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A distributed data collection and management framework for tracking construction operations

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ABSTRACT

Construction work typically means producing on shifting locations. Moving materials, equipment and men efficiently from place to place, in and in between projects, depends on good coordination and requires specialized information systems. The key to such information systems are appropriate approaches to collect de-centralized sensor readings and to process, and distribute them to multiple end users at different locations both during the construction process and after the project is finished. This paper introduces a framework for the support of such distributed data collection and management to foster real-time data collection and processing along with the provision of opportunities to retain highly precise data for post-process analyses. In particular, the framework suggests a scheme to benefit from exploiting readings from the same sensors in varying levels of detail for informing different levels of decision making: operational, tactical, and strategic. The sensor readings collected in this way are not only potentially useful to track, assess, and analyse construction operations, but can also serve as reference during the maintenance stage. To this extent, the framework contributes to the existing body of knowledge of construction informatics. The operationality of the framework is demonstrated by developing and applying two on site information systems to track asphalt paving operations.

1. Introduction

Construction projects often involve a number of specialized equipment, located not only on site, but also at distance. As the work procedures and productivity of the equipment highly depend on the location and activities of others, informing construction personnel about the project progress is an important task. In this setting, equipment operators can make decisions on how to proceed with their tasks and project managers can decide if some changes need to be introduced into the process by, for example, increasing the amount of trucks that transport construction material or adjusting the hauling route. Later, the documented data can be used to identify inferences between project parameters and develop suggestions about how to plan future construction projects.

Consequently, in the scope of construction informatics the question how to best connect on-site sensors, process the obtained data, and provide information to spatially distributed equipment operators and site managers in real time along with informing strategic decision makers within construction companies is essential. Though several ways to meaningfully collect readings from sensors located at construction sites were introduced earlier (see, for instance, [1,2]), the previous approaches did not consider the purpose to collect and process sensor readings in different levels of detail to support operational, tactical, and strategic decision making.

To address this gap, this paper proposes a framework that allows for distributed data collection and management acknowledging these three levels of decision making. The framework suggests to store sensor readings at different locations in different levels of detail that correspond to the sensor readings update rate. The readings, obtained with high update rate are stored at the moment of data collection. Then, the update rate of these sensor readings is reduced to support close to real time visualizations to timely inform equipment operators and managers about the ongoing processes. Based on such visualizations, operators can decide how to perform their next activities to comply with the project pace, while the managers can decide if additional equipment should be introduced to the project. These well-founded decisions will ultimately lead to improved work productivity. Besides supplying the real-time information delivery needs, highly precise readings (with significantly higher update rate) can later be analysed to find inferences between project-related elements. Such analysis can provide suggestions how to plan future construction projects.

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To illustrate the application of the framework for developing systems to track asphalt paving this paper describes the operationalization of the framework. Two framework-based information systems were implemented according to the dataflow and were applied for real construction projects. These instantiations demonstrated the expected functionality and were positively accepted by equipment operators and managers on site.

This paper is structured as follows: the next section briefly reviews existing technologies and approaches to collect construction-related information using sensors. Afterwards, the third section reveals the proposed distributed data collection and management framework. The fourth section delineates the research methodology adopted to apply the framework to track construction activities. Then, two illustrative information systems oriented to follow asphalt paving operations are described. The sixth section provides discussions over the proposed framework. Finally, conclusions regarding the proposed framework are drawn.

2. Collecting construction process-related information with sensors – a brief overview

Recent years have seen an increase in research about how to best use automated data sensors to track on-going construction operations. At the same time, as using sensors meaningfully always requires the development of the corresponding information systems, research efforts also concentrated on development frameworks to support construction personnel in their work tasks.

This section gives a short overview about recently published work in the area of automated sensing to control and support construction activities. The overview includes some of the most commonly used technologies to track construction processes: RFID tags, computer vision based sensors, and GNSS (Global Navigation Satellite System that correspond to a number of navigation solutions, such as GPS, GLONASS, and Galileo). Afterward, the section summarizes recent efforts to incorporate several on-site sensors into a single system using frameworks that aim to support construction activities that the here presented work built upon.

2.1. A brief review of utilizing sensor readings in construction projects

One of the most widely explored applications is the use of RFID tags to track construction material on site (see for example [3–6] or [7]). An example of a recent published case study in this area shows how RFID tags can assist in tracking and managing materials on water supply projects [8]. For in-depth view on the latest developments, trends, and research solutions the interested reader can refer to special issues on advances in RFID technology, such as [9,7]. Essential features of the technology result in corresponding technology-specific advantages and limitations that characterize RFID-based solutions. Thus, the RFIDs can naturally overcome previous documenting techniques, such as barcodes, by providing opportunity to store additional data in some types of RFID tags and by rejecting the need for the line-of-sight between the tag and the tag reader. However, as the effective range of tag readers is constrained, the possibility to use RFIDs in harsh environments (or to follow equipment and materials on distance) is limited.

Next to the RFID technologies, computer vision sensors were effectively employed on construction sites, for example as described in [10–13]. Work in this area was, for example, concerned with developing algorithms that allow for the combination of different images and video frames [14,15] or with the evaluation of different needs for accuracy of these sensors [16]. This theoretical work has motivated more practical applications to, for example, track the workforce on a construction site [17] or support safety management by predicting equipment operator's blind spots [18]. Researchers in the field of computer vision have also recently developed artificial intelligence based methods to, for example, classify the different actions of construction workers on site [19], or for productivity analysis [20]. Another closely related strand of study related to computer vision include research on utilizing range cameras for the purposes of the construction domain, for example for representing 3D workspace [21] and analysing worker posture in terms of ergonomics [22]. Altogether, the ongoing research on utilizing computer vision sensors hold promises for wider exploitation in the future, such as non-intrusive data collection technologies to track construction activities. However, some factors currently hamper everyday use of computer vision sensors. Among others, these factors include difficulties to track objects in cluttered environments and the necessity to consider weather and lighting conditions.

Particularly related to this study is the research strand related to the utilization of GNSS measurements to track equipment and human movement on site. Among others, systems to track construction activities include documenting equipment movements on asphalt paving sites [23] or automating earthwork operations for highway projects [24]. In current practice, the GNSS technologies appear to be the most common solutions to track construction activities, though their applications are also limited by the demand to maintain an unobscured line-of-sight between the receiver and satellite constellations. However, while this condition is fulfilled and the atmospheric effects are taken into account, for instance by utilizing correction signals from a base station, this type of sensors can track equipment with an accuracy within the centimetre range.

How to best select specific sensors to follow a construction project typically depends on the characteristics of the project at hand, the purpose of the specific information system, and limitations of particular technologies. For instance, the choice between RFID, computer vision, and GNSS technologies can be justified by site specifics. GNSS can effectively track outdoor equipment at both on-site and at distance. At the same time, to track equipment movements at construction sites on which surrounding objects obstruct GNSS signals, one could utilize RFID tags or computer vision technologies for non-intrusive tracking. However, the latter technologies are operational within a relatively short range and could demand an obscured line of view between the object and tracking devices.

As a result, this need to choose specific sensors for particular operations requires the meaningfully fusion of various data streams originating from different sensors [25–27]. For instance, common fusion mechanisms include combining GPS with inertial navigation sensors measurements [28] or tracking materials during construction operations by fusing RFID and GPS sensor readings [29].

2.2. Frameworks to integrating sensor readings

To address how to meaningfully combine different sensors on a more generic level, researchers recently proposed several frameworks. Some of these frameworks aim to organize mobile computing for information management on construction sites [2,30] and how to facilitate decision making by project managers who take corrective actions during ongoing projects [31]. Other examples include frameworks to describe operational processes and their functional aspects [32] and to consider ontologies to support development of information systems oriented to assist different management levels in making decisions [33].

While some frameworks acknowledge the need to holistically manage information in relation to different layers within construction companies, including executive management, department management, project management, site management, and construction operators (e.g. [33]), others highlight that decision makers on site can necessitate different sets of information (see for instance [30]). However, to the best of our knowledge, currently no framework aims to suggest organizing information systems to effectively support decision making tasks at all these different organization levels of construction companies.

To overcome this gap, this paper proposes a framework that considers the different hierarchical levels of a construction company including organizational, project, and operation levels. As decision making on each level has particular interests [34], specific characteristics of sensor readings can be of particular value at different decision making levels.

Specifically, close to real-time information can support equipment operators in making well-founded operational decisions, as well as inform project managers who can control and adjust project performance, for instance by introducing additional equipment into the project. This need for close to real-time information delivery is widely acknowledged and multiple researchers suggested solutions (see for example [1,35–39]). At the same time, the outcome of the projects performance analysis (performed in a post-processing manner) may assist managers in planning future projects. An exemplary scenario is to analyse productivity based on user queries to a database (e.g. such as in [26]) for estimating future equipment productivity in some regions based on already known production rates within other regions [40]. In such ways, applying data mining techniques to retrospectively analyse carefully documented construction processes can support in planning future projects or, in other words, in making strategic decisions.

The outlined differentiation between close to real-time and post-processing data analysis calls for consideration how fast the collected data should be transferred and processed. This lag in delivery requires particular attention in case of close to real-time systems. Particularly, though wireless-based solutions allow to effectively track machine movements on- and off-site, for example by adopting ultra-wideband communication [41,42] and ad hoc networks [43], the bandwidth of such solutions is lower than in case of wired connections. For instance, signal attenuation in case of long-range wireless transmission can lead to the expected degradation in frame rate in computer vision tracking systems ([1, p. 754]). As a result, to support timely delivery of close to real-time visualizations, there is a need to consider the amount of data that should be transferred, processed, and delivered to final users.

As a possible way to deliver close to real-time visualizations to support the corresponding decision making tasks, the sensors' original level of detail can be decreased. Such decrease can reduce demands for transmission bandwidths and avoid processing overwhelming amounts of data. However, during reducing the rate of highly detailed data some undesirable data losses can occur that can negatively influence later post-processing data analysis. Therefore, a suitable approach should provide opportunities to avoid irreversible data losses.

Altogether, to the our best knowledge currently no framework supports the distributed data collection and processing that handles sensor readings both in real-time rate with the reduced level of detail and utilizes the highly precise readings to form a single warehouse database. To address this need we developed such a framework which is outlined in the next section.

3. The distributed data collection and management framework

The proposed distributed data collection and management framework (Fig. 1) aims to support collecting, processing, and visualizing sensor readings from ongoing construction processes. The proposed framework supports both close to real-time and post-processing data analysis; provides opportunities to transfer sensor readings from numerous locations to multiple users who can track construction processes, and suggests to maintain the sensor readings in the local storage of the sensor device at construction equipment for later data analysis. Even though some sensors already accumulate sensor readings in inner memory, others such as RFID or cameras do not always store original sensor readings at the moment of their collection. In this case, the readings can be collected by and stored at a computer connected to a particular sensor. Such

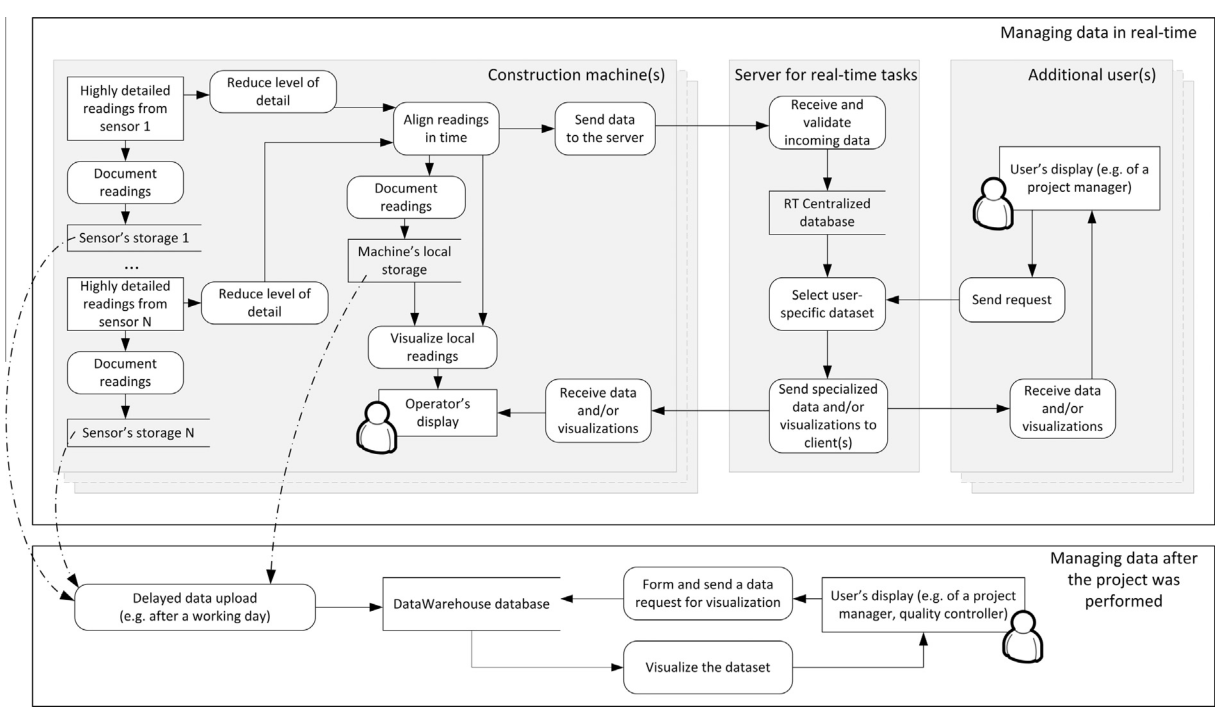

Fig. 1. The proposed distributed data collection and management framework.

a systematic approach of data storage allows to avoid irreversible data losses. As the framework is generic, it has no limitations to a particular set of sensors and can incorporate different tracking technologies described in the previous chapter.

The framework is organized as a generalized dataflow. First, the readings from different sensors are collected at individual construction equipment and are stored in a high update rate. Then, the level of detail is reduced and sensor readings are aligned in time. Afterwards, the readings are visualized in a meaningful way, documented in the storage located at the construction equipment, and sent to the remote server. The updates from the server (if needed) are then received and visualized on the operator's screen. The reduced level of detail allows to reduce the network throughput requirements and thus ensures the existence of contemporary information on the server even if the network bandwidth is low. The server can, therefore, provide close to real-time information to multiple different users. Altogether, these stages allow to collect highly precise sensor readings for documentation purposes, visualize the local readings to inform the equipment's operator, and communicate with the remote server that can update external users with the current equipment status based on user queries. The information obtained in this way could support operational and tactical decision making of personnel involved in the construction process, such as equipment operators and project managers.

After the project (or a part of it) is completed, the highly precise data can be transferred to a centralized data warehouse. Such warehouses accumulate precise information from different sensors within a single storage for further processing. For instance, data mining can be applied to identify major factors that influence the construction process. In these settings, the warehouse data (such as the one for quality assurance purposes) can support planning future construction projects. Thus, the additional information can directly benefit strategic planning of future activities.

As the approach proposed by the framework relies on several databases, the sensor-based infrastructures designed using the framework will benefit from the fact that the sensor readings are stored in different locations with different levels of detail. Such an approach ensures that no irreversible data loss occurs within the information system: the collected readings remain available for later usage in their high level of detail. Furthermore, such configuration of storage elements provides supplementary data backup. Additionally, as the framework relates the close to real-time and the post-processing data management schemes, the framework suggests to utilize distributed data processing elements.

To test the potential of the proposed framework we developed and implemented two information systems that particularly correspond to the framework's scheme to manage data in real-time. The next section describes the adopted methodology.

4. Adopted procedure to develop and test framework-based information systems

To demonstrate the potential of the proposed framework to collect, process, and deliver visualized sensor readings with different levels of detail in a distributed way we adopted the following procedure: (1) to illustrate how the framework can be operationalized we developed a dataflow for distributed data collection and processing for asphalt paving as a specific type of construction activities; (2) we developed two information subsystem to track specific equipment during paving activities; and (3) we ensured the functionality of the systems by deploying them on construction projects and discussing it with operators and managers on-site.

By instantiating the framework we aimed to ensure that the framework can assist developing information systems to support users in their daily work by providing effective visualizations to multiple users in close to real-time rate, while the collected data should be preserved for future processing and analysis.

We chose paving operations as both specific and illustrative examples of construction activities because such operations necessitate the coordinated work of different specialized equipment that move on- and off-site. This characteristic is pertinent not only to asphalt paving, but also for other construction activities. Therefore, we consider that the illustrative operationalization can be projected to other construction activities, as most of them involve specialized equipment that move in coordinated manner.

To identify meaningful information flows for finding a suitable arrangement of sensors to track paving activities at paving sites we conducted both literature review and field studies. The initial information flow was reconstructed by analyzing control variables (as described in [44,45]) that influence the asphalt paving process. After the literature study, the first author of this paper attended four paving projects to follow equipment operators in the field. This activity, as well as later system development and testing, was guided by the combination of ethnographic and action research principles [46] to further understand real world practice. Based on the outcome of this activity, we adopted the following arrangement of sensors in the context of this research: GPS sensors to follow trucks, pavers, and rollers; and temperature sensors on pavers to document distribution of the temperature of the asphalt mat.

Once the disposition of sensors was identified, we developed visualization systems according to the workflow described by [47]. The development activities were guided by the workflow and hence incorporated the following steps: equipment selection, infrastructure organization, data processing, and visualization. Besides, we utilized the steps as a mean to structure discussions about the system development between us and paving experts.

The next section illustrates the application of the framework to define a dataflow to track asphalt paving activities as a particular example of construction projects. Then, the details of implementations and testing of the dataflow are described.

5. Illustrative operationalization of the framework for the case of asphalt paving operations

Asphalt paving operations demand utilization of several specialized equipment, such as asphalt trucks, pavers, and rollers, to transport the asphalt mixture, lay down the asphalt mat, and compact the asphalt layer to a desired density. Coordinated equipment movements are crucial for obtaining a high quality road surface. Trucks continuously travel between an asphalt plant and a road construction site, while pavers and rollers move at the site. The information about current equipment locations and their previous movements can support construction specialists in making decisions on how to perform their tasks. For example, a paver operator could be interested in knowing when the next truck will arrive, a roller operator might desire to know what is the asphalt temperature after the paver, and a project manager could track equipment to ensure the continuous material delivery from asphalt plants to the construction site.

Particularly noticeable in relation to this research is the large international project OSYRIS (Open System for Road Information Support) [48] that aimed at providing a common infrastructure with open interfaces and thus connect previously fragmented and non-compatible different systems. The projects component-based framework linked its central element the product model to multiple components: office (road design, work documentation, worksite web, and on-site design viewer), on-board computer (on-board computer and setting-out), and measurement and control components (compactor measurement system and paver measurement system). According to the employed principle of modularity, the components can be interchanged and additional elements, such as cooling models or co-operation between paver and rollers, can be added.

However, though the OSYRIS project aimed to develop an information technological infrastructure for the road construction and maintenance, its purpose (similar to the purpose of the research project Computer Integrated Road Construction [49]) was mainly oriented to provide tools to track equipment-specific information, rather than suggesting frameworks for system development based on the assumption that different data granularity could be specially useful for different decision makers. By having a different purpose this paper complements the previously conducted research in the field and, as such, contributes to the existing body of construction informatics. In particular, the paper advocates the approach to develop information systems by means of exploiting readings from the same sensors with different levels of detail for informing different decision making levels: operational, tactical, and strategic.

As mentioned before, to illustrate how the proposed framework for distributed data collection can be operationalized, we developed an organization structure of an information system. The information system collects sensor readings from multiple on- and off-site locations and delivers visualizations in close to real-time rate to multiple users, located both at a construction site or at distance (Fig. 2). At the same time, the sensor readings are documented in high detail at different equipment and can be later uploaded to a centralized database for the careful analysis.

The proposed framework can be operationalized to track multiple types of equipment during asphalt paving projects as shown in Fig. 3. In particular, the dataflow elements related to every equipment follow the same structure: collecting sensor readings, storing them, reducing the level of detail, aligning readings in time, visualizing local data, and communicating with the server. Though some particular steps are omitted, the succession of the dataflow steps sustains. For instance, the developed dataflow does not include data transfer from the server to asphalt trucks and only one sensor type (GNSS) is used on rollers. Nevertheless, additional sensors can seamlessly be introduced and the omitted steps can be easily reintegrated.

Due to the extensive nature of the framework, we split the description in two parts that highlight characteristics of the framework from different viewpoints. In the first part, we describe a subsystem that trace locations of asphalt trucks that spend a significant part of their operations off-site. The second part depicts the implemented dataflow that concentrates on the central processing of massive amount of sensor readings. Though the subsystems track different equipment and perform different calculations, both of them are implemented using the principles depicted in the framework.

5.1. Tracking remotely located construction equipment using distributed data collection and processing

To illustrate data collection from distantly located equipment we focus on the example of asphalt mixture delivery to a construction site. Ensuring the continuity of paving the constant delivery of asphalt to the construction site is crucial for the quality of the asphalt layer. If the paver stops, the temperature homogeneity of the asphalt layer will be disrupted, resulting in a lower quality of the road surface. The continuity of paver movements ultimately depends on the number of trucks transporting the mixture from an asphalt plant to the construction site [50]. Road traffic can influence the timely asphalt delivery and, thus, introduce uncertainty about the estimated time of arrival (ETA) of the truck at the construction site. Altogether, the paver operator could benefit from the close to real-time information about the trucks' positions. By having such information at hand, the operator can adjust the paver's speed according to the trucks' ETA to avoid disruptions in the construction process. At the same time, the positional information collected at asphalt trucks can later be used for analysing and further planning construction activities. In the given settings, the proposed framework can support close to real-time data collection and visualization along with storing location data for further use.

Fig. 4 overviews the organization structure of the information system we developed and implemented to track remotely located construction equipment. In the embodiment of the information system delivery trucks are equipped with smartphones to collect, store and send sensor readings to a remote database. Communication with the remote server was established by a 3G connection.

To test the approach we developed a specialized Java program for an Android-based smartphone in addition to establishing and configuring a web-server. Firstly, the smartphone's program collects, stores, and sends out readings from the phone's GNSS, compass, and accelerometer sensors. In particular, the transmitted data include the identification number of the record, time stamp, latitude and longitude of the equipment position, identification

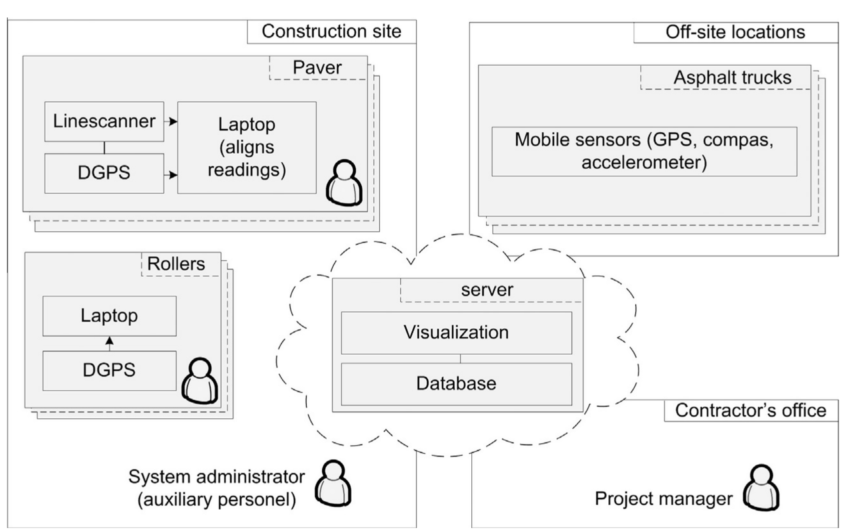

Fig. 2. The proposed organization structure of an information system to track paving operations.

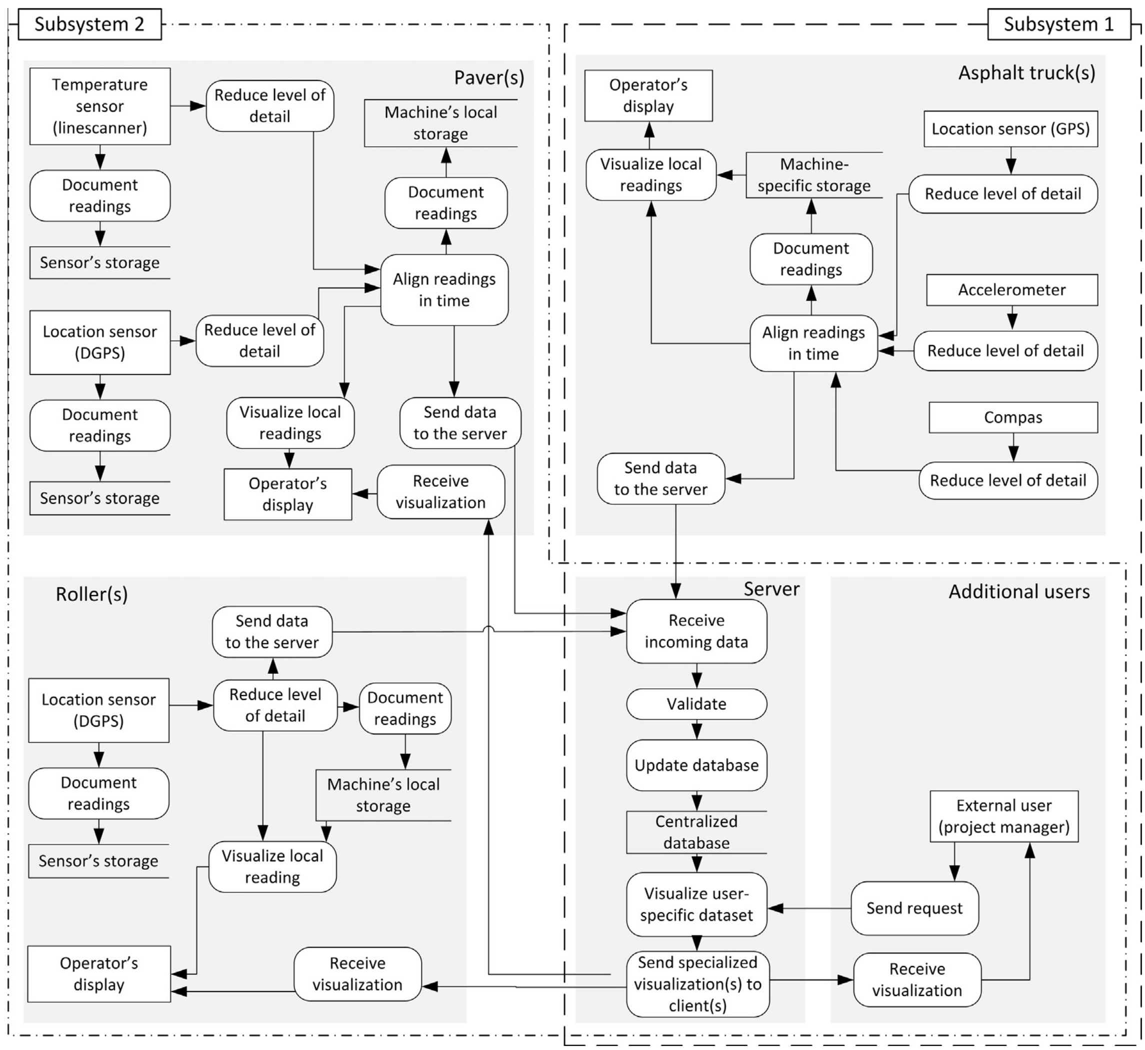

Fig. 3. Implemented dataflow for distributed data collection and processing for asphalt paving operations according to the proposed framework: subsystem one demonstrate tracking remotely located construction equipment; subsystem two illustrates a case with intensive computations at a centralized server.

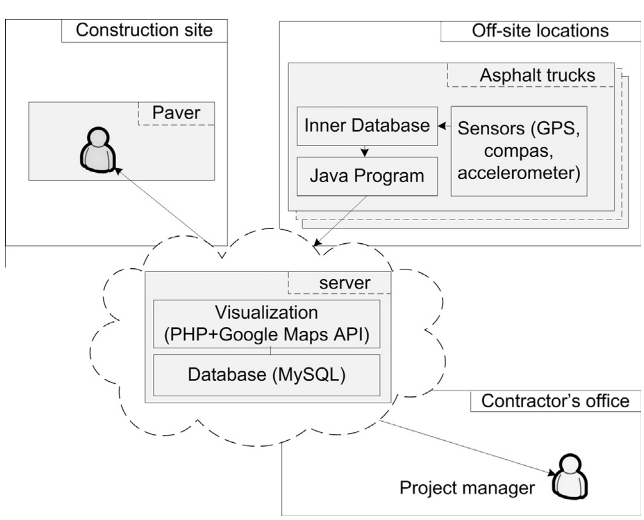

Fig. 4. Organization structure of an information system to track remotely located construction equipment.

number of the equipment, and readings from the phones' azimuth and accelerometer sensors. Then, the data are received by the server and stored in a central database. Later, the data are visualized to display the truck location superimposed on a geographical map. The following server-side software components were specially developed first author in line with the proposed framework:

1. A PHP program to receive the transmission from a smartphone, check if the received data are in the expected format, and store the data to the database.
2. A database to accumulate the received data.
3. A visualization web-page (an HTML document that utilizes Java script and Google Maps API) to display equipment positions.

The developed subsystem illustrates several characteristics of the proposed framework. Firstly, multiple clients can access the data to track different equipment almost in real-time. For instance, a paver operator can track asphalt trucks and reduce the paver's speed if the next truck is expected to arrive with a delay; also a construction manager can check the progress of the construction project and make decisions on how to improve it by, for example, adding additional transport vehicles to maintain continuity of material supply. Then, in addition to updating the server, the approach allows to use the Java program to store the data in inner memory at the moment of collection. In this sense, even if the data will not be transmitted to the server, it will stay available in the inner memory and, thus, will not be lost. Finally, the documented sensor readings can be downloaded from the local memory located at the smartphone to analyse the equipment's path by using adopted post-processing software, such as conventional GNSS processing or specialized software (for instance, discrete event simulators). To illuminate the framework's characteristics that support centralized data processing to support delivery of equipment-specific information from different sensors to multiple clients.

5.2. Performing intensive computations at a centralized server to track the construction process

The information about the temperature of the deployed asphalt mat can influence operators' decisions about how to conduct the compaction activities and, correspondingly, how to move their equipment. For instance, if the asphalt temperature after the paver drops down (in case a truck delivered a colder load of the asphalt mixture), the roller operators can decide to compact the mat closer to the paver. However, despite the potential value, the transfer of temperature information from pavers to rollers does not take place in current paving practices and a roller operator can only roughly estimate the temperature of the recently deployed asphalt mat based on personal visual observations.

A possible solution to transfer temperature data from pavers to rollers can be implemented according to the proposed framework. The organization structure of the corresponding information system is shown in Fig. 5. The structure employs several elements from the dataflow depicted in Fig. 3, namely the elements that correspond to a paver, a server, rollers, and auxiliary (additional) system users on site.

To provide roller operators with geo-referenced asphalt temperature of the deployed asphalt mat, an information system needs to obtain sensor readings of the mat's temperature along with locations of the construction equipment. For this purpose, we selected two different types of sensors: a temperature linescanner and differential GPS (DGPS). The linescanner is mounted behind the screed of the paver at the height of approximately three meters to continuously measure the asphalt temperature during asphalt paving (Fig. 6). Such non-intrusive installation allows to precisely document the surface temperature of the asphalt layer. We utilized a Raytek MP150 linescanner which is capable to document up to 150 measurement lines per second with 1024 discrete measurements points per line. In addition to temperature, the equipment

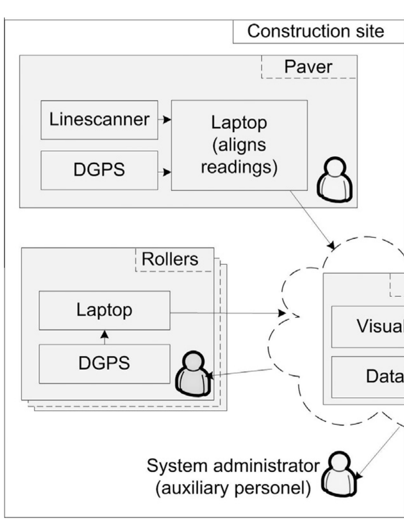

Fig. 5. Organization structure of an information system to track paving operations on site.

Fig. 6. Linescanner mounted behind a paver.

paths are documented using highly precise devices. For this study the field set-up included a Trimble SPS851 base station and two receivers (one located next to the linescanner at the paver and another on a compactor).

The obtained readings are processed and stored in different levels of detail according to the suggested framework. The roller's DGPS receiver documents (in its inner memory) the equipment locations in high level of detail using the manufacturer settings, specifically suitable for post-processing analysis. Then, the DGPS receiver reduces the sensor update rate to three Hz and transmits them to a laptop via Bluetooth. The laptop reduces the rate of the readings once again, now to the one Hz rate. These readings are displayed and stored in a specially developed Excel spreadsheet by means of a VBA (Visual Basic for Applications) program. To this extent, we incorporated the framework's functionality related to organizing extra storage of the collected data at a equipment. In other words, both readings in high and lower levels of detail were stored on the same equipment to ensure excessive data back-up, according to the design decisions made during the implementation of the illustrative information system. Then, the laptop sends the one Hz rate readings over the network to a server, which runs a centralized database. The changes of rate of paver's DGPS readings are similar, but the data processing additionally process temperature readings. The readings from the linescanner are initially documented in high level of detail using hardware-specific driver and software. Then, the linescanner readings were reduced from 1024 discrete measurements obtained at 150 Hz to 20 measurements at the rate of one Hz. As both location and temperature readings are reduced to a one Hz update rate, the readings can be aligned, stored, and sent to the server. As in the roller's case, we developed a specialized VBA program for the paver.

The server receives the readings from the paver and the roller, stores the data in a database, and processes them. Then, the geo-referenced temperature plots are calculated and visualized by using a large set of documented readings from the paver and the most recent location of the roller. To combine the temperature and location information from different sensors we developed a specialized data fusion approach. The computation and visualization modules were implemented using Matlab. To combine the GPS coordinates and temperature information the Matlab code generated a non-regular mesh where every node corresponds to a single temperature measurement. Though the details of the data fusion solution are out of the scope of this paper, it is necessary to note, that the core calculations are based on an automatically generated mesh. In the implemented information system, every obtained equipment location was combined with twenty temperature readings from the linescanner. Therefore, twenty new temperature points are introduced every second. As the sensor readings are accumulated during the paving project, a large amount of readings would require extensive processing power. For example, if a paver continuously spreads the asphalt mixture for five hours, the amount of the documented temperature spots — even after reducing the level of detail — can reach 360,000 points (20 points per second × 3600 s per hour × 5 h). Thus, with the current level of detail (20 readings per second) both tasks of creating a mesh and visualizing the temperature distribution is computational demanding and requires a robust database system together with a centralized high performance computing unit. Finally, the obtained visualizations (or the corresponding sets of data) can be transmitted back to equipment operators and to other external users. The highly precise readings can later be stored in a datawarehouse, according to the suggested framework.

In summary, the implemented solution illustrate the possible implementation of the proposed framework to collect information from different sensors and different locations, process it centrally and deliver it to different clients. Specifically, the documented path of the paver are combined at the server with the sensor readings that correspond to asphalt temperature after the screed of the paver. Later, the geo-referenced temperature plot are combined with the location of another navigation sensor to show its relative positioning in relation to the paved surface. As a result, an information originated at the paver can be transmitted to a roller. Meanwhile, as the highly precise sensor readings are stored at construction equipment, the readings are available for later scrupulous data analysis, quality assessment, and references during the maintenance phase of the construction project.

5.3. Applying the developed subsystems to track equipment in the field

After designing and implementing the framework-based solutions described above, the first author of the paper tested the two subsystems on asphalt paving projects conducted in the Netherlands.

The first subsystem was tested at several paving projects shortly described in Table 1. In particular, the described solution employed the remotely located server from a hosting provider that received readings from a smartphone via 3G connection. As the documented sensor readings were also stored in the phone's memory, they remained available for upload to a datawarehouse database.

The information system proved to be functional in the given conditions. The developed information system delivered the information about the estimate time of truck arrival to paver operators and to project managers, as well as stored the data for later processing. The system and the resulted visualizations were discussed with several operators and managers, who found the provided information valuable for performing their daily tasks. To this extent, the members of asphalting crews, interviewed during testing the system on site, suggested that such systems can support their operational and tactical decision making tasks.

The second information system was tested during a paving project near the city of Wijhe in The Netherlands. During the project about 300 tons of asphalt were paved and compacted by a construction team, formed by one paver and three compactors. The initial tests of the system incorporated GPS receiver and the processing unit located in the manager's car next to the constructed road. Further testing of temperature information delivery from the paver to other equipment included a highway paving project near the Dutch city of Leiden. This latter test was performed during two consequent days when two asphalt layers were constructed. Both layers were about 25 m wide and had a length of 500 m. The amount of asphalt mixture paved was about 1650 tons per day. On the first day construction activities lasted from 7.00 till 16.30 in the evening, and on the second day from 6.30 till 17.00. Again, the equipment movements and the surface temperature of the asphalt layer after the paver were documented, stored in sensors' inner memory, transmitted to the remote server, and visualized. Later, the highly precise readings from DGPS sensors were collected within a datawarehouse database and visualized. These visualizations were discussed during feedback sessions with equipment operators and managers involved into the corresponding projects according to the Process Quality improvement framework suggested by [44]. To this extent, highly precise sensor readings contributed to analysing previously conducted operations and formed the ground for strategic decisions about how to improve working practices.

Similarly to the first solution, the obtained close to real-time visualizations were discussed with equipment operators and construction managers who found the delivered information useful for their operational and tactical tasks. Therefore, we consider that the second subsystem is capable to track construction projects in real-time and, similarly to the first subsystem to track remotely located equipment, demonstrates the specifics of the framework.

In summary, the framework-based information systems demonstrated their ability to document highly precise data for post-process analyses and, according to the feedback from the operators and project managers, are able to support decision making of construction professionals in close to real-time rate. These cases validate that the framework can effectively guide the development of such information systems.

6. Discussion

The information systems developed on basis of the proposed framework demonstrated their ability to provide close to real-time visualizations to multiple users as well as storing highly detailed data for post-processing. The systems allowed to document and accumulate sensor readings with high levels of detail, process, and distribute location and geo-referenced temperature data from different equipment to multiple users in close to real-time rate in lower levels of detail. Additionally, after the construction projects were finished the collected data with high level of detail were transferred to a warehouse.

As the framework-originated systems deliver the functionality that was found useful by practitioners involved in tests, the framework proved to be an effective mean to guide development of such information systems to support operational and tactical decision making processes of construction specialists. The sensor readings with the high level of detail can later inform quality assurance tasks and scrupulous data analysis. Such analysis, targeted to find

Table 1
Characteristics of projects where the subsystem to track asphalt trucks was tested.

Location (area)	Short description	Mixture	Equipment	Mass of the paved mixture	Project duration
Gorinchem	Area near a hangar of ca. 40 × 60 m	AC 22 bind, 6 cm AC 16 surf, 5 cm	3 drum roller Tandem roller	940 tons bind 780 tons surf	7–16.30 h
Alkmaar	Road 7–8 m wide and ca. 800 m long	EME bind, 7 cm	Combi roller (steel drum front and tires rear) Tandem roller	Ca. 1200 tons	7-14 h

inferences between project activities and project performance, thus informs the strategic decision making by project planners and its scope unfolds further than tactical decision making of project managers. Ultimately, the combination of operational, tactical, and strategic decision making can lead to improvements in high quality outcomes of the ongoing and future construction projects.

As the conducted initial tests described in this paper were mainly oriented to demonstrate the applicability of the framework to support tactical and decision making of equipment operators and project managers, the outcomes of implemented systems were discussed with the construction personnel in free form. This approach is at variance with quantitative analysis of advantages correlated with specific implementations of the framework. Therefore, we see the instantiations of the framework as a proof-of-concept where the conducted tests aimed to evaluate their functionalities, rather than as examination of causal relations between variables related to testing particular implementations of the framework. Nevertheless, the discussed functionality of the developed information systems can directly be related to requirements to evaluate a specific system design, as described in [51]: fast communication, information sufficiency, and advantageous visualization. In particular, the first of the requirements was fulfilled by the proven systems ability to deliver close to real-time visualizations, while others can be related to the practitioners approval that the visualization can effectively support their needs.

The decision to additionally store the reduced and aligned readings locally (in addition to sending then to the server) depends on the design of a specific information system. For instance, such design decision can result in separating files to store different levels of detail and use a mapping or hashing system to retrieve the low level data from the high level information. Though using separate files can be memory intensive, the design decision can be based on the need to provide additional back-up of data.

Future research should investigate advantages related to specific operationalization of the framework as well as corresponding limitations, such as:

- Re-defining level of detail can reduce demands of the communication bandwidth and thus support tracking large amount of construction equipment at the same time. Moreover, the amount of information transfer from clients to a server can automatically be adjusted. For instance, if the bandwidth decreases, then the frequency of transferring sensor readings from clients to a server can automatically be reduced, but the data will still remain available in sensors' storages for future analysis.
- The centralized data storage and processing in real-time could allow to utilize some recent computing advantages, such as scalable computation power and storage capacity of the server. For instance, several additional computation nodes could automatically be activated if multiple construction projects might be tracked at the same time.

The latter advantages can be leveraged by utilizing cloud computing infrastructures. For example, the storage function can be supported by a cloud database, such as MongoDB or by adopting the MySQL solutions within the Amazon EC2 cloud computing platform. In a similar way, massive data processing can benefit from cloud computing, for example by utilizing specialized cloud interfaces, such as NCLab. Altogether, adopting cloud computing principles can benefit framework-based information systems because of on-demand network access to a shared pool of configurable computing resources. The five essential cloud computing characteristics (as outlined in [52]) can, according to our vision, be exploited as follows to support needs of a construction company to track construction processes based on the here presented framework:

- On-demand self-service. During the adoption of an information system within a company the need for increasing computing capabilities can be addressed directly by the company without disrupting the hosting providers.
- Broad network access to the data: mobile phones and tablets with thin clients can support professionals on-site in making operational and strategic decisions. The examples of such decisions include introducing additional trucks to transport construction material or altering the hauling route. At the same time, workstations with thick clients at the office can assist in computation-intensive analysis of the documented data.
- Resource pooling. All necessary resources (storage, processing, memory, and network bandwidth) are pooled dynamically by the service provider and are assigned according to the current demands of a construction company.
- Rapid elasticity. The computation capabilities can be increased if multiple construction projects might be tracked simultaneously.
- Measured service. The dynamic assessment of the utilized resources can support planning on how to utilize information systems according to the company-specific data processing demands.

We expect, that if cloud computing infrastructures will be widely adopted by major sensor manufacturers, the interoperability support between different tracking systems will improve. For example, though Topcon and Trimble tracking solutions can already upload the sensor readings to a cloud, currently there is no opportunity to combined the uploaded information in a centralized way, partially due to existing company-specific data formats. However, if communication and processing infrastructures of information systems would use a similar modular structure, as suggested by the framework, it could be possible to harmonize different formats due to the same underlying data collection and management principles.

In their current embodiments, we consider the described information system as merely illustrative examples of exploring the potential of the proposed framework for data collection and management with respect to construction projects activities, rather than final solutions. In this way, some limitations characterize the described systems. For example, some technical issues related to managing sensor networks and handling specific events, such as the introduction of a new sensor in the system (in other words, a new machine into the project), were intentionally left aside of the scope of the paper. These essential issues will need to be addressed at the moment the suggested framework will be operationalized into sophisticated information systems. To effectively handle the need to consider specific interactions of the new sensor with the existing ones, as well as interoperability and the system calibration issues, a potentially prominent solution will be to adopt a system design based on a service oriented architecture (SOA), such as proposed in [53]. According to the underlying concept of connecting loosely coupled services, systems designed in this way will naturally account for reliability, and scalability issues.

Also, the data processing algorithms can be improved, for instance the introduction of additional filtering or advanced data fusion solutions can benefit the systems [54]. Therefore, the developed processing methods were described in short and new data processing approaches are to be developed and described in details in future research. Besides, the implemented subsystems were oriented to support relatively small-scale construction projects, the system infrastructures were developed without using high-end resources. A server rented from a hosting provider was used within the first illustrative example, and a single-computer dedicated server was developed for the second information system. Additional limitations were introduced in the second example: an on-site processing unit was utilized and no long-rate communication channels were employed. Nevertheless, we anticipate the possibility to move the unit to an off-site location if a high-speed Internet access will become available on construction sites in the future.

Altogether, we see the proposed framework as a stepping stone from the specialized information systems that separately support either real-time or post-processing data analysis to a coherent system of data collection and management.

7. Conclusion

This paper proposed a framework for distributed data collection and management that can support operational, tactical, and strategic decision making of the specialized personnel involved in construction projects. The underlying framework's principles allow to track construction projects based on readings from on-site and off-site sensors that are connected to a central processing unit, accessible from arbitrary locations. The real-time data processing can be performed with decreased level of detail of the sensor readings, while all information is also preserved at multiple locations and stays available for later upload to a warehouse database for future scrupulous analysis.

To illustrate the framework's feasibility to follow construction equipment in real-time and document the sensor readings in different level of detail at different locations we proposed a dataflow for tracking asphalt paving operations as a specific example of construction activities. Then, we developed and tested two subsystems to illustrate equipment-specific elements of the dataflow. In particular, the solutions aim to provide additional information to paver and roller operators employed in asphalt paving projects in order to support them in making well-founded operational decision at a later point. All information stays available at a centralized server to assist construction managers in making operational and tactical decision. At the same time, the sensor readings are stored in high level of detail at construction equipment for further analysis. Such detailed data can then be used for scrupulous analysis after the project is completed. For instance, post-processing of the collected data may assist quality assessment tasks or help with finding inferences between different process-related factors and events that can negatively influence the construction productivity. In this way, sensor readings collected as suggested by the framework can potentially be useful not only to track, assess and analyse construction operations, but also to serve as reference during the maintenance stage.

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