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Collaborative Augmented Reality for increased efficiency and interactivity of infrastructure maintenance and inspection

FINAL REPORT

SMART BUILT ENVIRONMENT

Collaborative Augmented Reality for increased efficiency and interactivity of infrastructure maintenance and inspection

Final report

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Med stöd från

VINNOVA Sveriges innovationsmyndighet

Energimyndigheten

FORMAS

Strategiska innovations-program

Förord

Smart Built Environment är ett strategiskt innovationsprogram för hur samhälls-byggnadssektorn kan bidra till Sveriges resa mot att bli ett globalt föregångsland som realiserar de nya möjligheter som digitaliseringen för med sig. Smart Built Environment är ett av 17 strategiska innovationsprogram som har fått stöd inom ramen för Strategiska innovationsområden, en gemensam satsning mellan Vinnova, Energimyndigheten och Formas. Syftet med satsningen är att skapa förutsättningar för Sveriges internationella konkurrenskraft och bidra till hållbara lösningar på globala samhällsutmaningar.

Samhällsbyggnadssektorn är Sveriges enskilt största sektor som påverkar hela vår be-byggda miljö, men den är fragmenterad med många aktörer och processer. Att förändra samhällsbyggandet med digitaliseringen som drivkraft kräver därför samverkan mellan många olika aktörer. Smart Built Environment tar ett samlat grepp över de möjligheter som digitaliseringen innebär och blir en katalysator för spridningen av nya möjligheter och affärsmodeller.

Programmets mål är att till 2030 uppnå:

- 40 % minskad miljöpåverkan i ett livscykelperspektiv för nybyggnad och renovering
- 33 % minskning av total tid från planering till färdigställande för nybyggnad och renovering
- 33 % minskning av de totala byggkostnaderna
- flera nya värdekedjor och affärsmodeller baserade på livscykelperspektiv, plattformar samt nya konstellationer av aktörer

I programmet samverkar programparter från näringsliv, kommuner, myndigheter, bransch- och intresseorganisationer, institut och akademi. Tillsammans nyttiggör vi den kunskap som tas fram i programmet.

Collaborative Augmented Reality for increased efficiency and interactivity of infrastructure maintenance and inspection är ett av projekten som har genomförts i programmet. Det har letts av Rasmus Rempling och har genomförts i samverkan med NCC AB, WSP AB, Gothenburg University and The Swedish Transport Administration.

Sammanfattning

Besiktning och underhåll av transportinfrastruktur är idag i stor utsträckning baserat på manuella, analoga och fragmenterade processer, vilket är tidsödande, ineffektivt och kostsamt. Behovet av en digital uppgradering av gamla och ineffektiva besiktningsprotokoll och arbetsmetoder är därför mycket stort. Tillsammans med ledande industripartner arbetar Chalmers för att lösa denna utmaning, baserat på den senaste utvecklingen inom sensorteknik och IKT. Som en del av forskningskonceptet SensIT (Sensor driven cloud-based strategies for infrastructure management), arbetar vi med att utveckla en AR-plattform (förstärkt verklighet) för automatiserad besiktning och övervakning av infrastrukturer. Verktyget kommer att inkludera funktionalitet för att utforska, analysera och visualisera infrastrukturdata, såväl som funktionalitet för besiktning och annotering, vilket leder till stora effektivitetsvinster. Det föreslagna projektet fokuserar på behov och kravställning från slutanvändare på Trafikverket, genom att aktivt engagera våra partner i design och utvärdering av AR-plattformen. Detta kommer att radikalt förändra och effektivisera besiktning och underhåll av infrastrukturer. En digitalisering av hela informationskedjan, inklusive BIM/GIS, sensordata och simuleringsbaserad prediktion, leder till förenklade och effektiviserade arbetsmetoder.

Summary

Today, inspections of transport infrastructure and maintenance operations rely to a large extent on manual, analogue and fragmented processes which consequently make the current approach time consuming, inefficient and costly. A digital upgrade of the inspection protocols, methods, and workflows, which have not changed for decades, is urgently needed to increase the efficiency of on-site structural condition assessment. Together with industrial partners, Chalmers University is tackling this challenge by utilising the latest advancements in sensing technology together with the recent developments within the field of ICT. As part of the Chalmers research concept "Sensor driven cloud-based strategies for infrastructure management (SensIT)" we aim at developing a collaborative Augmented Reality (AR) tool for infrastructure inspection and maintenance. The tool will include functionalities to retrieve, analyse and visualise infrastructure data, as well as functionalities for on-site guided inspection and annotation, thereby greatly simplifying and optimizing the inspection process. The project will focus on the needs of end-users such as consultancies and the Swedish Transport Administration by actively engaging our partners in the design, evaluation and on-site testing of the AR tool. We believe that the here proposed integration of AR tools within a structural health monitoring framework has the potential to radically change the way inspections are done today. The digitisation of the entire information flow - BIM/GIS data, sensor data, in-situ simulation results, annotation, inspection history - will greatly reduce the time and costs of inspection processes and will guarantee a simplified and transparent workflow that even non-expert operators will be able to use.

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1 Introduction

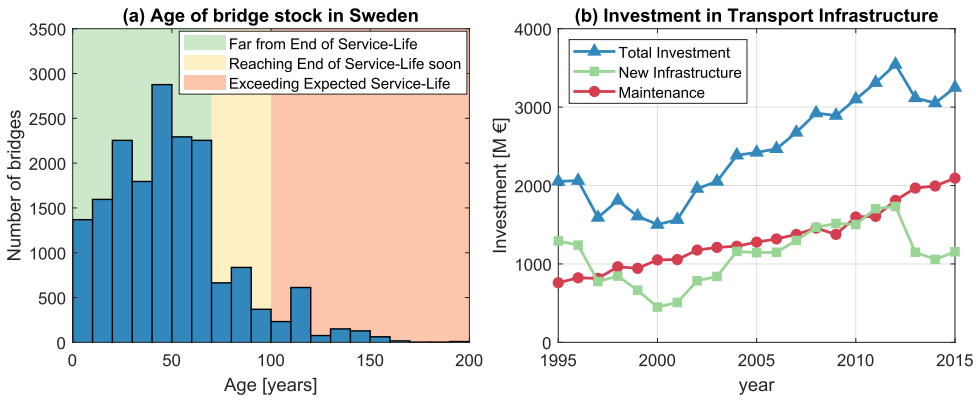
1.1 Background and state-of-the-art

1.1.1 Current challenges of infrastructure management

Maintaining the performance of the transport infrastructure is crucial to sustain all human activities, to guarantee the travelers safety and to ensure the welfare of society. However, the advanced age of many existing structures (see Fig. 1a) added to ongoing degradation processes and the ever-increasing level of demands in terms of traffic loads (Trafikverket 2017), represent an arduous challenge. Condition assessment and proper maintenance are imperative to ensure the integrity and serviceability of our infrastructure.

Moreover, maintenance operations are often disruptive and costly. In fact, inspection and maintenance operations constitute a major part of the recurrent costs of infrastructure, which represent a significant share of the annual budget in developed countries (see Fig. 1b). According to data reported by the OECD (OECD 2020), in 2015 Sweden invested nearly 2094 million euros in the preservation of the current transport network, with a high percentage of the expenditure devoted to inspection and maintenance operations of deteriorated structures. Moreover, the current trend shows that the investment in maintenance of the transport infrastructure has steadily increased over the last two decades.

Figure 1



(a) Age of the bridge stock in Sweden showing that approximately 20% of the bridges have already reached or will reach their service-life in the coming 30 years; (b) Yearly investment in the transport infrastructure in Sweden, according to data published by the OECD (OECD 2020).

Current infrastructure management strategies usually follow a time-based inspection philosophy where an operator performs an inspection of the structure, irrespective of its current condition, and collects data by hand (Omar and Nehdi 2018). Subsequently, those data are analysed and manually introduced into a database. The current inspection approach presents various important shortcomings:

1 Subjective: inspections are, in a primary stage, based solely on human visual assessment which limits their scope and makes them strongly dependent on the operator's experience.
2 Inefficient: inspections rely on journal records and photographs as documentation material, resulting in a tedious and time-consuming process with ineffective data handling.
3 Limited: data is only collected at a certain point in time with no regard for the events that take place in between consecutive inspections. Data is also limited to those areas where inspectors can have access.
4 Uncertain: recent research has shown that the limited data obtained from the inspection of corroding reinforced concrete bridges, i.e. surface cracks and cover spalling, correlates poorly with the actual degradation state of the structure (Tahershamsi et al. 2017).
5 Hazardous: inspections are often conducted in areas of difficult access, at heights or under adverse climatic conditions which entails safety risks for the operators.
6 Disruptive: Oftentimes inspections require the partial or full closure of the infrastructure for the safety of the inspectors, which becomes a burden to the users.

Thus, it becomes clear that a digital upgrade of the inspection protocols, methods and workflows is urgently needed in order to increase the reliability of structural condition assessment practices while reducing the social impact for the users and operators [Lundkvist et al. 2010].

1.1.2 The potential of digitalisation and Augmented Reality in the construction sector

The latest advancements in sensing technology together with the recent developments within the field of ICT (IoT, 5G networks, wireless connectivity) constitute a very promising platform for the development of novel structural health monitoring (SHM) systems enabling the collection of precise and accurate information about every event in the structure. Nevertheless, the information collected during on-site inspections is seen as complementary to the data provided by sensors (Agdas et al. 2015). Consequently, a digital upgrade of the inspection protocols and methods, which have not changed for decades, is urgently needed to address the identified issues and increase the efficiency of on-site infrastructure maintenance inspections.

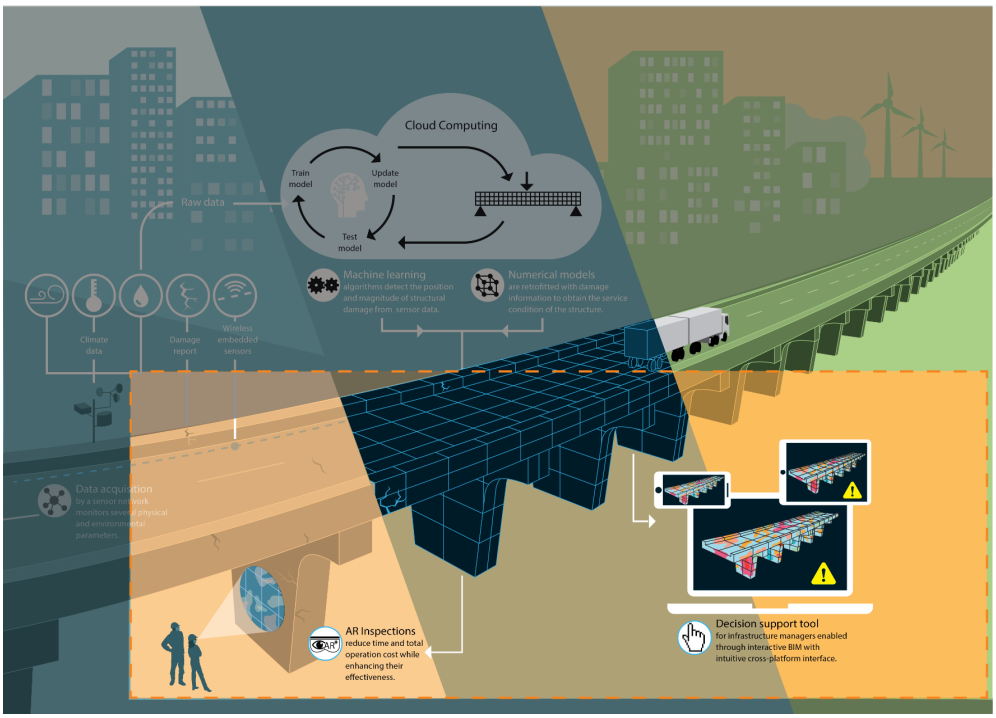
As the construction industry embraces technology innovation to address workforce challenges, augmented reality (AR) solutions have the potential to transform field operations for infrastructure inspectors by saving time, cutting costs and improving safety with intuitive equipment and connected intelligence (Barbosa et al. 2017, Schober and Hoff 2016). A computer aided system can accurately track user location as they move around large structures, such as a bridge or harbor. With instant access to an intuitively searchable digitized database, an inspector can accurately align and compare observed damage and faults with data from a Building Information Model (BIM).

Manual measurement processes become automated and more accurate. Capturing and documenting data become less time-consuming. The inspector can snap photos on demand or add and retrieve virtual notes that stick to a location which can be shared across multiple devices in real-time. Problematic areas become easier to recognize and serious concerns can be identified and notified instantly to decision-makers, thereby avoiding delayed and costly repairs as well as potential major structural failures. Information including important inspection notes, safety reports and adopted measures can be stored and later recalled for use in the management of future structures. A collaborative AR tool can change the paradigm of infrastructure inspection by providing efficiency and higher accuracy while saving time and money.

1.1.3 Current state-of-the-art

Together with industrial partners, Chalmers University of Technology developed an innovative concept, SensIT, that aims at bringing together several cutting-edge technologies to deliver a decision-support tool that enables owners and managers of the civil infrastructure to make timely and informed decisions to improve their asset management (Berrocal et al. 2018). The main idea behind SensIT, which is depicted in Fig. 2, is to apply the concept of Internet of Things (IoT) to the civil infrastructure by using wireless sensor networks in order to create a seamless flow of information that can be safely stored in, and be readily accessed from, the cloud.

Figure 2



Infographic illustrating the different elements of the project “Sensor-driven cloud-based strategy for infrastructure management (SensIT)” and how they are linked to each other. The area highlighted in orange indicates the focus of the current project.

By using specifically developed Artificial Intelligence (AI) algorithms and advanced numerical analyses (Karypidis et al. 2019), the sensor data can provide information about the health condition of the monitored structure and, more importantly, it may be used to predict its service life. A web-based open BIM tool designed with a user-friendly and intuitive interface is devised as a suitable platform for the retrieval and exchange of information, thereby enabling the communication of critical information to the operators in a quick and effective way.

During the recent last years, several initiatives similar to SensIT have started emerging in different countries, see e.g.:

- Sacertis, (http://www.iotty.it/sacertisbuildings), a spin-off company created from a consortium of universities in Italy.
- SISGES (Muñoz et al. 2018), a European research and development project carried out by consultancy companies and research institutes in Spain.
- SensCrete, (https://gtr.ukri.org/projects?ref=102829), a development project conducted by several industrial partners in the UK.
- Autori, (https://www.autori.fi/), an initiative from Finland that has received funding from the European Regional Development Fund.

At the same time, the construction industry is slowly but steadily entering the market of mobile applications. Over the past years, the use of AR through head-mounted devices (HMD) and hand-held devices (HHD) for building workflow has increased significantly. Moreover, the appearance of open AR development kits, has enabled many construction companies to incorporate augmented reality into their working processes. As of today, the use of AR in the construction industry has been studied and tested in several applications, mostly related to the construction of buildings and for the conceptual, design and construction phases.

Within that area, there are currently several examples of AR solutions that are already out there, including applications related to project planning, verification of reinforcement placement or tracking of changes during the building process:

- Verification of reinforcement: https://bit.ly/3S1L9n4
- Project planning: https://sitevision.trimble.com/building-construction/
- Tracking of building process: https://www.xyzreality.com/

Even though the potential of AR technologies in the Architecture, Engineering and Construction (AEC) field worldwide is undeniable, the need for relatively high up-front investments for implanting an AR system together with the low level of digitalization across the companies in the AEC field has hindered the mass implementation of AR in the construction sector.

According to experts (Dunston and Wang 2005, Ohta and Tamura 2014) another of the main obstacles for widespread endorsement of AR in industrial settings is the distinct natures of handheld (HHD) and head-mounted (HMD) devices. Both types of devices present shortcomings and benefits; thus neither can be considered the standard when it comes to real work environment applications. The ease of use of HHDs proves

inconvenient when moving forward, since users dislike holding their mobile devices at eye height for extended periods of time. Contrarily, a hands-free HMD implementation creates a much more comfortable user experience, but requires special (and usually expensive) equipment, provides much shorter battery life and lacks the on-board GSM network capabilities of a phone or a SIM card enabled tablet. A common problem to both devices in the construction inspection field, where safety is the number one concern, is the increased risk of accident that AR devices may entail due to users paying less attention to their surroundings. Conclusively, HMD and HHD serve different needs and both have a place in the AR user base, as long as the user experience provided is satisfactory.

On the other hand, the application of AR for the management of civil infrastructures that are already commissioned and in service remains, so far, largely unexplored. In particular, the use of AR for enhanced inspection and monitoring of large structures has not been feasible in the past due to several factors, among others, a combination of technical shortcomings and the lack of standardisation in the sector. However, with the advent of open-source mobile toolkits for AR and the continuous efforts of the sector for the standardization of BIM file formats, the cost of developing an AR application is becoming lower and the possibilities to expand the applications of AR are growing larger, which may enable small-to-medium businesses to start harvesting the benefits of AR construction.

1.2 Purpose, aim and goals

The overall purpose of the project is to make current Structural Health Monitoring practices more effective while boosting their time and cost efficiency by using cutting edge visualization tools and interaction design.

The specific aim is to develop a collaborative AR tool for infrastructure maintenance and inspection and to integrate the tool into the SensIT research concept as presented in Fig 2. The aim of the project can be divided into the following project goals:

1. **Development of a web-based decision-support tool**: The main objective is to develop the basic functionalities (including the ground backend framework, a web-based frontend that can illustrate imported BIM data, sensor information and simulation results) of the software. The most crucial aspect is to ensure: (i) a robust backend (ii) a clean and intuitive web-based interface, and (iii) efficient data handling of BIM, sensors and simulation output data.
2. **Development of AR inspection tool**: The main objective is to create the prototype of the AR application software. The initial prototype should then be connected to the backend, in order to be able to retrieve live data from both the IoT sensors and simulations and project them on the real 3D world. The most crucial aspect is to ensure: (i) correct visual alignment of projected data on the physical world, (ii) efficient connection of the clients to the backend, (iii) UI cleanness and user friendliness.
3. **Implementation of collaborative interaction design**: The main objective is to investigate how to extend the developed UI for multi-user on-site collaboration and enable two-way communication between the backend and the devices.

The goals are reached through transdisciplinary research at Chalmers and with external partners, where the domain knowledge represented by structural engineering researchers and the know-how from NCC, WSP and Trafikverket is combined with visualization and interaction design expertise of researchers at the division of Construction Management at Chalmers.

The developed tool must include functionalities for infrastructure analysis and monitoring, as well as functionality for on-site guided inspection, thereby greatly simplifying and optimizing monitoring and inspection by digitalisation. In the proposed project, the mentioned issues will be tackled with a user-centered approach, that focuses heavily on providing the needed user experience.

1.3 Limitations

The current project is limited to show the viability of the proposed solutions by developing a prototype of an AR inspection tool. The development of a full-fledge commercial application is outside the scope of this project.

1.4 Project organisation

1.4.1 Project team

The project team consists of 6 members:

- Rasmus Rempling, Chalmers Tekniska Högskola/NCC (project leader)
- Carlos G. Berrocal, Chalmers Tekniska Högskola/Thomas Concrete Group
- Ignasi Fernandez, Chalmers Tekniska Högskola
- Mattias Roupé, Chalmers Tekniska Högskola
- Mikael Johansson, Chalmers Tekniska Högskola
- Eric Knauss, Göteborgs Universitet

2 Theory and method

2.1 Sensing technology

As previously mentioned, one of the main problems of the current inspection and maintenance philosophy for the transport infrastructure is the time-consuming and disrupting nature of the operations which result in traffic interruptions and great costs for society. By implementing a structural health monitoring system relying on a distributed network of sensors to collect and transfer data regarding the real-time state of the structure, more objective and timely decisions could be made regarding the actuation methods to be applied on structures without the need of causing disruption to the infrastructure users. Therefore, sensors are critical elements in a structural health monitoring system, which must be chosen adequately to serve the intended purpose under the expected conditions and time frame.

Sensors can be classified based on many of their characteristics. In the following, some of these characteristics are introduced.

2.1.1 Classification of sensors

2.1.1.1 Wired and wireless

One of the main reasons preventing the widespread adoption of structural health monitoring systems in large structures is that traditional sensors are wired, i.e. a physical connection between the probe and the acquisition system in the form of a wire, cable or lead is required in order to collect the data and/or power the sensor. This fact has naturally hindered the deployment of large sensor networks due to both economical and practical reasons.

However, wireless technology is present in many fields today, including sensor technology, which has pushed forward again the idea of structural health monitoring systems. A wireless sensor is able to collect and send data to the acquisition unit without the need of a physical connection. The downside of wireless sensors is that they often require an antenna and a battery, which may result in larger sensors, limit their service life or restrict their location. Nevertheless, great advances have been made in the field of Micro Electro-Mechanical Sensors (MEMS), which have managed to incorporate all the necessary components in devices featuring dimensions similar to a coin [16].

2.1.1.2 Embeddable and external sensors

Another crucial aspect of sensors when considering SHM systems is their location in the structure. For the particular case of concrete infrastructure, sensors might be either embedded in the structure during the construction process or attached to the surface once the concrete has hardened. Today, most handheld monitoring equipment is based on techniques that measure a certain property from the surface of the structure. However, for sensors that are expected to remain at the same location for long periods, it might not be desirable to have them externally placed, since they could be damaged by external agents. Moreover, in the case of concrete structures, it might be of interest to determine certain properties by taking measurements from within, e.g., near the reinforcement. Conversely, the casting process and the high alkaline environment in the concrete are factors that might pose a threat to the integrity of the

sensors. Furthermore, in thick structures, embedded wireless sensors might have difficulties to send data at long distances due to signal attenuation through the material.

2.1.1.3 Active and passive

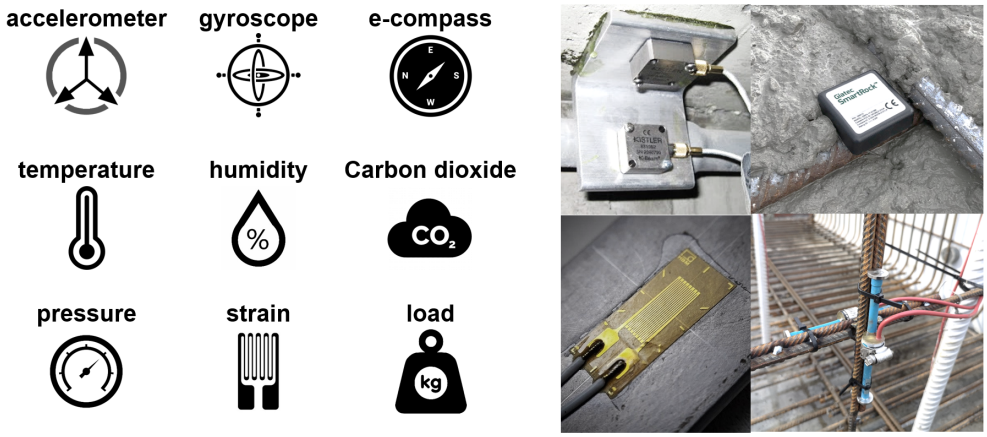
Sensors can also be classified as either active or passive depending on the way they collect data. Active sensors are those that actively collect and send data to the acquisition system at a certain time interval without the need of any external trigger. Active sensors must be powered, generally using an internal battery, which makes them more expensive, larger in size and limits their life span to the battery life. However, they usually possess internal memory and data can be both sent and received by the sensor, which can be used for instance to update the reading frequency of the sensor. Passive sensors, on the other hand, are sensors that remain dormant in the structure until the operator uses a reader or interrogator, to send a signal that activates the sensor and transmits the data. The main advantage of passive sensors is that they are usually smaller than active ones and they do not consume energy while the sensor is not being activated.

2.1.2 Measured Properties

Currently, there are sensors available to measure a very wide range of properties, from gyroscopes and accelerometers in our cell phones to heart rate monitors in wearables or pressure sensors in car tyres, see Fig. 3 (left). However, most of the existing sensors are designed for applications in the telecom, aerospace, medical or car industries. Even though some sensors have also been developed to meet the needs of the construction industry, the range of properties and alternatives is certainly more limited. For SHM application, the most commonly used sensors encompass the measurement of one or several of the following quantities:

- **Kinematic**: displacements, strains and accelerations
- **Dynamic**: vibrations and forces
- **Environmental**: temperature or relative humidity (RH).

Figure 3



Different types of properties that can be measured by commercially available sensors (left). Example of different types of sensor for concrete structure applications, from top

left to bottom right: accelerometer, wireless temperature sensor, foil strain gauge, embeddable strain gauge (right).

Traditional SHM systems have often relied on relatively large, electrically powered sensors, such as displacement transducers, inclinometers, accelerometers, etc. However, several research projects and technical reviews have shown that such sensors used in SHM applications present a series of drawbacks that hinder performing stable and reliable readings in the long term.

Many sensors can be easily affected by changes in external factors such as temperature, humidity, cable length, magnetic or electric fields, etc. For instance, most of the conventionally used corrosion monitoring systems for reinforced concrete structures rely on embeddable probes which can be affected by electromagnetic interference (EMI) caused by the proximity of electromagnetic field sources such as power lines, radio transmitters, cell phones, etc. Other sensors need to be powered, which requires the use of batteries, thus limiting the service life of the sensors or requiring a periodic change of the batteries. Nevertheless, the common problems that are often encountered with conventional sensors today will most likely be overcome in the future as new sensing technologies are developed for bridge monitoring and other large structure applications.

2.1.3 Distributed Optical Fibre Sensors (DOFS)

Over the last years, the use of optical fibre sensors in SHM for strain and temperature monitoring has gained popularity due to several reasons that makes them very appealing for SHM applications. Optical fibres sensors can be easily bonded or embedded into any structure thanks to their small dimensions (the core is often <200 µm in diameter), they are also lightweight which facilitates their transport and handling, they are chemically inert, corrosion resistant and they are able to operate over a wide range of temperatures, thus being suitable for a variety of applications. Moreover, unlike electrically powered sensors, optical fibres are not affected by EMI caused by nearby sources of electromagnetic fields. More importantly, one single optical fibre sensor can accommodate numerous sensing points along its length, thereby saving tremendous amounts of time and money in wiring and installation.

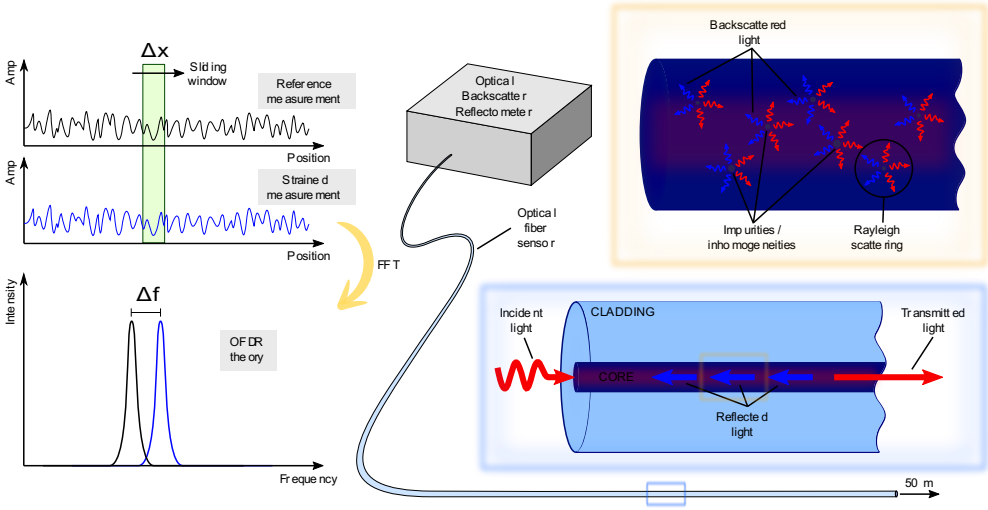
Among the different types of existing fibre optical measurement systems, those based on Fibre Bragg Grating (FBG) are the most widely used (Barrias et al., 2016). However, these systems present certain limitations with respect to spatial resolution (number of sensing points per fibre), hence they are regarded as discrete or quasi-distributed systems.

Distributed Optical Fibre Sensors (DOFS), on the other hand, measure the return loss of the emitted light caused by the backscattering that occurs along the fibre due to different phenomena. Accordingly, every segment in the fibre acts as a sensor, thereby achieving a significant improvement in spatial resolution compared to FBG systems. Three different scattering phenomena occur simultaneously which can be used to measure variations of temperature and/or strain along a fibre: Raman, Brillouin and Rayleigh scattering (Soga & Luo, 2018).

Rayleigh scattering analysis is based on Optical Frequency Domain Reflectometry (OFDR) where the Rayleigh scattering pattern occurring along the fibre is initially

measured and stored as a fingerprint or signature of the fibre in a reference state. The Rayleigh scattering profile is measured again when the fibre is subjected to mechanical strain or temperature perturbations and subsequently both data sets are divided into small segments that are Fourier transformed into the frequency domain. By performing a cross-correlation operation between the reference and perturbed states, a spectral shift in the correlation peak can be found which can be then calibrated to strain or temperature changes (Ding et al., 2018). The principle of OFDR of Rayleigh backscattering is illustrated in Fig. 4. Systems using Rayleigh backscattering based on OFDR are able to deliver unprecedented spatial resolutions, reaching down to the sub-millimetric scale, and thereby offering new possibilities for the development of damage detection systems.

Figure 4



Working principle of Rayleigh backscattering optical fiber sensors based on OFDR.

2.2 Real-time web-based condition monitoring

A promising approach to obtain a deeper insight into the behaviour and condition of our infrastructures is the use of the so-called “digital twins”. A digital twin is a virtual replica of a physical asset that combines numerical modelling and updated sensor data to simulate and visualize the behaviour of its physical counterpart in real-time.

The emergence of digital twins occurred in the early 2000s in the product design and manufacturing industries, where today are well-established tools to evaluate and optimize products and processes (Tao et al. 2019). In the field of Civil Engineering, the systematic adoption of Building Information Modelling (BIM) by the construction industry, enabling access to detailed 3D models of buildings and other infrastructure assets, as well as recent advancements in sensor technology, IoT, and cloud computing have also spurred significant research efforts aimed at exploring the development of digital twins in the context of the built environment.

Even though fully operational real-time digital twins may not be yet a reality for most buildings and infrastructure, some examples can be found in the literature where

researchers have combined the use of sensors, IoT, advanced data analysis and 3D modelling to develop applications that share all or parts of the main features of digital twins. Among these applications exist, to mention a few, monitoring of room occupancy, thermal comfort, or air quality in buildings (Dave et al. 2018, Natephra et al. 2017). Some research has also been directed towards the implementation of digital twins in the transport infrastructure, e.g., for the development of a smart road de-icing system for bridge decks (Chen et al. 2014) or for aggregating and mapping multiple-source results from non-destructive testing of bridges (Kim et al. 2016). For Structural Health Monitoring (SHM), some studies have presented applications for seismic activity (Kaya et al. 2017) and for the dynamic behaviour of buildings (Chang et al. 2018). One of the most advanced applications of a digital twin to date is, perhaps, the assessment of fatigue in marine oil and gas platform structures made of steel by Ramboll (Tygesen et al. 2018). Nevertheless, the development of digital twins for the structural assessment of buildings and infrastructure is still in a very early stage.

In this study, our own concept of digital twin is developed to improve the current asset management strategies for reinforced concrete infrastructure such as bridges, tunnels, harbors, dams, etc. The concept relies on distributed optical fiber sensors (DOFS) for the collection of data, cloud computing, and a web-based application as the user interface for the retrieval and visualization of results. The developed concept has the potential to deliver critical information in a clear and straightforward manner in near-real time, which could be valuable as a decision-making tool for infrastructure owners and inspectors.

The development of a digital twin concept requires the integration of multiple technologies as well as cross-disciplinary knowledge. Today's information and communication technologies (ICT) are undoubtedly one of the core areas required to create a robust and seamless data flow that enables a continuous update of the sensor data. Data analysis as well as in-depth knowledge of the application field, structural engineering in this case, are equally important areas to deliver meaningful results.

The system's architecture devised in the present work can be divided into three main modules: Monitoring Module, Analysis Module and Interface Module.

The Monitoring Module comprises the elements required to acquire measurements of physical properties of the structure, namely the sensors and the interrogator, as well as the devices used to enable remote access to the data, i.e., a gateway or router and a server. All the elements in the Monitoring Module must be physically placed at the location of the structure being monitored. Conversely, the elements in the two remaining modules are a set of cloud resources that may be located anywhere in the world with a reliable internet connection.

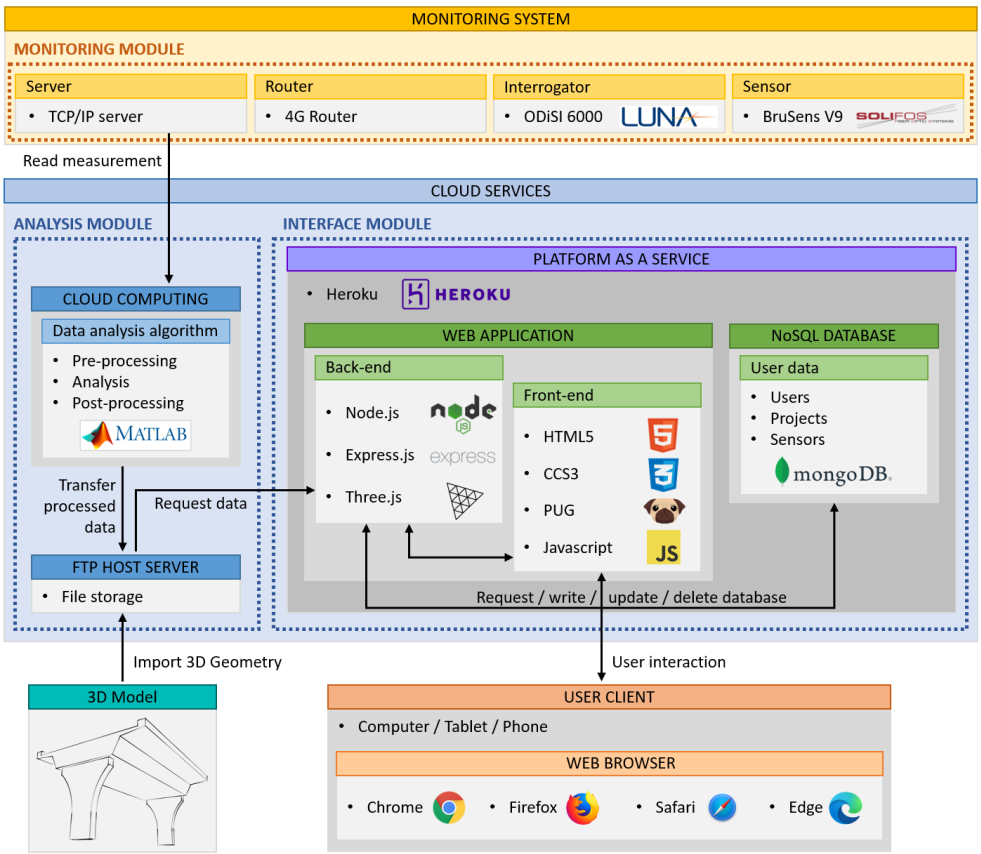
The Analysis Module includes a computer or cluster of computers with specifically developed algorithms used to pre-process, analyse and post-process the sensor data received from the Monitoring Module. Thereafter, both the pre-processed and post-processed results are transferred and stored in an FTP server from where data can be served to an external client on demand.

The Interface Module includes the elements that enable users to access and interact with the digital twin. In this study, a web application has been developed using different open-source frameworks and libraries to implement the front-end and back-

end. Moreover, a non-relational database was chosen to store data created in the web app, such as projects, users or sensor information. The application is hosted in Heroku, a Platform as a Service (PaaS), that offers multiple features for deploying and running web applications.

It should be noted that the FTP server used to store the monitoring data is also used to store files containing the 3D geometry of the structure, i.e., the 3D model, which can be uploaded via the Interface Module. However, 3D models need to be created using dedicated third-party software outside of the application. The system's architecture showing the interconnection between the three modules and its components is schematically depicted in Fig. 5.

Figure 5



Schematic representation of the web-based asset management system's architecture.

2.3 Data analysis and visualization – Case study of a reinforced concrete beam

The applicability of the system described in the previous section is investigated through a case study of a reinforced concrete beam subjected to flexural loading in the structural engineering lab at Chalmers University of Technology. The case study is used to investigate the ability of the system to identify and locate the formation of

cracks as well as to determine the beam deflection and the width of identified cracks. In the following, detailed information about the most relevant aspects of the experimental programme is presented.

2.3.1 Beam geometry, loading and sensor deployment

The specimen used in the case study was a reinforced concrete beam with a total length of 3000 mm and a rectangular cross-section of 200×250 mm. The longitudinal reinforcement consisted of three Ø16 mm rebar at the bottom and two Ø10 mm at the top. Moreover, six Ø8 mm closed-loop stirrups with a 200 mm spacing were placed on either side of the beam. The reinforcement was made of normal ductility carbon-steel (B500B) with a nominal characteristic yield strength of 500 MPa. Plastic spacers were placed between the stirrups and the bottom and lateral sides of the form to ensure a clear concrete cover of 25 mm. The ends of the bottom bars were bent upwards to improve the anchorage.

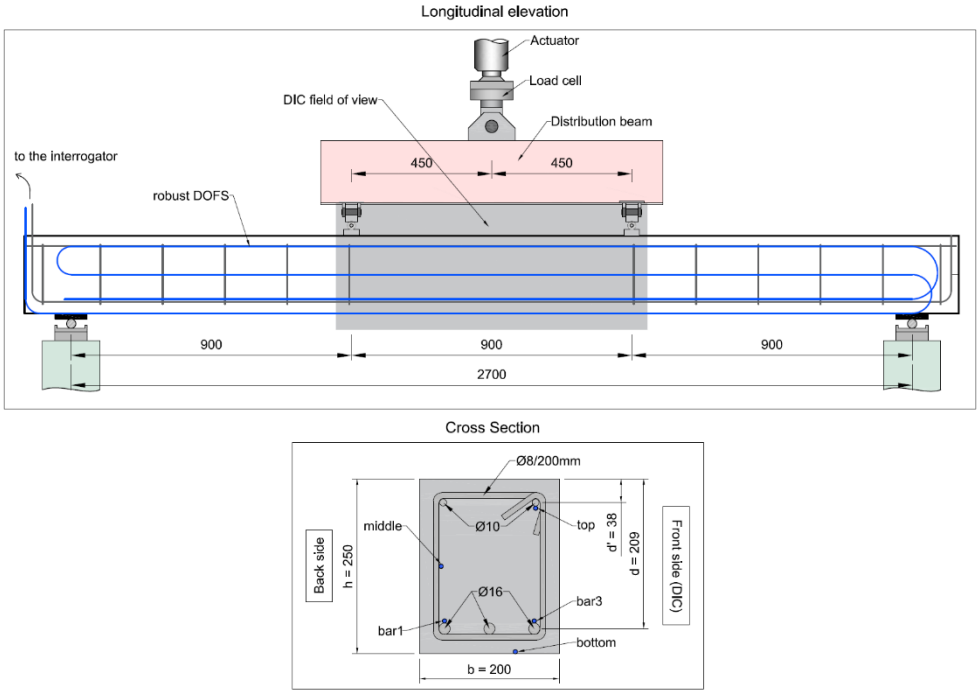
The beam was simply supported on rollers and loaded under four-point bending. The clear span between the centre of the supports was equal to 2700 mm. The load was introduced using a single actuator acting on the middle of a steel distribution beam equipped with two movable bearing supports symmetrically placed at 900 mm from the rollers, which divided the beam in three equal spans of 900 mm. Loading was applied under displacement control using a closed-loop feedback system at a displacement rate of 2.5 mm/min. Two load cycles were performed reaching a maximum total load of 60 kN and unloading down to 5 kN total load.

The DOFS used in this study was the BRUsens V9 cable from Solifos, featuring an inner steel tube and an external rugged polyamide cladding, which can be easily handled and deployed without the risk of rupture, even when embedded in concrete.

A single DOFS was used to monitor longitudinal strains in the free span between the supports at five different positions in the cross-section of the beam: above the two-outer tensile rebars (bar 1 and bar 3); beneath one of the compressive rebars (top); at mid-height (middle); and at the bottom surface of the beam (bottom). The DOFS was installed by fixing it with electric tape either to the longitudinal rebar, the stirrups or the base of the formwork.

DIC was used on one of the lateral sides of the beams to measure the full-field deformation and surface strains. For that purpose, the commercially available system from GOM, ARAMIS®, consisting of an adjustable stereo-camera setup was employed with a sampling rate of one picture per second. The results of the DIC were used as reference to assess the accuracy of the DOFS in determining the position and width of the cracks as well as the beam's deflection. Fig. 6 shows the geometry and reinforcement layout of the tested beam as well as the loading setup and DOFS configuration.

Figure 6



Geometry, loading setup and DOFS installation configuration for the RC beam specimen.

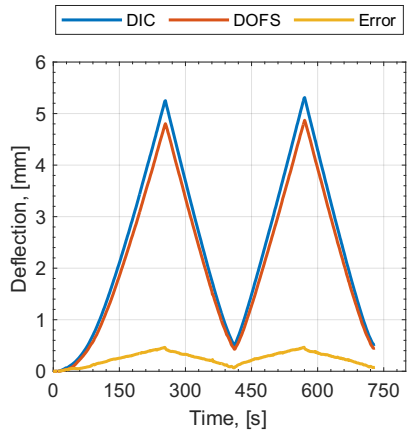
2.3.2 Analysis of sensor data

In most cases, raw sensor data do not provide useful information that can be directly interpreted by inspectors to make informed decisions. Therefore, the collected data must be processed and analysed to reduce data volume and increase data value. Data analysis can take multiple dimensions from simple analytical equations to complex numerical models, or even deep learning algorithms. For this concept, two well-stablished analytical equations grounded on classical beam theory and analysis of reinforced concrete members are adopted to analyse the tested beam.

Based on Euler-Bernoulli beam theory, the curvature distribution of a beam can be obtained by deriving two times the deflection with respect to the spatial coordinate along the beam axis. Consequently, a method has been implemented to back-calculate the beam deflections based on curvature distributions determined as the ratio between the difference of strains measured by two DOFS at different heights and their separation. By integrating the curvatures twice and applying the right boundary conditions, i.e., zero deflection at the supports, the deflections can then be successfully calculated.

The evolution of the maximum deflection calculated based on the DOFS measurements is compared in Fig. 9 to the maximum deflection measured by the DIC system for the entire loading procedure, where the error determined as the difference between DIC and DOFS measurements is also included.

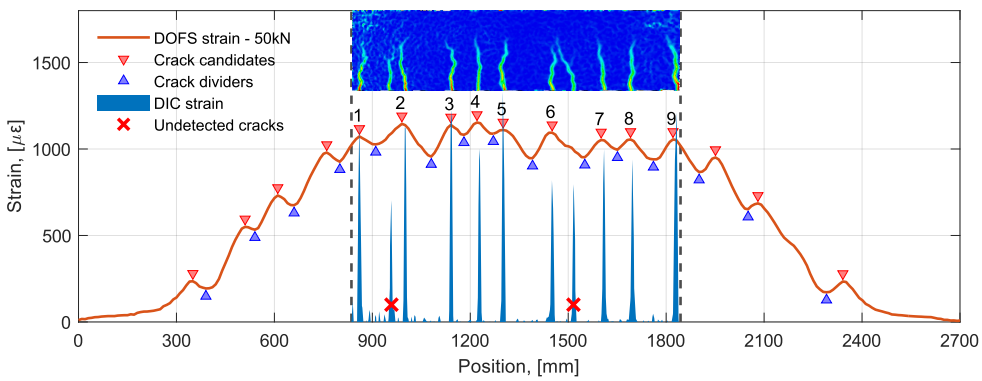
Figure 7



Comparison of beam deflections computed by DOFS strains and measured by DIC.

It has been previously shown that the existence of cracks is evidenced in the strain measurements of DOFS embedded in concrete by the presence of strain concentration peaks. Fig. 8 shows the strain profile in bar3 for a load level of 50 kN, where the locations of the crack candidates, i.e., those corresponding to strain peaks, have been identified. In the same figure, a picture of the 2D strain field computed by the DIC has been added as an overlay to show the actual crack pattern on the concrete surface. Additionally, the (re-scaled) surface strains along a horizontal line at the height of the tensile reinforcement, obtained from the DIC, have been drawn in the same plot to facilitate the comparison of the crack locations.

Figure 8



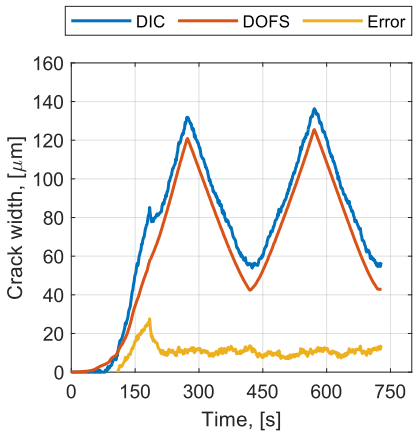
Determination of crack location based on DOFS and comparison with crack pattern from DIC.

Figure 5 reveals the existence of 11 distinct cracks on the concrete surface based on the DIC, whereas only 9 crack candidates could be identified within the same region by

the DOFS. Out of the 9 crack candidates, 7 were successfully detected as individual cracks, the location of which agreed with the DIC. The remaining two crack candidates, namely 2 and 6, corresponded to two individual cracks each, for which the DOFS strain measurements displayed a convoluted strain peak instead of two distinct peaks. The gradual merging of the strain peaks is likely due to the progressive deterioration of the steel-concrete bond with increasing load. This observation suggests that crack detection should be performed as a recurrent process taking the load history into account.

Subsequent to crack detection, the estimation of the crack width is addressed. A method proposed by the authors in (Berrocal et al. 2020), which is based on the mechanical models included in current structural design codes, is used in this study. The principle behind those models is that the width of a crack equals the relative displacement between the reinforcement and the surrounding concrete occurring within a certain region at each side of the crack due to imperfect bond between both materials. Assuming the fulfilment of certain conditions, the crack width can be estimated as the integral of the steel strains in the vicinity of the detected crack location, see (Berrocal et al. 2020) for further details. Based on this method, the crack width evolution for crack number 5 (cf. Fig. 8) is compared to the crack width measured by the DIC in Fig. 9, together with the error computed as the difference between DIC and DOFS.

Figure 9



Comparison of crack width computed by DOFS strains and measured by DIC.

As observed, the proposed method can be effectively used to estimate the crack width of individual cracks provided those are correctly identified and isolated by the DOFS. The method shows slightly higher errors during the crack formation stage, but the error stabilized after the first load cycle for a value below 0.02 mm. Nevertheless, the accuracy of the method for larger crack widths remains to be further investigated.

2.3.3 Data post-processing for improved visualization

For SHM systems to be of practical use, the analysed data must be conveyed to engineers and decision makers in a clear and accessible way. In the case of crack monitoring in RC structures, the potentially large number of existing cracks can pose a challenge when delivering critical information.

One of the most straightforward and intuitive ways to present massive amounts of information is through contour plots, sometimes also referred to as heat maps, similar to those often used in the post-processing of finite element analyses (FEA). Therefore, in this work the possibility of post-processing the monitoring data from the DOFS in an analogous way as in FEA in order to produce contour plots has been explored.

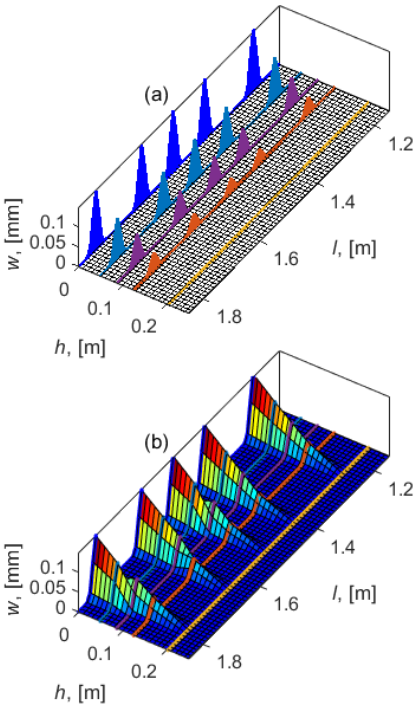
The approach developed in this work requires that DOFS measurements are available at two or more different levels, or in this case heights of the beam, where the greater number of levels will produce more accurate contour plots. The main idea is to transform the strain profiles into crack profiles, which hold the relevant information about all the cracks, i.e., their position and width. This is achieved through "crack functions" the value of which is zero everywhere except in the vicinity of the cracks, where they present a peak of value equal the width of each crack.

These crack profiles are then superimposed onto a mesh representing the surface of the beam, each crack profile at its corresponding height. The nodes of the mesh serve as the query points where the known data points in the crack functions are used to feed an interpolation function, whereas the elements of the mesh act as the canvas where the interpolated results can be drawn to generate the contour plots. Fig. 10a shows the superposition of four crack profiles onto a structured mesh grid with 1×1 cm square-elements for the central part of a beam.

A scattered interpolant is then used to create a 2D linear interpolation between the known data points (the crack profiles), and the query points at the nodes of the mesh. The scalar field resulting from the 2D linear interpolation which is shown in Fig. 10b as a surface plot, can be then flattened to create the targeted contour plot where the colour scale indicates the magnitude of the crack width. Further information about this procedure can be found in (Berrocal et al. 2021).

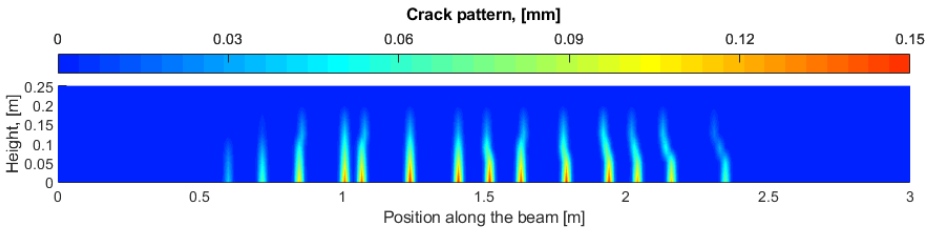
The crack contour plot obtained after completing the entire post-processing is shown in Fig. 11. As observed, the result of the described procedure provides a quick and straightforward way to read critical information about the cracking condition of RC elements. Furthermore, an additional advantage of this type of data post-processing is that it can be readily used in combination with 3D objects, either a 3D model of a digital twin or together with augmented reality on a real structure.

Figure 10



Comparison of crack width computed by DOFS strains and measured by DIC.

Figure 11



Comparison of crack width computed by DOFS strains and measured by DIC.

2.4 Augmented reality

Recent years have seen an increased interest in Augment Reality (AR) for use within construction, mainly driven by new hardware, such as Microsoft Hololens, as well as availability of feature-rich AR frameworks for mobile phones and tablets, such as ARKit (Apple) and ARCore (Google). These systems use camera-based simultaneous localization and mapping (SLAM) algorithms to build a (simplified) internal 3D representation of the environment where virtual objects can be placed, such as placing a virtual chair on a physical floor. Unfortunately, the Hololens is still a rather expensive device, and this project therefore opted for a hand-held device solution using a mobile phone.

There has also been a recent effort to bring AR to the web through a new Web-based AR framework called WebXR. Although it is still only available on Android systems (using ARCore in the background), it is expected to be available also on Apple devices in the near future. By using a web-based interface it is possible to support many more devices with a single source code. WebXR has most of the ARCore features and uses WebGL for 3D-rendering.

Therefore, as with the SensIT Manager, a web-based solution using WebXR was chosen also for the AR-tool. Thanks to this, it was possible to (re-)use the same web-rendering technology, Three.js, and 3D-file and data-formats. The main challenge with the AR part of this project was how to detect and align a real element, in this case the beam of the case study, with its virtual representation in order to present and augment the various sensor data. In order to better explain that journey some general AR-concepts are first introduced.

Anchors. Modern AR systems, such as WebXR, use an (mainly image-based) technique called simultaneous localization and mapping (SLAM) to construct an internal 3D representation of the environment. This also means that the system gets a better and better understanding of the environment over time, which has introduced the need for something called anchors. Instead of a fixed position in space, anchors provide virtual positions in relation to physical locations. As an example, an object might be anchored to a floor surface, and in such a case the position of the object will be updated if the AR-system gets a different understanding of the floor level. That is, relation between physical and virtual object are prioritized before absolute positions in space. Without anchoring, the object might instead appear “floating” above the floor (i.e. if the system gets new knowledge about the floor).

Image and marker tracking. WebXR provides functionality to track images. These can be general images or more typically “markers”, like a QR code. The images are first registered with the WebXR session together with an approximate world-space size (physical size of the printout). During the session, WebXR will then provide information if any of the images are recognized or detected, together with a position and orientation. The tracked origin is the centre point of the image and the local X and Y axis align with the horizontal and vertical edge of the image. That is, if a printout of an image is placed slightly tilted, a tilted orientation will be reported. Also, as part of the ARCore toolkit (which is the underlying WebXR toolkit on Android systems) a “scoring software” is provided which will rate an image depending on how suitable it is for image recognition and tracking. For instance, typical QR code images naturally get a high score.

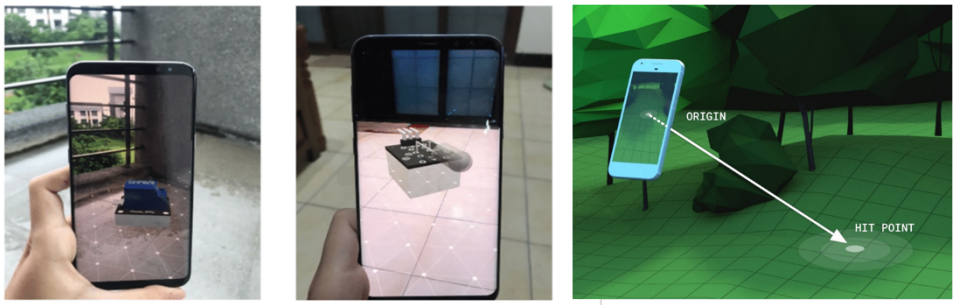
Alignment. Placement and alignment of virtual objects can be done in several different ways. The easiest way to control where a virtual object should be placed is by using a “marker”, such as an image printout placed on a table, for instance. The WebXR session will then detect and track this image and report a position in 3D-space where a virtual object should be positioned and rendered, see Fig. 12.

Figure 12

Examples of marker-based AR to aid positioning of virtual objects.

The SLAM algorithm in WebXR mainly detects large planar surfaces, such as floors and walls, and it is also possible to perform a “hit-test” against these in order to find a position on the floor, for instance, as seen in Fig. 13. This functionality is reflected in many existing (consumer) AR applications where it is possible to position, i.e., anchor a sofa or chair on the floor in a room.

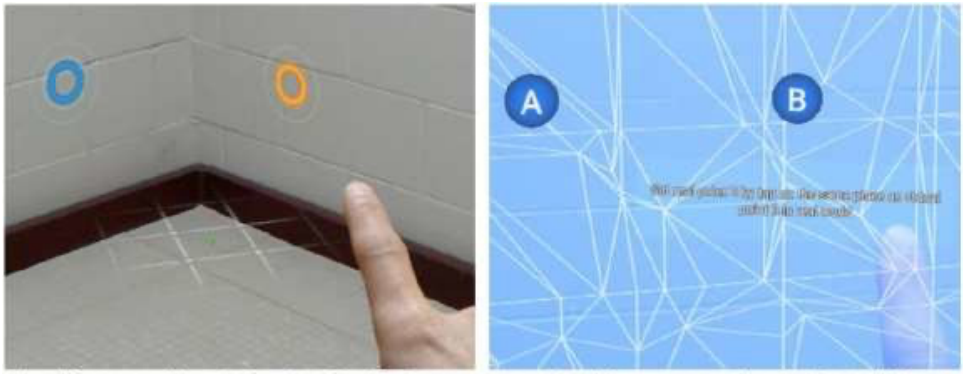
Figure 13



Hit-testing in WebXR will return the underlying plane (surface).

For more complex models, commercial BIM-AR viewers use either marker-based alignment, where markers are placed at positions that correspond exactly to positions in the BIM, or on markerless solutions. The markerless approaches take advantage of large plane detection but typically also require some manual input or interaction. The 3D-model, i.e. BIM, is often correctly aligned horizontally (i.e. “on the floor”) automatically, but then has to be manually rotated and translated by the user in order to correctly align with the walls, etc. However, in some systems the user identifies instead two walls and a floor, and then their counterparts in the real world Fig. 14. This alignment can be done a bit more automatically, by using a corner inside a building as reference. In the software a user can first indicate the corner in a 2D or 3D-view and then position the mobile phone towards the same real-world corner and let the AR system detect the three planes in the corner.

Figure 14



Identify two walls and floor in Trimble Connect Identify any two points in MR Builder

Examples of two- and three-point alignment in commercial BIM-AR viewers.

3 Results and dicussion

3.1 Decision support tool – Asset management portal

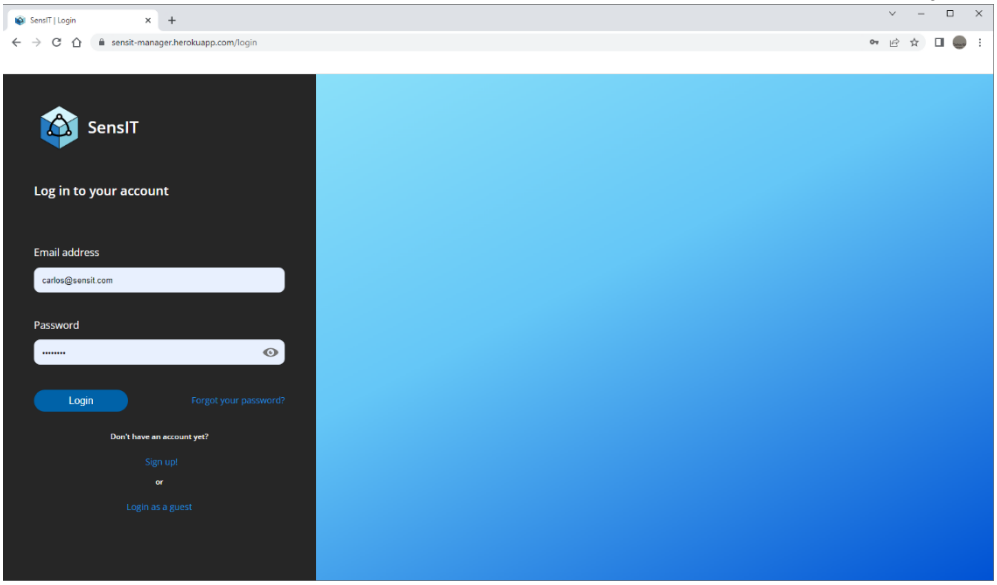
Using the system architecture described in Section 2.2, an online web application, the SensIT Manager, was developed and published, which can be accessed through the following link (https://sensit-manager.herokuapp.com).

One of the main advantages of the application is that it does not require downloading or installing any additional software or plugin in the user's computer. Moreover, the application is compatible with most modern web browsers, and it has been developed (albeit not optimized) to be cross-platform so that users can access it from their smart phones, tablets, laptops and desktop computers provided a stable internet connection is available.

The SensIT Manager has been envisioned as a collaborative space where different stakeholders, such as contractors, operators and owners, could meet and coordinate. Currently, app users can create new projects and decide whether they want to make them public so that everyone can have access to the monitoring data, or they want to keep the project private and share it only with a few people by sending an invitation to other registered users.

When a user navigates to the web app, the user is redirected to the sign-up/login page (see Fig. 15). In this page, new visitors have the possibility to sign up and set up a new user profile or access as guests whereas registered users can access their profile by logging into the web app using their e-mail address and password. The app also includes the possibility to restore a user's password.

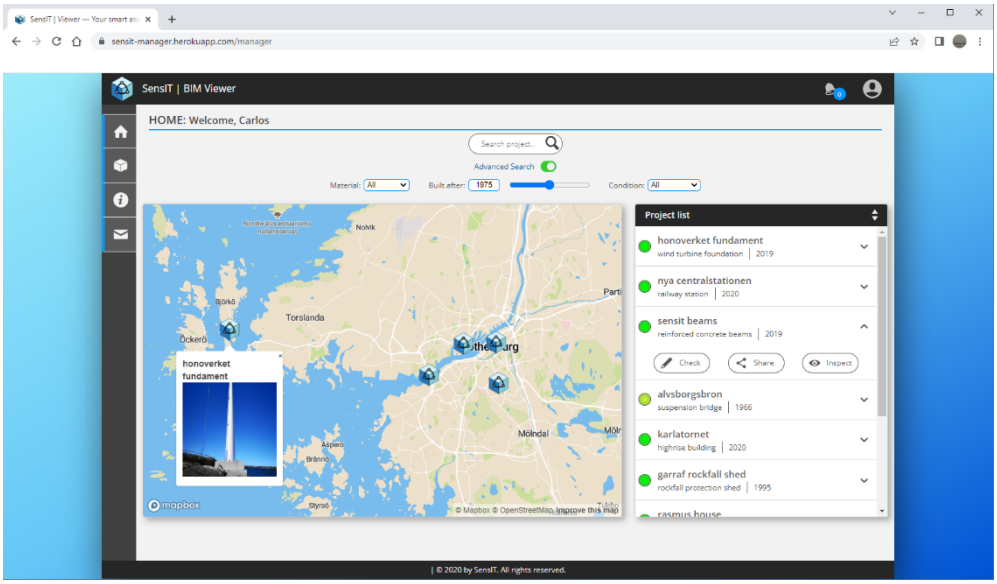
Figure 15



Landing page of the SensIT Manager web app.

Once the user has logged in or signed up, the home page is shown (see Fig. 16). In this page, the list of currently available projects is shown together with a map displaying the location of each project. Feature-wise, the SensIT Manager app is provided with basic search and filtering functionalities, which include searching by name and filtering by main construction material, year of construction or current condition of the structure. Similarly, from the home page the users access the lateral menu where they can choose, e.g., to create new projects or contact the SensIT team via an online form. Similarly, in the top navigation bar, the users can find the notification menu where they can manage the invitations from other users, and they can access the user menu to update their profile or change the password.

Figure 16



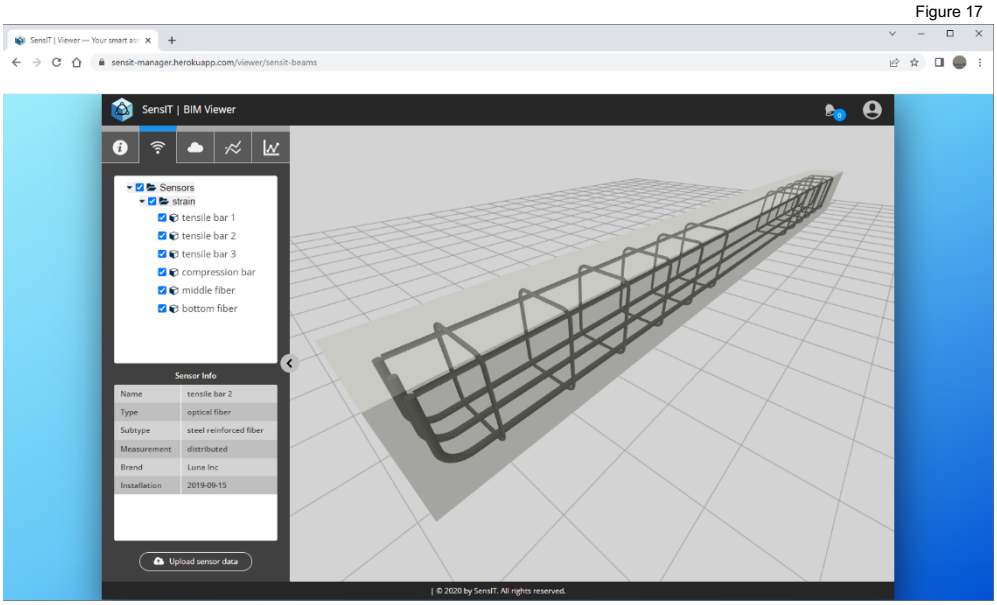
Home page of the SensIT Manager web app.

When one of the projects in the project list is selected, a dropdown menu unfolds revealing several options. One of the options is a button to share the project, which displays a text field where the user can search for the name of other users and select the recipient of the invitation from a list. A second option allows the user to access the project information page, where general information about the project is displayed. Although not yet implemented, in the same page, the users should be able to find a summary of the condition information, i.e., statistics about the evolution of the functional requirements. Similarly, a space is intended for inspectors to upload information regarding on-site inspections, whether photographic material or journal notes, so that remarks discovered during inspections can be accounted for in the app.

A third option in the project menu redirects the user to a project inspection page where 3D models can be seamlessly rendered in the browser using modern graphic libraries (BIM viewer). The first time that a user accesses the inspection page of a project, a dialog box is shown offering the user the possibility to upload a 3D model of the structure. If the model has been previously uploaded, then it is visualized upon

loading of the page. Fig. 17 shows the 3D model of the reinforced concrete beam used for the case study described in Section 2.3.

Figure 17

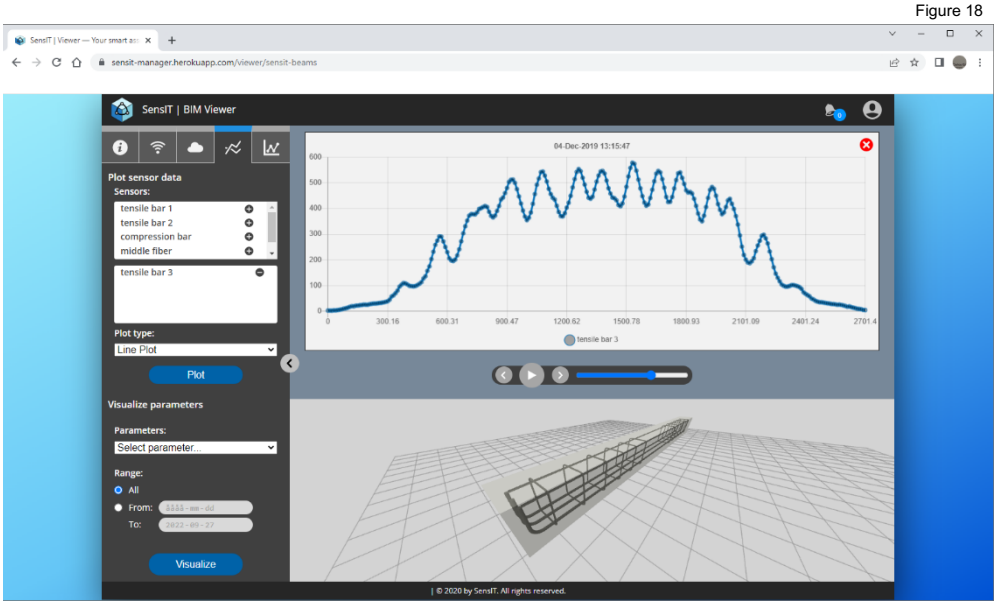


Project inspection page of the SensIT Manager web app for the cast study beam.

The project inspection page provides a powerful yet intuitive interface for quick and effective communication of critical information. A single tab menu guides the user through the different features of the inspection page. The first tab displays geometrical data from the uploaded 3D model. The second tab displays information about the sensors, which the user needs to upload in a separate JSON format file. The third tab allows users to download raw sensor data in common text format for further analysis in the desired software of choice. The fourth tab is the visualization tool where both raw sensor data and post-processed data can be checked. Finally, the fifth tab, currently under development, is meant to hold predictive functionalities to perform a prognosis of the structure's condition.

Among the different functionalities, data visualization is central to the SensIT Manager app. As previously mentioned, the visualization tab enables users to inspect raw sensor data by selecting the desired sensor from a list. Moreover, users can examine sensor data for the entire time history (or part of it) of each individual sensors by either dragging a scroll box along a horizontal scrollbar or by pushing a play button that enables dynamic visualization of the data (see Fig. 18). This feature can be especially advantageous to find long-term correlations between external events and the behaviour of the monitored structure.

Figure 18

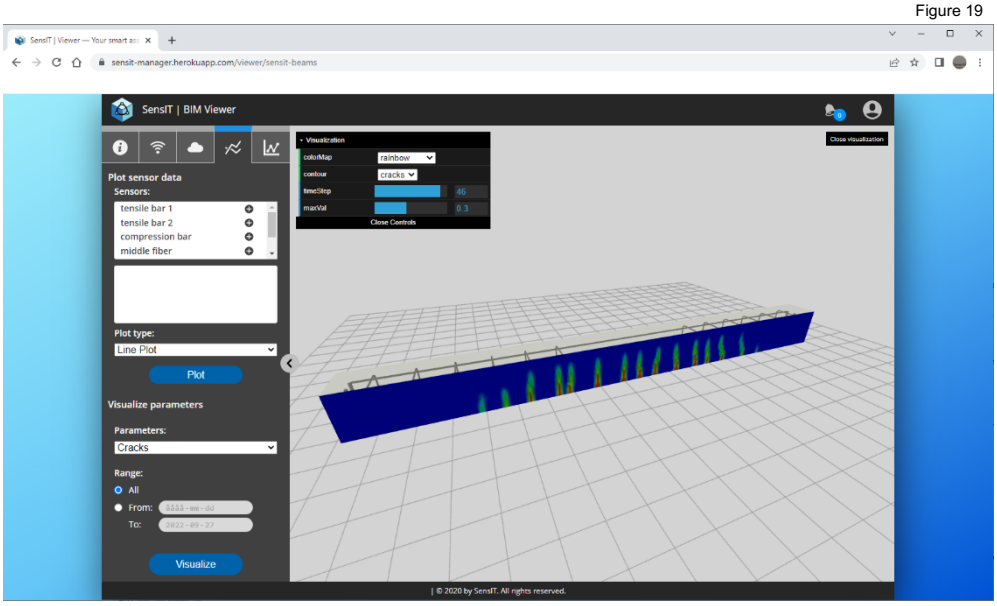


Inspection of raw sensor data in the project inspection page of the SensIT Manager web app for the cast study beam.

Finally, the contour plots generated according to the methodology described in Section 2.3.3 can be visualized directly onto the surface of the 3D model to provide additional value to the monitoring data (see Fig. 19). This way of visualizing data is not only intuitive and straightforward, but it also enables users to pinpoint the probable regions with more severe damage and correlate them with the geometry of the structure. When the user chooses to visualize contour plots, an auxiliary menu is displayed with several additional functions.

The auxiliary menu offers the user the possibility to, for instance, change the colormap used to draw the contour plots or easily switch between different magnitudes, e.g., strains, deflections, crack width, etc. Similar to the visualization of the raw sensor data, the user can also navigate through the data history by scrolling along a bar. Furthermore, to aid the detection of damage at different scales, users can also change the upper limit of the colour scale in order to highlight smaller magnitudes.

Figure 19



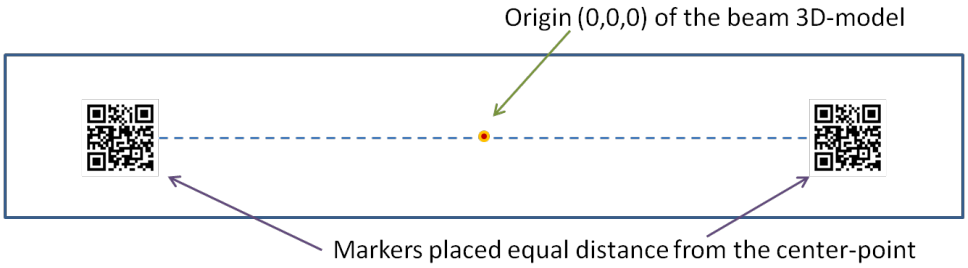
Inspection of contour plots in the project inspection page of the SensIT Manager web app for the cast study beam.

3.2 The SensIT AR inspection tool prototype

Although a markerless AR solution would be the easiest choice from an end-user perspective, existing approaches are not yet suitable for arbitrary objects, like the beam in Fig. 17, mainly as it is not guaranteed to provide equally trackable and stable large planar surfaces as a floor or a wall.

Because of this, a marker-based solution was used instead. As illustrated in Figure 20, it requires two markers to be placed equally apart from the edges of the beam, so that a mid-point between the markers identifies the centre of the beam. Even if theoretically a single marker would also work well, in practice it would be more sensitive to any tilting of the images and therefore two markers were preferred for the initial AR prototype. Hence, once the two markers are identified, the virtual beam can be positioned at the real-world origin.

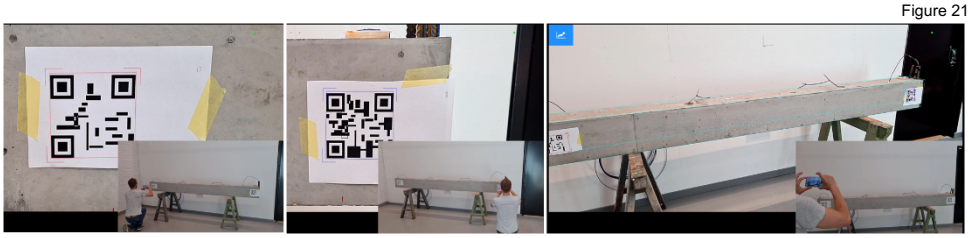
Figure 20



Markers positioning and internal origin.

So, in order to align the virtual and physical beam, the user only needs to make sure that the mobile device detects the two markers, as seen in Fig. 21. Upon detecting the images, two anchors are also created internally. During initial tests anchors appeared to provide better tracking stability compared to only using the "raw" positions of the markers. Once the markers are detected and the virtual beam is aligned to the real one, a wireframe 3D model of the beam is displayed, see Fig 21(right).

Figure 21



Procedure to align the real and virtual beams in the AR tool using two markers.

Regarding the data that should be displayed, as previously mentioned, it is exactly the same as in the SensIT Manager thanks to having chosen a web-based AR toolkit. However, since AR tool prototype possesses a touch interface on a mobile screen, a new user interface was specifically developed. Fortunately, WebXR makes this fairly simple as it is possible to use conventional Hypertext Markup Language (HTML) and Cascading Style Sheets (CSS) to define and style a web interface and then render it as an overlay on the AR interface. As illustrated in Fig. 22, the simplified interface makes is possible to display strains, cracks, or deflections using a contour plot overlay with max and min values presented. In addition, it is possible to select a specific timestamp using a slider. Using this interface, it is then possible to walk around freely and inspect any part of the real-world element at the same time as strains, cracks, or deflections can be visualized.

Figure 22

The SensIT AR Tool interface (https://youtu.be/y8yFHzpmzI8)

For future work it would be straightforward to also implement the additional features from the requirements engineering analysis, such as 3D-rebars and possibility to make notes. Also, it would be interesting to simplify the alignment process and an initial effort would be to only require a single marker. Although tilting has been identified as a risk of orientation error with a single marker, always using the global Z-up axis instead would probably be a solution. Going further it would also be interesting to investigate the possibilities for a markerless alignment using some sort of AI-training or conventional image analysis using OpenCV. However, many concrete structures

might also be a lot more complex in shape than a simple beam, which tells us that a marker-based solution will perhaps still be required in practice.

3.2.1 Challenges of AR in the construction industry

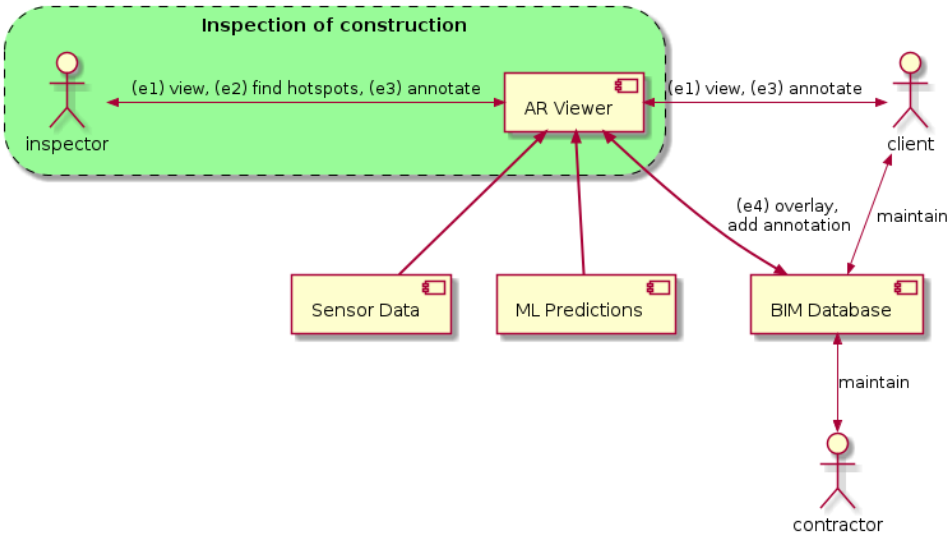
The prototype described in the previous section has shown that an AR inspection tool could have manifold benefits for the evaluation of infrastructure health condition during on-site inspections. However, as any other emerging technology, augmented reality has also some drawbacks and limitations that need to be addressed before a full-scale deployment of the technology becomes a reality.

The first and foremost concern at a working site is safety. However, today not all head-mounted devices developed for AR are compatible with hard hats, which is one of the compulsory personal protection equipment (PPE) items on any work site. Furthermore, the use of an AR tool at the work site can be potentially dangerous due to an increased lack of attention to the surroundings. If an inspector is walking while focusing on overlaid data on the mobile phone, that person might not see potential hazards like a hole in the floor or a crane's hook hovering nearby.

The presented web-based solution for the AR has many advantages, but it also requires a stable internet connection. Having a bad internet connection at a bridge somewhere in a remote location far from any urban area is a likely scenario and also an issue that needs to be addressed for the tool to be fully functional anywhere.

3.3 Collaborative interaction design

We have systematically explored the requirements of using augmented reality for inspection. Here, we present our main conclusions.



Within the scope depicted in Figure NNN and in relation to the phases, SensIT AR aims to reach the following business goals:

Goal 1: Increase effectivity of inspection. SensIT AR BIM Viewer should increase the likelihood of detecting potential problems (i.e. those that should be reported) during inspection. This is done by providing an "inside view" of the construction, e.g. of a concret beam based on sensor data and machine learning based prediction, which is shown as a heatmap overlay in the AR.

Goal 2: Increase quality of inspection report. SensIT AR BIM Viewer should increase the quality of the report by providing new means of locating findings in relation to the construction through AR and by synchronizing this information with the web based bim viewer.

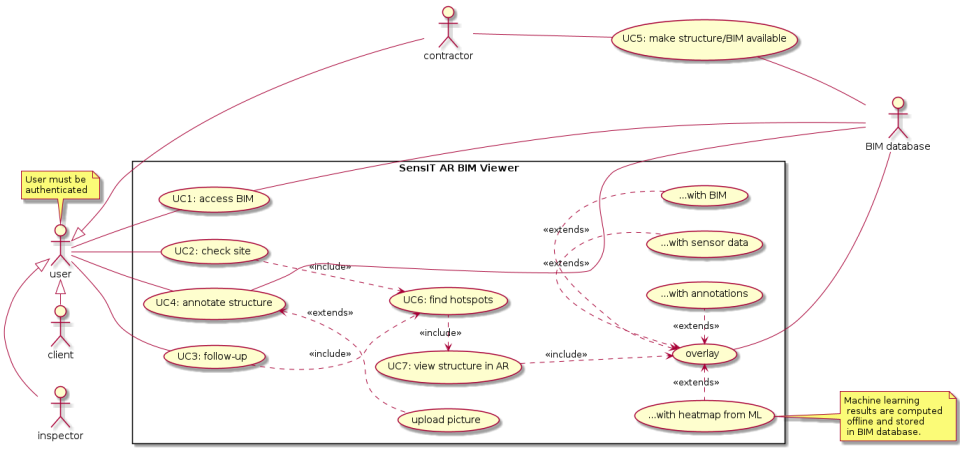
The following table shows how the events and quality attributes relate to the business goal:

Table caption: Goal Domain Tracing emphasises the key functions and qualities of AR based inspections

Tabell 1

Goal	(e1) view	(e2) find hotspots	(e3) annotate	(e4) overlay	(qr1) accuracy
Goal 1: Better inspection	x	x	x	x	x
Goal 2: Better inspection report			x	x	x

The core functionality is depicted in the following Figure:



The following user stories elaborate on these main use cases and describe how value to each stakeholder is provided:

UC1: As a user, I want to access the BIM remotely and at all times so that I can for example check the BIM while on site.

UC1.1: As a user, I want to select the construction site in the BIM Viewer.

UC1.2: As a maintainer, I want to see potential cracks in the BIM of a particular construction.

UC2: As an inspector, I want to check a construction site for potential problems

UC3: As an inspector, I want to follow-up on previous defects within the construction so that the development of deflections, cracks, or strains can be monitored.

UC4: As an inspector, I want to annotate a finding on a structure, so that potential defects such as deflections, cracks, or strains can be followed-up on. A picture may be uploaded to show the finding. The AR viewer should properly locate the annotation on the virtual structure.

UC5: As a maintainer, I want to share the construction site in the BIM Viewer with collaborators.

UC5.1: As a maintainer, I want to be able to authorize users to access the application

UC6: As a user I want to find hotspots so that I can focus my inspection of a construct.

UC7: As a user I want to view a structure in AR so that an overlay from the BIM database is provided on site.

When considering the functionality above, the following quality attributes should receive focus:

QR1: Accuracy.

Accuracy of AR overlay and location of potential problems is crucial for the SensIT AR BIM Viewer. Without sufficient accuracy, the AR viewer will not be useful.

Examples of Accuracy:

> Example 1: If a potential problem is shown, it must be accurately placed.
> Example 2: The alignment of the AR overlay (heatmap, wireframe) with the real world structure must be exact.

Open question: We also must find ways to encourage inspectors to look beyond the displayed potential problems.

QR2: Performance.

The AR interface must load relevant information sufficiently fast so that it does not affect usability.

Note on Performance: Performance is secondary, but it should not affect usability: Alignment should be quick and accurate enough, so that the app is useful.

4 Conclusions and future outlook

The current projects looked into how digitalization and specifically the use of AR tools can be used to increase the efficiency of infrastructure management and inspection. To that end, prototypes of a web-based decision-support tool for asset management as well as an AR inspection tool for mobile devices have been developed and tested with a case study in the laboratory.

The developed decision-support tool brings together three different aspects that make it a promising tool for infrastructure management: real-time sensor data, advanced analysis and visualization tools and web-based rendering of 3D models. The combination of these three aspects provides many advantages compared to traditional inspection approaches, where data is more efficiently, more frequently and more exhaustively collected and stored without the need of on-site inspectors while information is conveyed in an easier and more straightforward way, facilitating the decision-making process.

The prototype of an AR inspection tool was built using a recently developed web-based AR framework called WebXR which is currently available only on Android systems. Thanks to that, a customized intuitive user interface could be created using common web development language while file and data formats could be shared with the SensIT Manager. The tool enables the alignment of a virtual 3D model with its real counterpart, which is displayed on the tool as a wireframe 3D model. Thereafter, users can easily visualize post-processed sensor data as an overlay on the real structure to identify critical locations easily and accurately. Moreover, data history can be easily accessed by using a slider.

A live demonstration test is planned to showcase the possibilities of the developed tools for infrastructure inspection. The test will consist of a reinforced concrete wall with a hole, outfitted with distributed optical fibre sensors and tested until failure in the structural engineering lab at Chalmers University of Technology. During the test, the audience will be able to follow the progress of the damage live and through the SensIT Manager. A mobile device will also be used to visualize the evolution of damage and cracks in the structure using the AR tool prototype, which attendees will be able to compared with a naked eye inspection of the element.

4.1 Recommendation for further development of the presented tools

Today the implementation of the data transfer in the SensIT Manager done by file transfer protocol (ftp), which has two main disadvantages. On one hand, currently the system updates the saved data files in the ftp server, which then is used to retrieve data from it. This means that over time, files become larger and transfer of data slower, to the point that loading a long data history with multiple sensors and postprocessed contour plots might become unreasonably slow. On the other hand, the current system allows for real-time monitoring, but the user is required to refresh the browser in order to reload new data, which can be problematic based on the aforementioned issue. A more efficient way to store and transfer data is required for the tool to be scalable to larger projects with longer monitoring periods.

Data transfer can be an equally or even bigger issue for the AR inspection tool considering that mobile phones are often relying on slower internet connections than desktop computers. However, from a user experience point of view, the implementation of a marker-less alignment procedure would greatly facilitate the use of the tool in larger, more complex and less accessible structures. Moreover, an extension of the information visualized in the AR tool, such as 3D reinforcement layouts, and the possibility to toggle them on and off, as well as the possibility to make annotation and link them to the position of the BIM model would boost the collaborative potential of the tool.

The SensIT manager decision-support tool has been devised with several features that are not yet functional on the website. The implementation of such features, such as synchronization of annotations from the AR tool, possibility to manually upload pictures or reports and attach them to a certain project, or the ability to carry out performance predictions based on previous trends are examples of features that may be implemented in the near future.

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