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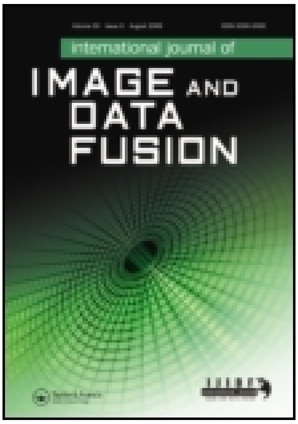

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RESEARCH ARTICLE

Information fusion infrastructure for remote-sensing and in-situ sensor data to model people dynamics

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The term "real time" regarding airborne remote-sensing data can only seldom be found in recent literature on geospatial research. In the course of the German Aerospace Center (DLR) project VABENE, an airborne monitoring system has been developed which is able to pre-process remotely sensed images in real time by an on-board computing system. Afterwards, the data is directly transferred to a ground station via a microwave data transfer system installed on the aircraft. In contrast to remote sensing, the real-time aspect of other types of geo-sensors has been ubiquitous for several years. This article presents a novel concept for an information fusion infrastructure to fuse remote-sensing data and in-situ measurements for the integration in real-time applications via a spatial data infrastructure (SDI). Furthermore, an offline experiment will prove the concept by means of data sets that can already be provided by real-time systems. The study addresses the use case of agent-based modelling of people dynamics for security issues during major events to support avoiding tragedies.

Keywords: information fusion; sensor fusion; spatial data infrastructure (SDI); remote sensing; smartphone sensing; agent-based modelling; people dynamics

1. Introduction

Today, a huge variety of geospatial data 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 on geospatial research 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. Regarding airplanes and UAS, the data are typically readout 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 Center 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

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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).

Combining the real-time airborne remote sensing and the Sensor Web, this article presents a concept for the fusion of real-time remote-sensing data and in-situ sensor data 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 used sensor carrier. In this study we apply passive optical imagery. However, those particular 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 remote-sensing image. However, geolocation of the recorded detailed information depends on the positional accuracy provided by the sensor systems via GPS, 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 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.

Moreover, the presented concept is based on redundancy of "information" via multiple independent and different systems recording at the same time (i.e., remote and in-situ data) that can be used to cross-check the input data. Furthermore, we combine information already extracted from raw input data where we expect that basic signal and data processing already filtered outliers and wrong measurements.

The main objective of this article is to present a concept for an information fusion infrastructure to fuse remote-sensing data and in-situ measurements for the integration in real-time applications via a spatial data infrastructure (SDI). For this, a first offline experiment using sensor data that can already be provided by real-time systems will assess the potential of the developed concept for online use in the future. The study addresses the use case of agent-based modelling (ABM) of people dynamics for 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.

This article is structured as follows: in the second section background information as well as related work in sensor and information fusion, real-time remote sensing, mobile in-situ sensing via smartphones and ABM for people dynamics are described. Section 3 illustrates the methodology of this work by describing the presented information fusion infrastructure and the adaption to the presented use case. Furthermore, the experimental set-up for the conducted experiment and the combination of remote-sensing and in-situ sensor data in an agent-based model are described. The findings of the experiment and the first modelling results are presented in Section 4. Section 5 concludes the article and gives a closing outlook for future research.

2. Background and related work

This section provides background information and related works in the field of sensor and information fusion, real-time remote sensing, mobile in-situ sensing via smartphones and ABM. These facets are reviewed in consideration of a future integration into a SDI for real-time applications.

2.1. Sensor and information fusion

Searching the literature for related work in sensor fusion one will quickly notice a broad range of terms describing almost the same topic. Examples are “data fusion” (Waltz and Llinas 1990), “information fusion” (Pavlin *et al.* 2010), “image fusion” (Klonus and Ehlers 2009) and “multi-sensor fusion” (Ehlers *et al.* 2010), just to name a few. Early approaches concerning the term “sensor fusion” were made in the fields of robotics (Shafer *et al.* 1986), medical science (Lee and Leahy 1990) and remote sensing (Ehlers 1991). All these terms describe the combination of data or information from multiple sources to gain enhanced or improved information about the measured object(s). Regarding “sensor fusion”, these data – as the name implies – can be derived by any kind of sensor. The upcoming work on and the establishment of geo-sensor networks as an explicit research field among environmental scientists (Nittel *et al.* 2004) brings up new research potential for the fusion of geo-sensors.

Kooistra *et al.* (2009) introduced a dynamic web mapping service using Earth observations and in-situ sensor data. In this near real-time application, Moderate Resolution Imaging Spectroradiometer (MODIS) 250-m daily surface reflectance data are combined with meteorological data from sensors of an SWE server by the Royal Dutch Meteorological Institute (KNMI). The information of the two data sources is used in an environmental model to estimate the vegetation productivity for the Netherlands.

A real-time workflow for geo-sensor information analysis is presented by Sagl *et al.* (2011) which is based on portable self-made sensor pods. The development focuses on fast geo-processing and rapid information distribution and visualisation as it is used for time-critical emergency support for radiation protection. Concept and implementation of a sensor fusion service (SFS) for real-time integration of sensor measurements are introduced by Resch (2012). The proposed solution is based on an open-source GeoServer and offers the possibility to fuse heterogeneous sensor data into common OGC WMS (Web Map Service)/WFS (Web Feature Service) output for visualisation and analysis.

Researchers in the field of computer vision and mobile computing utilise data fusion of smartphone sensor and image data. Langlotz *et al.* (2011) present an augmented reality algorithm to generate panoramic images on-the-fly by sweeping a camera over a scene. The algorithm is mainly based on information resulting from image processing techniques which are combined with the user's orientation derived from the inertial and magnetic sensors of a smartphone. Bitsch Link *et al.* (2012) introduce a similar approach by combining video and movement sensor data to show the potential for smartphone-based indoor navigation on wheels and by foot.

These recent studies clearly show that the integration and combination of various data sources and sensors is an ongoing research topic with a number of problems already solved. However, the use of smartphone sensors in combination with remote-sensing data as well as its possibilities and opportunities are widely unexplored. On the one hand, smartphone sensed data are often used in closed systems like augmented reality applications (Langlotz *et al.* 2011) and indoor navigation (Bitsch Link *et al*. 2012), whereas these data are merely used for universal and cloud applications mostly due to privacy concerns. On the other hand, remote-sensing data are used predominantly for traditional issues like mapping or monitoring but are rarely combined with non-remote-sensor data (see, for example, Kooistra *et al*. 2009).

2.2. Real-time remote sensing: the project VABENE

VABENE stands for the German acronym for "Traffic Management during Major Events and Disasters". VABENE is a DLR project with the goal to develop efficient tools for agencies and organisations with security functions and 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 is the used data links. A commercial microwave data link (SRS 2013) is used as a basic data connection to the ground. Additionally, an optical data transfer system based on the work of Horwath and 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 SDIs 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 and Reinartz 2013).

2.3. *Mobile in-situ sensing via smartphones*

As the name implies, a mobile in-situ sensor does not have a fixed 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.

In this section, 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 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). 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)). Therefore, smartphone sensor data are convenient to use and integrate 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, PS has its own privacy debate leading to various approaches to satisfy privacy needs (Christin *et al.* 2011, Groat *et al.* 2012).

2.4. *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.

Nowadays, ABM is used in many application areas, 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 geographical information system (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 and 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 sometimes because of 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 made concerning human behaviour during 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 (see González *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.

In summary, it can be stated that the potential of ABM to model people dynamics is very high and the combination of ABM and GIS technologies allows for an actual spatial representation of the modelling parameters and results.

3. Methodology

Given that remote-sensing data and in-situ smartphone measurements can potentially be integrated in real-time applications via the internet, a generic concept for an SDI-based information fusion infrastructure is presented (Figure 1).

Multi-source sensor data can be provided via OGC standards like the WMS, WFS, WCS (Web Coverage Service) or SOS (Sensor Observation Service). The data are then integrated in the information fusion service (IFS) which consists of (i) the information extraction processes, (ii) the information fusion process and (iii) the information database.

The information extraction processes (i) are sensor specific algorithms to extract relevant information from a given sensor data set. The OGC standard WPS (Web Processing Service) provides the framework for an easily adaptable online processing. New processes can be implemented depending on the current use case which might be deriving water surfaces from radar satellite imagery or the extraction of traffic flow information from vehicle sensor data. Subsequently, the extracted information is sent to the information fusion process (ii). This process gathers the manifold information and stores it in the information database (iii) in a generic format by saving timestamp, value, location or geometry, and sensor type. Thus, the information fusion process handles

Figure 1. Information fusion infrastructure to fuse multi-source sensor data in a spatial data infrastructure.

several key aspects of the IFS. The incoming information stream might vary depending on the sensing frequency of the sensor, the complexity of the information extraction or the rate of transmission of the sensor. By caching these information sets in the database, the information fusion process is able to synchronise 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.

After passing through the IFS the information can be included in any kind of application like visualisation or modelling implementations as well as in traditional GIS software. Thereby, the information is provided by the information fusion process via an interface of defined queries and filter options.

A proof-of-concept of the generic information fusion infrastructure (Figure 1) is provided by conducting a first offline experiment based on sensor data that can be provided in real time. This section shows the methodology used for an exemplary use case of modelling people dynamics for security issues during major events to support avoiding tragedies. Figure 2 illustrates the introduced information fusion infrastructure adapted to this modelling use case. Remote-sensing data, smartphone sensor data and cadastre data are used. These data sets are capable of being provided in real time via the OGC standards WMS and WFS. For the offline experiment the information is extracted and provided manually for the integration into the ABM process.

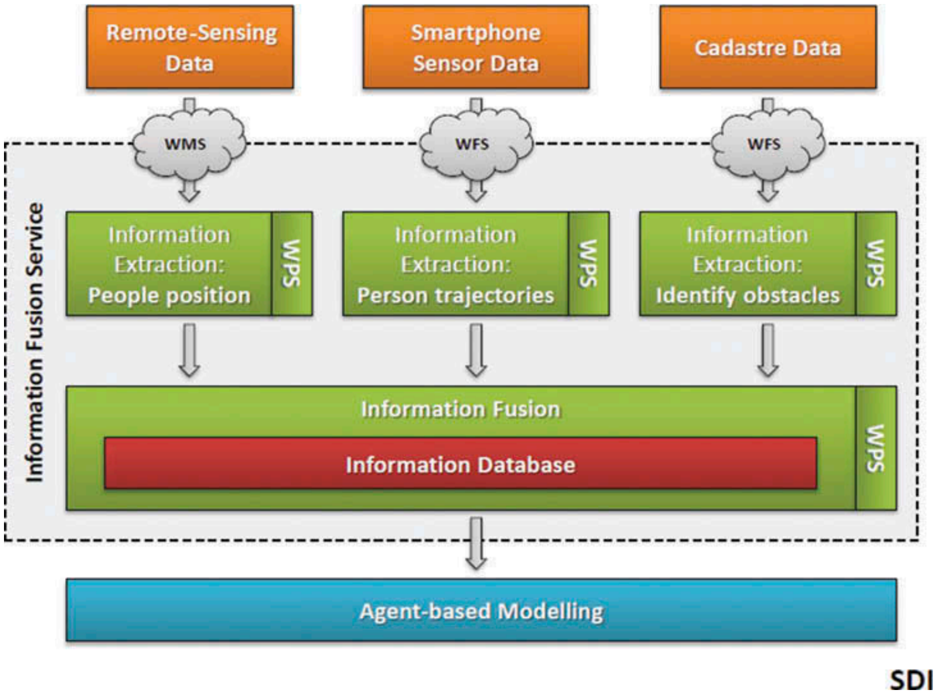

Figure 2. Information fusion infrastructure adapted to the use case of modelling people dynamics for security issues during major events.

3.1. Data sets and experimental set-up

A simulated remote-sensing campaign acquisition 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 airborne campaign. The spire of the Marienkirche in Osnabrueck (Germany) is chosen as an ideal recording platform as it is one of the highest buildings in the inner city of Osnabrueck (Germany) with approximately 40 m height and as it holds an observation deck with an almost clear view over the ancient market place of Osnabrueck.

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 and 55 mm are the ones closest to typical airborne image recording systems whereas a focal distance of 18 mm increases the recorded area significantly.

The relatively low height of the recording platform (compared to aircraft) results in an oblique view so that the images have to be precisely rectified based on very accurate and reliable ground control points. A 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 permits an automatic processing of image series.

Figure 3 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. This results in an oblique view of buildings and objects in the recorded area. For this work, the images with a focal distance of 18 mm are used, because it increases the study area significantly and the distortion resulting from the varying focal distances is apparently negligible. Due to the low recording height, both focal distances provide a highly sufficient image resolution.

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

Figure 3. Georectified images from the observation deck of the Marienkirche with different focal distances (left: 18 mm [zoomed in]; right: 48 mm).

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). 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 synchronised. 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.

3.2. Combining remote-sensing and in-situ sensor information in an agent-based model

The headings derived from the in-situ sensor data can be included in an agent-based model to calculate new locations of the test person at each time step. Additionally, the actual positions at each recording step of the test person and the other pedestrians are derived from the image data and are included in the model as well. The open-source software Agent Analyst (ESRI 2013) is used in this work. Figure 4 shows the starting position of the ABM approach.

The model consists of two types of agents, (i) the actual agent to be modelled (in this case the test person and from now on exclusively referred to as "agent" (red star in Figure 4)) tracked via images (green circles) and smartphone (blue rectangles) and (ii) the

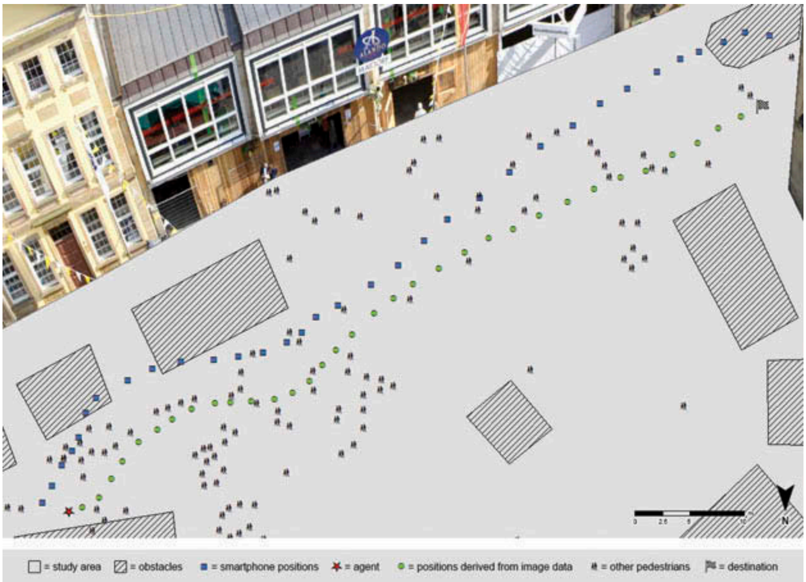

Figure 4. Starting position of the agent-based model.

other pedestrians (black people icons) around him derived from image data. The start point of the agent is set during the model initialisation using the first image of the recording series with the recording time as an accessible parameter to match the location with the smartphone data. In this experiment, the smartphone data is selected via the timestamp of the recording so that real-time data is capable of being integrated as well.

The walking speed of the test person is extracted from the smartphone sensor data at each time step. In contrast, the destination of the agent (chequered flag) 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. If the destination is defined, the model assumes that the agent wants to reach the end point directly, so 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.

With the given moving speed and heading, the only missing factor for this model is the other pedestrians (black icons) 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. To demonstrate the possiblity of a real-time integration of new data, the pedestrian data is updated every 5 seconds.

4. Results and discussion

The offline experiment provides remote and in-situ sensing data that are analysed and processed according to the adapted information fusion infrastructure presented in Figure 2.

4.1. People trajectories from smartphone sensor data

The recorded position data are visualised in a GIS with the possibility to include base layers like the recorded image data. Figure 5 presents the recorded Smartphone positions (yellow) and the positions derived from the image series (red) for test person 1 (left) and test person 2 (right). The tracks are roughly similar to each other although the smartphone positions apparently vary in their accuracy. This fact is supported by the positions of the Garmin hand-held GPS (Figure 5: right, green). This should be more accurate than the GPS device of the smartphone, but it displays also differences from the actual positions (red). Hence, the deviation is not only a result of the smartphone's GPS receiver inaccuracy but is apparently also due to the conditions of the study area which in fact is surrounded by high buildings. The buildings occlude large parts of the sky and thus reduce the number of satellites for precise positioning. 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 6a illustrates a subset of positions and headings for test person 2 (blue) and the derived positions from the image series (red) with the respective moving directions. One can clearly see that the GPS positions are not very accurate as the test person starts the recording in front of the Marienkirche which results in a poor GPS signal. 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. Figure 6b supports this observation by

Figure 5. Recorded smartphone positions (yellow) and the positions derived from the image series data (red) from test person 1 (left) and test person 2 (right). Additionally, the later recording of test person 2 was enhanced with a Garmin hand-held GPS (green).

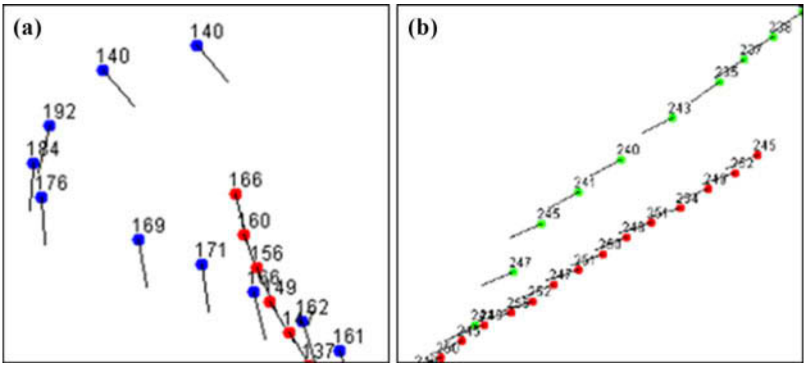

Figure 6. Positions and their respective headings of (a) test person 2 (blue: smartphone; red: extracted manually from images) and (b) test person 3 (green: smartphone; red: extracted manually from images).

showing the smartphone-measured positions (green) and headings of test person 3 as well as the respective image-derived values (red). The difference between the headings has a maximum of 10 degrees whereas the positions have 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 a future real-time integration of 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 the IFS without any difficulties.

4.2. Modelling results

The calculation of the agent-based model leads to the results shown in Figure 7. The calculated walking path (red stars) obviously differs from the actual walking path (green circles) which is derived from the image series. However, the general track of the test person is well represented by the modelling result.

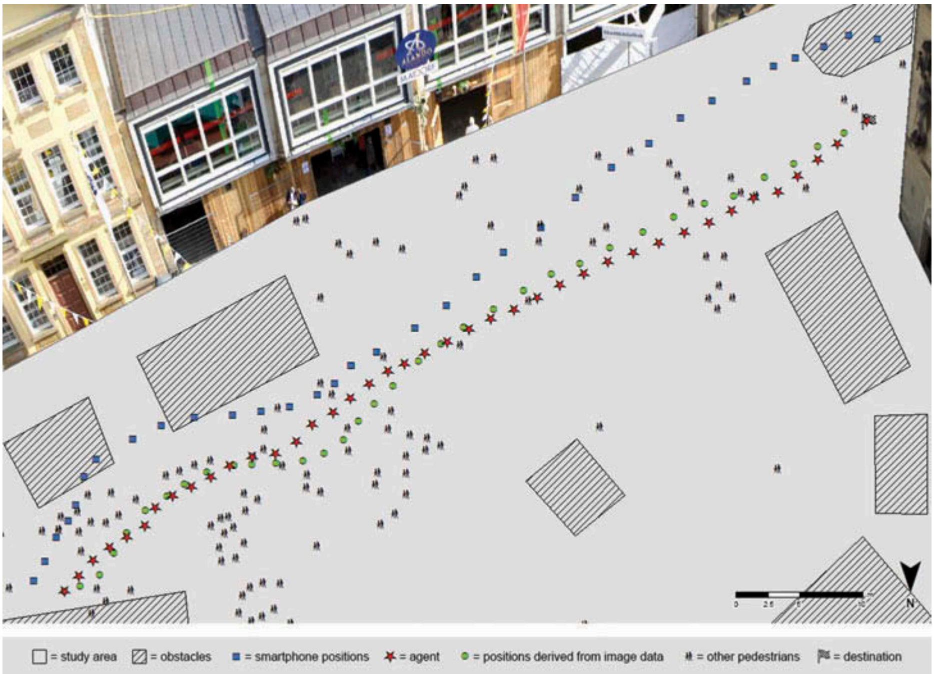

Figure 7. Result of the agent-based model.

Concerning the focus of this work, the capability of real-time information integration is more relevant than the actual quality of the modelling result. Therefore, the adaption of the modelling process to the continuous stream of new pedestrian data is visualised. Figure 8 presents four subsets of the modelling result 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 data is loaded whereas the subsets 2 and 4 illustrate the subsequently changed data set. 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 (see Section 3.2.) 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 moving path. The situation at 17:10:25 CEST in subset 3 would change the walking direction of the agent significantly compared to the acutal walking path derived from the image data. The agent has 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 data shown in subset 4. The new data reveals that the group dissolved itself in the meantime so that the agent can stay on his path.

The importance of a continuous data stream of new pedestrians is illustrated in Figure 9. Subset 1 shows the modelling situation at 17:10:50 CEST before new pedestrian data are loaded. The agent has no chance to reach his destination (chequered flag) without ignoring his comfort zone. 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 data (subset 2) no pedestrians are present between the agent and the destination. The modelling can be continued and leads to the result visualised in subset 3.

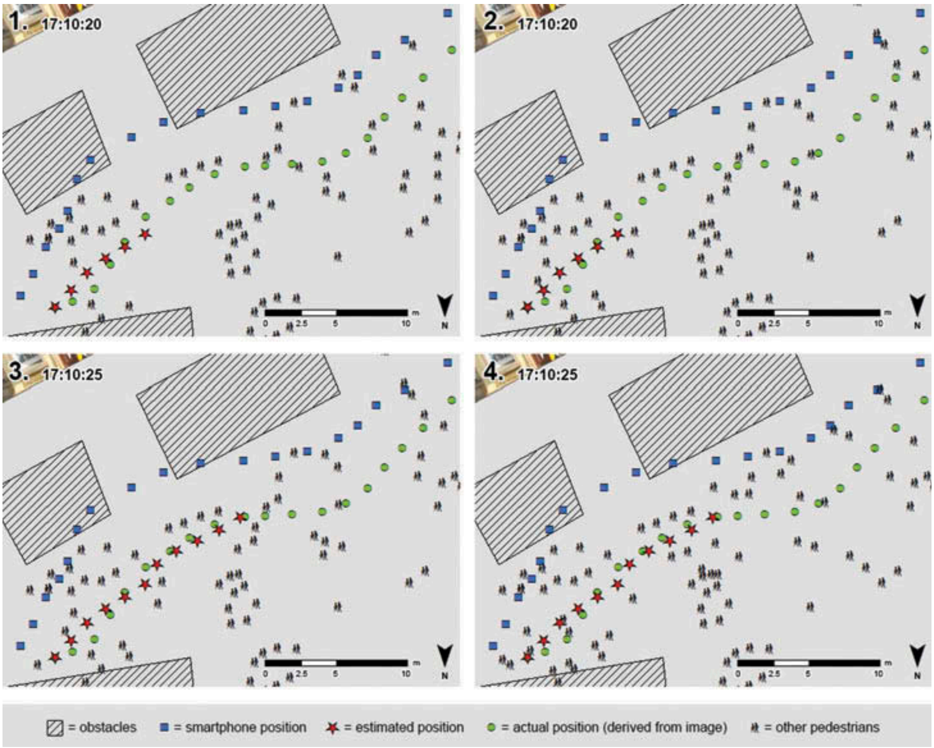

Figure 8. Subsets of the agent-based modelling result at different timestamps before (left: 1 and 3) and after new pedestrian data are loaded (right: 2 and 4).

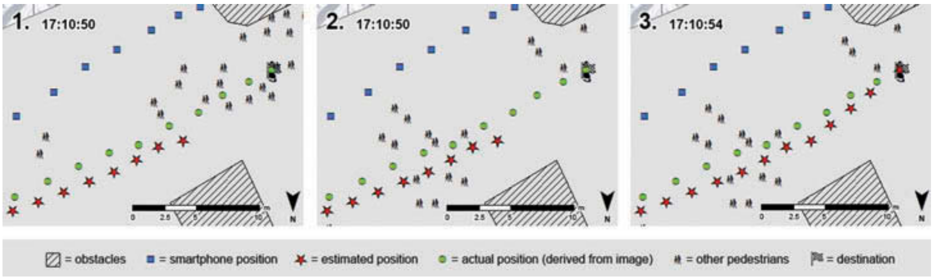

Figure 9. Subsets of the agent-based modelling result at different points in time showing the importance of continuously reloading new pedestrian data.

5. Conclusion and outlook

This article presents a generic concept for an SDI-based information fusion infrastructure. Furthermore, it describes opportunities that arise from the availability of real-time remote-sensing data in combination with geodata obtained from in-situ sensors. These data are, for example, acquired by “human sensors”, equipped with mobile devices such as smartphones.

To prove the concept, an offline experiment for the use case of ABM of pedestrian dynamics based on sensor data that can be provided in real time is conducted. Even though the smartphone's GPS accuracy in the urban study area turned out to be low, the measured headings are found to be sufficient for modelling single-person movement. Above that, it can be stated that the movement of the test person could be modelled in a straightforward way by integrating information derived from simulated remote-sensing and in-situ data. Additionally, both smartphone sensor data and simulated remote-sensing data are found to be capable of an actual real-time integration. Thus, the results of the offline experiment confirm the information fusion infrastructure for a future use for real-time applications. It is assumed that fusion of redundant information acquired by independent sensors can improve the overall quality of the final result. However, the amount of measurements and sensors, their spatial and temporal resolution, needed to guarantee reliable information fusion results have to be addressed in future research.

The results also demonstrate the importance of real-time information integration for modelling approaches. By continuously loading new information the modelling process can adapt to recent changes within the study area such as moving people or newly appearing obstacles. This would not be possible without real-time data.

Due to the promising results of the offline experiment, a main focus of future research should be put on the real-time aspect including airborne-derived pedestrian tracking results. This means the actual physical integration of the fusion and modelling processes in an SDI by using various OGC standards. A major challenge that has to be faced in this context is the known problem of "big data" and its integration in Web applications. The accuracy of the smartphone data will be investigated in more detail using person tracks derived from remote sensing.

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