **How can the process of fusing real-time geo-information be integrated into an SDI?**

Concrete objectives and tasks have been derived from these research questions and have been solved in the course of this thesis. In the following the findings regarding these objectives are used to successively address the research questions from above and fill the research gaps with new knowledge:

- **To develop and implement different use cases showing the benefits of geo-information fusion for different aspects of geo-information science.**

  Three use cases have been developed and implemented addressing three different facets of geo-information science:

  Use case #1 introduced Geo-reCAPTCHA, an adaption of the reCAPTCHA idea to **capture** new user-generated geo-information. An extensive empirical user study has been conducted using the example of digitising building geometries. Geo-information fusion was applied in the post-processing of the gathered information by fusing all digitisations of one single building to generate a building geometry with a higher accuracy. The generic concept of Geo-reCAPTCHA can also be utilized for the integration in time-critical geo-applications.

Use case #2 dealt with the agent-based **modelling** of single person movement through a crowd based on information from aerial images and smartphone sensor data. Geo-information fusion was an integrative part of the second model in which movement information from the smartphone sensor data and position information about the people in the crowd from the aerial images are combined. The fusion of both information increases the model prediction quality and allows for an extensive analysis of the benefits of real-time information integration for geo-information fusion.

Use case #3 presented an approach to enhance the data basis with geo-information fusion for conducting a traditional geospatial **analysis**. Two time-critical applications are introduced that are based on a least-cost routing through a crowd with the local crowd density representing the routing costs. Geo-information fusion is applied to combine the crowd density information from aerial images and in situ smartphone measurements to create a joint information basis for the least-cost calculation. Without geo-information fusion such applications could not exist.

> This objective provides new knowledge on benefits of geo-information fusion for geo-applications → **research question #1**.

- **To investigate and tackle the challenges that accompany the fusion of geo-information from different sources.**

The challenges that accompany geo-information fusion are manifold. The most obvious challenges were tackled during the work on the use cases of this thesis.

One basic challenge, e.g. for use case #1, is the selection of an appropriate **algorithm or methodology** to conduct the fusion. Here, a raster-based quantitative analysis by Klonner et al. (2015) was adapted, but it could have been any other algorithm to combine the information. In this connection it is important to handle **different temporal resolutions** of the sources within the algorithm or methodology. If, for example in use case #2, a smartphone delivers movement information every 200 milliseconds and information from the aerial images can be extracted at most every second, one has to handle the large mass of more information from the smartphone in a reasonable way. This means for this particular example that one has to decide whether to interpolate the information from the aerial image or to delete the "unnecessary" information from the smartphone.

Use case #1 revealed another challenge that accompanies geo-information fusion. Here, different sources of information are synonymous with different users of the user study that digitised a building. Some digitisations were drastically wrong and might be seen as intended errors. However, in this specific case those errors are automatically eliminated in the course of the fusion by the digitisations of the other users. Yet, this example is representing a generic challenge for geo-information fusion concerning **varying information qualities** of the different information sources (e.g. quality of VGI, cf. Goodchild & Li 2012). Another example to make that clearer can be the different position accuracy of information from a smartphone sensor and another sensor that utilises differential GPS. The latter one is always providing its information with a much higher position accuracy than the smartphone sensor.

Another major challenge is the extraction of the **same type of information** which is in fact a fundamental pre-processing step regarding geo-information fusion. Using the example of use case #3, it would make no sense to fuse the crowd density information from the aerial images with the information about the movement speed from the smartphone. It is essential to previously calculate the crowd density based on the movement speed from the smartphone before performing the geo-information fusion.

One challenge that was not investigated during the work on this thesis but is nevertheless important for using geo-information fusion for real-time purposes in practice is the reasonable handling of data gaps or **information gaps** respectively. These gaps might occur due to a missing data connection (e.g. mobile internet connection of a smartphone), bad conditions during data recording (e.g. cloud cover during flyover) and many more reasons. Regarding geo-information fusion, information gaps result in severe consequences as the actual fusion process might not be possible anymore (e.g. if only one information source is left). It is important to be aware of this challenge and to address the occurrence in the algorithm or methodology.

> This objective provides new knowledge on challenges that accompany geo-information fusion → **research question #2**.

- **To exploit the potential of citizen sensors in combination with information from other geo-sensors.**

  The concept of Geo-reCAPTCHA was introduced and a prototype was implemented to address the potential of citizen sensors in combination with information from other geo-sensors. One can argue that the capturing process of Geo-reCAPTCHA itself is a geo-information fusion as the information of the citizen sensor (i.e. the digitisation of the user) can only be recorded because of the information of another geo-sensor (i.e. the remote sensing image as the digitisation background). However, in this work the actual information of the citizen sensor is only combined with information from the same geo-sensors, i.e. the digitisations from other users.

Use case #1 demonstrated that citizen sensors can be integrated in geo-information fusion. The quality of the geo-information captured with Geo-reCAPTCHA shows the potential for the combination with information from other geo-sensors. Information from citizen sensors can for example be fused with automatically derived information from remote sensing images regarding damage detection after an environmental disaster (e.g. flooding, earthquake). Another application that picks up this idea can be the classification of satellite images. An image scene can be classified with common automatic algorithms and regions with high uncertainties can be enhanced with crowdsourced information from citizen sensors. This might also be applied for classification of 3-dimensional point clouds for which an automatic classification is more difficult. The combination of information derived by automatic machine-based approaches, no matter from which geo-sensors, with information from citizen sensors for specific parts is close to a perfect symbiosis and holds an enormous potential for future application. This statement is underlined by the ongoing rise of crowdsourcing and micro-tasking platforms like Amazon's mechanical turk[45].

> This objective provides new knowledge on user-generated geo-information from citizen sensors as well as the benefit of geo-information fusion in general → **research question #4 and #1**.

- **To study the resulting differences of integrating real-time and near real-time geo-information in an exemplary modelling approach**

  The differences in the modelling results with integrating real-time or near real-time geo-information has been studied with model #2 in use case #2. In a nutshell one can state that the integration of **real-time geo-information increases the quality significantly**. Information integration frequencies of 1, 2, 10 and 15 seconds have been tested. The modelling results with a near real-time integration frequency (10 or 15 seconds) are more smoothed and do not represent the actual walking path of the test person whereas the real-time integration frequencies (1 and 2 seconds) show more sudden steps in the modelling results. However, those steps are corrections due to the new information and generally increase the quality of the estimation instead of decrease it. Thus, one can conclude that the more up-to-date the input information for the model is, the more realistic is the estimation resulting from the model.

> This objective provides new knowledge on the impact of real-time information integration regarding geo-information fusion → **research question #3**.

[45] https://www.mturk.com/mturk/welcome

- **To design a concept of integrating geo-information fusion in SDIs that allows for a seamless integration in existing infrastructures (e.g. GEOSS, INSPIRE)**

  A first concept for integrating geo-information fusion in an SDI has been introduced by Hillen et al. 2013. This information fusion infrastructure is mainly dependent on different OGC standards. However, this concept has some shortcomings that have been addressed and have led to a new conceptual design (section 4.4). The centre piece of this new infrastructure is the Information Fusion Service (IFS) Controller which is implemented in Python as a first prototype (section 5.4). Different data sources in the form of OGC Web services (e.g. WMS, WFS, SOS) (orange) can be registered on the IFS Controller. Processes to extract the corresponding information from the data (here in form of WPS processes) can be registered on the IFS Controller as well and are stored together with the corresponding data source. While running, the IFS Controller triggers the processes with new data in a given frequency and stores the returned information. Applications are then able to retrieve this information from the IFS via defined interfaces of the IFS Controller.

  The conception and implementation regarding the SDI integration of geo-information fusion is an ongoing process and also an ongoing topic of research. As the challenges regarding geo-information fusion are manifold (see above), a future concept might require a more complex structure to address as many aspects as possible of geo-information fusion.

> This objective provides new knowledge on the SDI integration of geo-information fusion → **research question #5**.

The last objective is separated as it contains many parts that belong to the outlook and perspectives of geo-information fusion. However, it provides valuable information regarding the benefit of geo-information fusion in general (research question #1) and thus has to be a part of this section. Yet, this objective can be seen as a direct transition to the future development of geo-information fusion that is addressed more accurately in the following section:

- **To reveal new application possibilities that accompany the idea of geo-information fusion which might encourage and inspire developers to pick up some ideas and increase the awareness of geo-information fusion.**

  Some new application possibilities have been already mentioned in this section that are mostly motivated on real-time information from remote sensing systems like VABENE in combination with other sensors like smartphone sensors. The idea of use case #2 and #3 might inspire developers to implement applications that rely on real-time crowd density information in the future based on new technologies for a comprehensive sensing like UAVs or helicopters. Such applications might be helpful for short-term crowd monitoring like before and after football games as well as for a long-term monitoring like during music festivals or funfairs (e.g. Oktoberfest). As stated earlier, such applications significantly increase the security during the event for all participants from organisers to rescue teams to visitors.

Several other application ideas are provided with Geo-reCAPTCHA and the possibility of generating high quality geo-information. The combination of geo-information from automatic algorithms with user-generated geo-information has lots of potential in terms of classification, early warning, monitoring and so forth. As stated earlier even 3-dimensional point cloud data, which is difficult to fully classify automatically, can be tackled with an application that is able to utilize the crowd for this task. Reference databases that are often needed for point cloud classification could be filled or even enhanced with a large number of reliable new information that can be used as training data for an automatic classification.

A totally different field of application is agriculture or precision farming in particular. Today, more and more sensors are installed on agricultural vehicles that measure different parameters. Above that, sensor networks of micro-sensors already deliver information for the whole field and not only for the area in front of or behind the vehicle. In the future, this set of sensors might be improved by one or several UAVs that fly in front of the vehicle and record important information about the field, the crop or similar. This might open up the market for remote sensing related applications that combine information from UAVs and the other sensors utilizing geo-information fusion.

> This objective provides new knowledge on the benefit of geo-information fusion for geo-applications → **research question #1**.

7 Outlook and Perspectives

In this thesis, several scientific aspects of geo-information fusion for time-critical geo-applications have been addressed. Most of the presented approaches, implementations and ideas are a sneak preview of the future. Lots of geo-data is available at the moment that could be used for lots of questions. Current programs like Copernicus as well as the ongoing debate on data preservation for security issues clearly shows the trend to collect and store even more data in the future. Geo-information fusion is necessary to combine this data and will become a key aspect to solve problems from agriculture to security in the following years.

To date, only a few time-critical applications exist and those often use near real-time data and information instead of actual real-time information. In particular, if one considers the so-called big data supplying sensors like imaging sensors (airborne or satellite) as well as laser scanners, time-critical applications can seldom be found. This thesis emphasises the future potential for these data with regard to the ongoing rapid progress in processing capabilities (e.g. GPU processing, technical advances in general), up- and downlink speeds to and from recording platforms, faster data networks to send and retrieve data and higher spatial resolutions of remote sensors with a higher amount of information.

Pioneer work on geo-information fusion has been conducted in this work that might affect many future developments regarding remote sensing. Starting with the ongoing rise of UAS and the increase of loading capacity that already allows for installing multi-spectral imaging sensors and even hyper-spectral imaging sensors. With such recording systems a continuous data acquisition is possible. Above that, it is already possible to install laser scanners on a UAS as recently demonstrated by RIEGL[46] which offers the opportunity to gather high-precision 3-dimensional airborne point clouds instead of moving a terrestrial laser scanner at varying positions to cover a certain area. In combination with the presented geo-information fusion approaches imaging sensors and laser scanners installed on UAS might raise certain application possibilities in the future that are not feasible today. For example, in the field of precision farming, UAS can monitor a whole agricultural area in a short amount of time to derive certain parameters which can be fused with information from other sensors (e.g. soil moisture sensors) to estimate the current plant conditions. By doing so, the perfect time for the harvesting can be calculated and the crop yield might be increased.

[46] http://www.riegl.com/products/uasuav-scanning/riegl-ricopter-with-vux-sys/

Following the example of use case #2 and #3 presented in this thesis, security can be a big issue in the future that can be addressed with geo-information fusion approaches. Considering a continuous image-based monitoring of crowds, e.g. during major events, several applications are conceivable to support the event organisation, from the best way to deliver new beverages to a booth for logistics staff, to general navigation applications as outlined in use case #3, to crowd flow simulations that might identify potential danger zones. One can think of zeppelins as possible carriers for a continuous monitoring system in this regard. Another field of application is rapid damage assessment, for example after disasters. Here, UAS might deliver up-to-date images and even height information to identify collapsed buildings or damage in general (e.g. on streets). This information can be enhanced by other sensors on the ground like traffic cameras or even with citizen sensors that provide user-generated geo-information. Another example in this regard can be damage assessment or monitoring in general for network systems like power lines or railways.

Those applications might benefit from the rising number of devices that allows the gathering of 3-dimensional geo-information for anybody. Besides stereo cameras in older smartphones (e.g. LG Optimus 3D[47]), even small laser scanners for smartphones and tablets are currently in an early development stage (e.g. Bevel[48]) that might lead to an enormous amount of crowdsourced 3-dimensional information. Today, a fully automatic classification of 3D point clouds is not possible which would make the large amount of data that might be available in the future more or less useless. In this regard, the Geo-reCAPTCHA concept can be adapted to work with 3-dimensional information and can assist in generating a large reference database for an automatic classification of 3D scenes. Thus, Geo-reCAPTCHA in combination with geo-information fusion can be used to address this and other potential future trends.

Besides all application possibilities, the research conducted in this thesis combined with future technology might also increase the impact of and the need for systems like GEOSS, Copernicus and INSPIRE or concepts like Digital Earth drastically. All of them provide platforms in which real-time data or real-time information can be stored, retrieved and shared. GEOSS, Copernicus, INSPIRE, Digital Earth or any not yet foreseeable system is thus supposed to build the basis for geo-spatial processing and geo-applications in the future. This trend can already be seen today with big players in the geo-domain, for example ESRI or even a non-primary geo-related company like Google, tend to shift their own platforms and businesses to the Web, as can be seen with ArcGIS Online[49] and similar. Hence, future research regarding geo-information fusion should also focus on Web issues in general comprising a more generic SDI integration, possibilities of online geo-processing, in particular concerning streaming input data and seamless integration in time-critical geo-applications over the Web.

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47 http://www.lg.com/de/handy/lg-P920-OPTIMUS-3D

48 https://www.kickstarter.com/projects/matterandform/bevel-3d-photography-for-any-smartphone-or-tablet

49 http://www.esri.com/software/arcgis/arcgisonline

Concluding, one can say that this thesis has revealed many insights in the "black box" of geo-information fusion (compare with Section 1 and Figure 1) and stated the high need for research in this field for the future. However, more research is needed to completely exploit this "black box" called geo-information fusion with a particular focus on its online integration.

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Publications

1. Information Fusion Infrastructure for Remote Sensing and In-Situ Sensor Data to Model People Dynamics

Authors

Florian Hillen, Bernhard Höfle, Manfred Ehlers and Peter Reinartz

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Contribution statement

Florian Hillen carried out all implementations of this study and wrote the majority of the manuscript. Above that, Florian Hillen and Bernhard Höfle conducted the data acquisition. Bernhard Höfle, Manfred Ehlers and Peter Reinartz supported this publication through frequent and productive discussions. The extensive proof-reading by all co-authors led to substantial improvements to the manuscript.

2. Geo-reCAPTCHA: Crowdsourcing large amounts of geographic information from earth observation data

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Florian Hillen, Bernhard Höfle

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Florian Hillen carried out all implementations and analyses for this study and wrote the majority of the manuscript. Bernhard Höfle enormously helped to advance and develop the idea of the publication through frequent and productive discussions and suggestions. The extensive proof-reading of Bernhard Höfle led to substantial improvements to the manuscript.

3. Routing in Dense Human Crowds Using Smartphone Movement Data and Optical Aerial Imagery

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Florian Hillen, Oliver Meynberg and Bernhard Höfle

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Florian Hillen carried out the smartphone and information fusion implementations of this study and wrote the majority of the manuscript. Oliver Meynberg implemented the image processing part of the study and wrote the respective parts of the manuscript. Bernhard Höfle supported this publication through frequent and productive discussions. The extensive proof-reading by both co-authors led to substantial improvements to the manuscript.

4. Fusion of Real-Time Remote Sensing Data and In-Situ Sensor Data to Increase Situational Awareness in Digital Earth Applications

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Florian Hillen carried out the literature review and the resulting concept of this study and wrote the majority of the manuscript. Manfred Ehlers, Peter Reinartz and Bernhard Höfle supported this publication through frequent and productive discussions. The extensive proof-reading by all co-authors led to substantial improvements to the manuscript.

5. Fast-Echtzeit vs. Echtzeit - die Auswirkungen von Echtzeit-Datenintegration am Beispiel einer agentenbasierten Modellierung im GIS

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Contribution statement

Florian Hillen out all implementations of this study and wrote the majority of the manuscript. Bernhard Höfle supported this publication through frequent and productive discussions. The extensive proof-reading of Bernhard Höfle led to substantial improvements to the manuscript.