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Intuitive Self-Inspection Techniques based on BIM for Energy-efficient Buildings: EU Horizon 2020 Research Project INSITER

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Abstract

More than 70% of all buildings in the EU nowadays are based on prefab components. The critical mass of energy-efficient buildings in Europe by 2020 can, therefore, be achieved through sustainable building industrialisation. Prefabricated architectural, structural, MEP and HVAC components nowadays are designed and manufactured according to high quality and performance standards. However, realising the targeted performance in design is hampered by critical shortcomings during on-site construction and refurbishment that cause a lower built-quality and sub-optimal energy-saving in the building lifecycle.
The INSITER research project within the EU Horizon 2020 Programme aims to eliminate the gaps in quality and energy-performance between design and realisation of buildings with prefabricated components. The key innovation of INSITER is an intuitive and cost-effective Augmented Reality (AR) system that connects the virtual model based on Building Information Model (BIM) and the physical building in real-time.
The new concept of self-inspection that is performed simultaneously with on-site processes has a strong contrast with the traditional post-inspection approach. INSITER will develop a new methodology and supporting toolset for self-instruction and self-inspection by construction workers, subcontractors, component suppliers, and other stakeholders during on-site working processes.

Keywords

Self-inspection, quality control, performance assessment, energy efficiency, Augmented Reality, Building Information Model

1. Introduction

Energy-efficient buildings (EeB) have become a priority of the European Commission (EC) to promote and maintain sustainability in the construction sector. Within the recently launched EU research programme "Horizon 2020" (http://ec.europa.eu/programmes/horizon2020/), a particular attention is given to quality-gap and performance-loss between design and realization both in new construction as well as refurbishment of EeB. Today's availability of critical components to energy efficiency (such as façade systems, HVAC installations and equipment) has proven to have significant impact for buildings

(European Commission, 2002). There is an urgent need for ensuring that the potential benefits of these components will not be lost due to lack of knowledge or bad implementation during the construction processes, which may affect the final performance of the building. The construction sector is characterised by a segmented approach involving a variety of skills and expertise with different roles and responsibilities. During construction, each actor of the construction value-chain must ensure that his contribution fits into a quality framework defined collectively at the design level.

The European Commission calls for collaborative research and development of new self-inspection techniques and quality check methodologies for efficient construction processes (http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/2174-eeb-03-2014.html). Self-inspection and quality checks are to be implemented to guarantee the final thermal, acoustic and energy performance of the building which will be quantified during commissioning. This means that quality control is of utmost importance to guarantee that the energy performance at commissioning stage will meet the one expected at design stage. Research needs to focus on new self-inspection techniques and quality check measures for efficient construction processes, enabled by portable and robust systems that can be easily handled in the construction site. The techniques to be developed should also be able to avoid or reduce economic and time deviations of the construction processes.

This paper is descriptive and it presents the INSITER project, which responds to the abovementioned EC Call through 4-year collaborative research and innovation actions in 2014–2018. INSITER stands for 'Intuitive Self-Inspection Techniques using Augmented Reality for construction, refurbishment and maintenance of energy-efficient buildings made of prefabricated components'. The project aims to eliminate the gaps in quality and energy-performance between design and realisation of energy-efficient buildings based on prefabricated components. It will develop a new methodology for self-instruction and self-inspection by construction workers, subcontractors, component suppliers, and other stakeholders during on-site working processes, supported by a coherent set of hardware and software tools.

The key innovation of INSITER is the intuitive and cost-effective Augmented Reality that connects the virtual model and the physical building in real-time. INSITER will substantially enhance the functionalities and capabilities of measurement and diagnostic instruments (like portable 3D laser scanners, thermal imaging cameras, acoustic and vibration detectors, real-time sensors) by means of a smart Application Programming Interface (API) and data integration with a cloud-based Building Information Model (BIM). The triangulation of Geospatial Information, Global and Indoor Positioning Systems (GIS, GPS, and IPS) will support accurate and comprehensive Virtual and Augmented Reality (VR and AR).

In the following sections of this paper, the state-of-the-art of self-inspection techniques in construction will be reviewed; the research methodology of INSITER will be explained; and preliminary case studies will be presented. As the INSITER project has just started, intermediate results are still expected. Concluding remarks in the end of this paper will address the current progress, actual challenges and the forward-moving strategy.

2. INSITER concept and state-of-the-art review

The EU construction sector is rapidly shifting from traditional craftsmanship towards smart and sustainable manufacturing. Prefab architectural, structural, MEP / HVAC (Mechanical, Electrical, Plumbing / Heating, Ventilation, Air Conditioning) components nowadays are designed and manufactured according to high quality and performance standards. More than 70% of all buildings in the EU nowadays are based on prefab components whereby the EU countries represent 50% of world's export of prefab building components (UN Comtrade, 2009). The critical mass of energy-efficient buildings (EeB) in Europe by 2020 can, therefore, be achieved through sustainable industrialisation of high-performance architectural, structural and building-service components. However, the critical bottleneck of industrialised EeB is during on-site assembly and commissioning. As a result, the energy-efficiency potential as designed is not realised in the new or refurbished buildings based on prefab components. In many projects, miscommunication and misinterpretation between designers, general contractors, subcontractors, building owners and building occupants have caused sub-optimal assembly, lower performance and financial outcomes of prefabricated systems, and more severely, 'sick building syndrome' due to set-up errors of the prefabricated HVAC systems.

INSITER deals with these existing bottlenecks by introducing an innovative set of solutions that incudes Systems (integrated hardware and software) and Methodology (process guidelines and calculation methods) for real-time self-inspection and self-instruction to eliminate or reduce the gaps of quality and performance.

In terms of hardware, the thrust of INSITER Systems is given by advancements in: 3D laser scanning, thermal and acoustic imaging technologies. INSITER aims to resolve the current limitations of existing technologies for 3D laser scanning, which are mostly integrated in total stations and digital cameras, and as such are constrained by the need for continual update and relatively low speed of acquisition and accuracy of the data acquisition. Other limitations that will also be dealt with regard the operating range, points cloud optimisation and cleaning, and interface flexibility (Arayici, 2007; Dias et al, 2003; Lagüela et al., 2011).

Furthermore, INSITER will integrate thermal/acoustic output with 3D scanner images to produce 3D spatial-thermal-acoustic models of buildings and environment. INSITER will exploit infrared (IR) imaging for self-inspection on industrialized building during construction (Fokaides and Kalogirou, 2011; Grinzato et al., 1998; Lehmann et al., 2013; Revel et al., 2012; Yuan, 2010; Zong en Liu, 2012). A dedicated procedure based on both in-situ and lab tests will be developed with the aim to lower the U-value measurement uncertainty below 10%, which is a challenging target satisfying the requirements from construction industry. Along with this, INSITER will apply innovative acoustic imaging systems e.g. the SoundBrush –an easy-to-use and portable tool combining a sound measurement sensor and a camera for position and orientation tracking– that can tackle the problem of acoustic insulations in buildings with remarkable time saved (Deblauwe et al., 2009; Janssens et al., 2013a, 2013b).

In terms of software and data management, INSITER will extend the state-of-the-art Building Information Model (BIM) for lifecycle performance and asset management of energy-efficient buildings by addressing the following aspects:

- generating 3D model from laser scan;
- BIM as central information connector and visualisation tool;
- use of BIM on site on mobile devices connected to project or enterprise collaboration software regarding data distribution, update, versioning and management;
- BIM for project management and construction phase, instead of for design only, thus including data interfaces, visualisation and navigation functionalities of end user viewers;
- modelling energy efficiency initiatives, including the use of spatial technologies in linking BIM and FM asset management for improved life management;
- managing and maintaining information during operations by integration with Building Maintenance Systems (BMS); preventative maintenance and occupancy management;
- managing 'whole life cycle' costs, from handover to operations and maintenance;
- deploying BIM model server with clash detection, model checking, and versioning (tracking).

Furthermore, INSITER's impact will encourage all actors in the value-chain to connect the physical and the virtual building sites by connecting BIM with Geospatial Information Systems (GIS). Integrated BIM of prefab components as well as the whole building on its site and within its surroundings, supported by virtual process simulations of design, construction, refurbishment and maintenance can, therefore, be validated against the design models.

In terms of methodology, the INSITER's real-time self-inspection concept has a strong contrast with the traditional approach of 'post-inspection' where inspections are done by an observer / auditor / controller after a working process is finished. In such as a traditional approach, errors and defects are always discovered 'just too late', followed by a long and difficult process to point out 'who to blame' and to decide 'how to fix the mistakes done'. INSITER will prevent costly repair actions; make the process transparent regarding liability, accountability and insurance. INSITER Self-Inspection' encourages, enables and equips the construction workers to check their own working processes and the results respectively, both individually as well as peer-to-peer with other workers. Using Augmented Reality (AR), 'INSITER Self-Instruction' engages a pro-active approach to provide the workers with interactive guidance during their working processes, facilitated by workers' mobile devices. Workers will be able to receive continuous updates of pre-planned process as well as actual progress. This will prevent wrong actions, and help the workers to rectify any error immediately.

Self-inspection and self-instruction will not disrupt on-site working processes by additional effort; it will save time and cost by making the processes efficient and accurate. INSITER will develop process guidelines consist of 8 key steps by the relevant measurement and diagnostic instruments will close the gap between design and realisation in new construction, refurbishment and maintenance projects. The key steps within INSITER guidelines are:

1. Taking an accurate reference situation: Mapping the actual technical conditions of the site and building, and performing economic valuation of the property and land.
2. Selecting high-performance building components: Self-inspection at procurement, production and delivery of prefab components.
3. Creating realistic models of buildings and sites and their performance target: Modelling of the building, site and surroundings in Building Information Model (BIM).
4. Virtual validation of quality and performance in BIM: Model Checking and Clash Detection; as well as value and process optimisation by Virtual Reality simulations.
5. Intuitive use of Augmented Reality (AR) by workers on site: Generating and deploying BIM-based Augmented Reality (AR) for self-instruction and self-inspection.
6. Validating site conditions: Self-inspection during preparation of sites and logistics.
7. Validating preliminary results: Validating Self-inspection and self-instruction during construction / refurbishment / maintenance process.
8. Connecting performance target and user operation / behaviour: Self-inspection during pre-commissioning, commissioning and project delivery; self-instruction for users.

The overall approach of INSITER is geared to enhance and integrate state-of-the-art methods for energy-related self-inspection for new construction, refurbishment and maintenance projects through the following ways:

- non Destructive Test (NDT) by non-contact solutions for quality check of prefab components;
- non-contact solutions using IR thermal imaging exploited in conjunction with blower door testing, which pressurizes or depressurizes the building, for air leakages identification; IR thermography employed in building diagnostics for the determination of the thermo physical properties of building envelopes; and standardised procedures with automated image processing;
- measurement of 3D global thermal distribution by IR camera for the estimation of U-value global distribution;
- virtual self-inspection / self-diagnosis in BIM focusing on critical elements by placing BIM checking points where leakages / air-tightness problems commonly are found; connecting self-diagnosis in BIM with monitoring and analysis software;
- use of RFID (Radio Frequency Identification) –a wireless non-contact radio system used to identify objects equipped with tags (markers); the RFID systems consist of reader and active or passive tag will be connected with INSITER Systems;

- Augmented Reality (AR) to deal with discrepancies between design model and the actual situation, tackling deviations and defects that are often caused by impossibility to completely follow the design instructions due to too narrow or too little space for installing these components by workers;
- early detection of acoustic leakages by means of innovative acoustic imaging systems (SoundBrush and beam-forming);
- early detection of leakages / air-tightness problems at pre-commissioning of new buildings or during condition assessment / mapping of existing buildings by utilising a combination of Blower Door Test with pin-point control of the prefab joint / connections between building and MEP/HVAC parts;
- systemic approach for self-inspection by distinguishing main systems (e.g. particular rooms or storey) and sub-systems; and
- appropriate set-up for optimal operation and comfort (e.g. HVAC settings); electricity consumption measuring; ultrasound flow measuring.

3. INSITER research methodology

The collaborative research approach of INSITER is geared towards progressive activities and achievements throughout 4-year duration. The project relies on both applied-research as well as action-learning methodologies as follows:

- Desk, lab and field research is performed simultaneously in complementarity with each other. Feedback from peer experts and skilled professionals are incorporated in collaborative research methodology.
- Technical and scientific impacts of the project are ensured by enabling methodology through practical trainings as well as common methodology for technical and process standardisation and certification.
- Market and economic impacts of the project are ensured by real-life demonstrations and development of business plan that strengthens European SMEs (Small and Medium-size Enterprises) and general contractors in the whole value-chain.

The INSITER research project will progress from TRL (Technology Readiness Level) 4 towards TRL 6. INSTER departs from state-of-the-art technologies that are available and cost-effective. It will make new developments to substantially enhance these technologies by advanced hardware and software, integrated with new self-inspection methodologies. The project will demonstrate the applicability of the results to achieve targeted impacts particularly in the energy-efficient building (EeB) domain.

Collaborative research in the INSITER project is carried out by a consortium consisting of 14 partners: 10 industrial partners (3 large companies + 7 SMEs) and 4 research organisations. SMEs are the largest group in the consortium; they play a key role, both in leadership of the project as well as in research, demonstration and exploitation. All main geographical regions of Europe (Western, Central, Southern) with their climate-related, regional and cultural characteristics are covered by the INSITER partners that represent 6 EU countries (Netherlands, Belgium, Germany, Bulgaria, Italy, and Spain). Generalisation and wide dissemination of the knowledge and project results are thus guaranteed.

The INSITER consortium is multidisciplinary with partners that represent all actors in the value-chain of energy-efficient buildings. More importantly, the consortium partners represent all professional domains that are essential to eliminate the quality and performance gaps between design, construction, refurbishment and maintenance of EeB. These domains are:

- professional domain of EeB design, engineering, energy management and construction site management;
- professional domain of component manufacturing, building construction, refurbishment and maintenance;
- professional domain of equipment and software tools for measurement, diagnostic, inspection and analysis; and

- research and standardisation domains, knowledge platforms for construction workers and subcontractors.

The project is organised in 7 inter-dependent work packages which are structured as follows.

- Four work packages for research and technology development (WP1 – 4) covering research on self-inspection methods, hardware, software and BIM. The work packages are:
    - WP1: Self-inspection techniques and process methodologies
    - WP2: Portable and robust systems and equipment for self-inspection
    - WP3: User-friendly software applications for self-inspection
    - WP4: BIM for self-inspection and self-instruction
- One work package for testing, validation and demonstrations (WP5: Validated solutions for closing the quality and performance gaps)
- One work package for training, standardisation, communication, dissemination and exploitation, including development of business plans (WP6: Training, communication, dissemination and exploitation)
- One work package for project and technical coordination (WP7)

The inter-relationship between the work packages is shown in the following scheme (Figure 1).

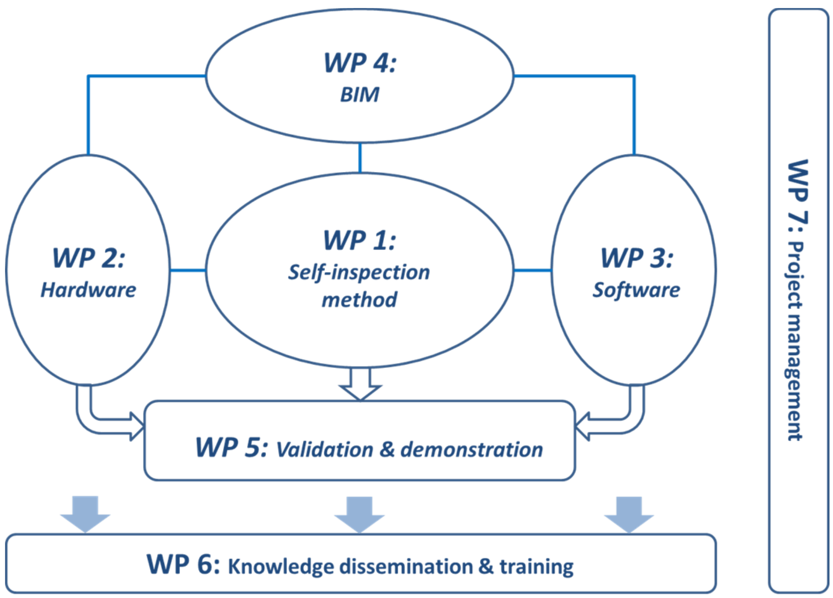

Figure 1: Work package structure in the INSITER project

4. Plan for laboratory testing and case-based validation

The INSITER research project will progress from Technology Readiness Levels (TRL) 4 and its final results are expected to reach TRL 6. This TRL range means that the project departs from state-of-the-art technologies that are available. The project will make new developments to substantially enhance these technologies by integrating hardware, software and self-inspection/self-instruction methodologies, as well as substantially improving the cost-effectiveness and user-friendliness. At completion, the project will demonstrate the applicability of the results to achieve targeted performance impact.

The subjects of testing, validation and demonstration during the research project are:

- methods and techniques, i.e. workflow, self-inspection manual, protocols and techniques;
- instruments, i.e. hardware tools, software applications and interfaces, BIM data models;
- stakeholders' competencies, i.e. knowledge and skills of construction actors who are conducting self-

inspection based on pilot training workshops during the research project.

At TRL 4 (i.e. technology validated in lab), activities will focus on testing and calibrating hardware and software instruments, as well as preparing follow-up validation protocols in real cases. Virtual testing will take place using BIM –components and buildings are modelled in 3D BIM, and then virtual self-inspection is performed using process and performance simulations, BIM clash detections, model checking and energy checking. Along with this, prototype software architecture, platforms, calculation tools, plug-ins, interfaces and apps are tested for consistency and inherent performance according to standard protocol for software development. In the lab / factory, calibration and testing of measurement and diagnostic equipment for self-inspection will be performed. Critical building components and MEP/HVAC systems will be subjected to Non-Destructive Testing (NDT).

Factory facilities will be used to evaluate the different innovations implemented on prefab components before going to real mass-production. This evaluation process will be done through: 1) design and construction evaluation, where aspects as constructive feasibility, components integration problems or needed resources are evaluated; and 2) testing of component performance both at individual and integrated level, including energy efficiency monitoring. In order to allow integrated evaluation of different components, 3D mock-up modules will be used where several components are installed and work in an integrated way. The results from the monitoring and evaluation will then be shared with the technical design and construction teams in order to introduce the necessary modifications.

At TRL 5 (i.e. technology validated in relevant environment), validation of INSITER Systems and Methodology will be conducted on-site using real case studies, i.e. limited scale construction and refurbishment processes of prefabricated buildings. Field-validation protocols, review criteria, and worker safety rules will be defined beforehand. The field validation is organised in such a way in order not to disrupt the real projects. Action-learning feedbacks are collected to adjust/improve INSITER prototypes.

At TRL 6 (i.e. technology demonstrated in relevant environment), the objective is to show the building final performance (i.e. thermal, acoustic, energy, quality) when INSITER Systems and Methodology are used. Demonstration activities during construction process will show the final performance / real achievement in terms of reducing and eliminating gaps of quality and energy-performance between design and realisation, delay avoidance, as well as improved productivity, health and safety of workers. Several new construction and refurbishment projects will be selected as real demonstration cases. The case selection criteria and the demonstration approach will be elaborated during the research project.

5. Concluding remarks

This paper describes the recently started European research project titled INSITER. The key objective of the project is to eliminate or significantly reduce the quality-gap and performance-loss between design and realisation of energy-efficient buildings. The project's focus on buildings based on prefabricated units increases the likelihood of success given a greater control over design quality. The INSITER concept addresses difficulties and challenges faced by construction workers. The innovation approach relies on a balance between software and hardware development, the training, and trans-disciplinary validation and implementation. INSITER will innovate in the application of Augmented Reality; while not creating new technologies, it aims to enhance the applicability of the AR technologies through the application of smart API and its integration with BIM.

During the project, challenges regarding cost-effectiveness and user-friendliness of INSITER Systems (hardware and software tools) need to be tackled, especially considering the main target group of construction workers. In relation to this, a positive impact is expected on reduction of labour-intensive on-site costs as well as resolving health and safety issues. Attention is also given on the measures to promote the project results, among others by making them accessible to the targeted users and attracting a larger and more active client community across Europe.

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