An Integration of Augmented Reality in Structural Health Monitoring Workflow: Installation and Training

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ABSTRACT

Structural Health Monitoring (SHM) has emerged as the most economical and efficient approach for maintaining large structures. A reliable SHM system assesses the structural condition by leveraging Industry 4.0 technologies. Advancements in smart sensor technology have made it feasible to monitor anomalies at hard-to-reach areas and along with a reliable wireless network, facilitated by the Internet of Things (IoT). This advancement is important as it eliminates the need for disassembly during inspections, thereby reducing time, effort, and costs. For a large-scale implementation of SHM however, one of the critical factors to consider is the installation process of the sensors itself. Say, in the case of installing hundreds of sensors on an aircraft panel or instrumenting an operating wind turbine blade or installing sensors on a busy bridge (traffic or rail), having a structured installation protocol with minimal loopholes is critical to ensure limited delays and non-conformities. Some of the challenges faced by sensor installers when instrumenting a large-scale (several sq.m area) include, a. comprehending complex structural drawings accurately and then marking the sensor positions on the structure. b. lack of standard working procedures. c. precision errors as a result of fatigue (repeated evaluation of sensor position from 2D drawings and manually correlating the same with a 3D structure) and adverse weather conditions (in the case of outdoor installation) that may add to any of the points mentioned previously.

In order to overcome the challenges and to streamline the installation processes, we propose a novel workflow using Augmented Reality (AR) to guide and support installers, trainers and supervisors. The workflow is envisioned to guide installers with these complex installations and provide them the tools to visualize sensor positions, access installation guidebooks or relevant documents, report non-conformities and record pictures and videos post-installation, all hands-free. In addition to installation support, such a workflow aims to empower trainers and supervisors to access and support their installation team remotely in case of a need. We believe such a tool would enhance efficiency, reduce human errors and optimize the overall time needed for sensor installation.

INTRODUCTION

Structural health monitoring (SHM) systems have been widely adopted across several structures due to their ability to monitor complex structures (for example aircrafts, bridges, wind turbines etc) with minimal manual intervention. For a successful SHM implementation (on any scale), one has to ensure that the sensors used for the measurements follow a defined and validated installation protocol. This ensures reliable data acquisition, which is a critical input for prognostic and diagnostic assessments [1].

Typically, for SHM implementation, the information on sensor positioning and the installation protocol are prepared by the design and engineering team, respectively. This information is then translated into two dimensional drawings for the sensor installation team. Although this approach works well for small scale implementations, we observe that such a workflow leads to errors and confusions in the case of SHM implementation on large structures. Figure 1 is a typical example of a structure wherein several hundred strain guages are installed as a part of routine inspections. To start with, such a large structure is divided into smaller sections, each section then represented as a two dimensional drawing. These drawings illustrate the exact positions where the sensors are to be installed. This information is then passed over to the engineers on the field, who would then use the same to complete the installation. Since the positioning of the sensors are critical for reliable data acquisition, the risk of misinterpretation and errors in translations could lead to a false diagnosis and/or prognosis [2]. This gets further complicated when combined with having to work in challenging environments, like on the bridge with vehicles/ trains running on [3]. Within a confined area where mobility is restricted, having the drawings at disposal are very critical to ensure accurate sensor placement.

In this context, we investigate a hands-free solution based on Augmented Reality (AR) as a potential tool to provide support and assistance for engineers on the field. The proposed solution standardizes SHM sensor installation, to ensure high quality of delivery with low experience personnel [4]. We propose a AR-based workflow for SHM implementation incorporating the inputs from design/engineering. Thereafter, we validate the performance of the AR-based solution by performing tests in a lab environment.

Figure 1. Global representation of a typical bridge work order where the red dots represent different sections of the bridge that are later up-scaled to extract exact sensor points [5]

PROPOSED WORKFLOW

This section proposes an optimum workflow, which is also illustrated in Figure 2; including the AR-based solution to address the challenges as described in the previous sections.

As the first step, we propose to replace two dimensional installation drawings with three dimensional models. Since the solution being proposed is AR-based, these 3D models would be our primary input. To better visualize the sensor installation points on the 3D model, we propose reworking the model also to include the sensor installation points in the form of guides. 3(b). These visual guides help the sensor installer by providing precise locations for installing the sensors maintaining precision. Such a representation particularly helps in cases wherein the structure has complex geometric features. Overlaying the 3D model including the sensor points could help reduce the overall effort for installation, eliminating possible errors. To further enhance the experience of the user, we propose also including installation instructions, guidelines, reference multimedia etc. All of this information would then be transferred to the AR hardware.

The installation procedure for respective structure is launched with scanning a task specific QR code. Upon a successful QR code scan, a list of steps are presented to the user. The first and most critical step is calibration. This is to ensure that the 3D model would overlay without mismatches on the physical structure. In addition, this step ensures precise projection of the 3D object at the required scale, pose and orientation. This step is to be done one time before the start of the installation (one time for one structure). Broadly, calibration can be categorized into marker-based or marker-less. In this context, considering that the structures in question are large and might not be visible in entirety to perform feature identification, we use marker-based calibration methods. Accurate calibration ensures minimum alignment error by means of anchoring the 3D model at precise position and orientation. A minimum of three anchor points are required for calibration, each anchor is responsible for three degrees of freedom.

After the information is prepared on the AR-hardware and a successful calibration is performed, the workflow is ready to be implemented. One could envision using the workflow for different cases including (but not limited to),

1. Installation support - this is, as described the primary use-case for the proposed workflow. We envision the installation engineers to be empowered with the data made available on the AR-based platform. This would include information about sensor location, sensor installation instructions, possibility of report support, capturing images etc. This could also be extended to supporting in case of repairs.

2. Inspection support - another possible use-case for the workflow could be to use the same for inspecting the sensors during operation. By creating a bridge between the data collected (on a cloud or server, for example) and the AR-hardware, one can envision visualizing the data, either as a number (sub-sampled) or as a color (representing a threshold).

3. Training support - one other possible use-case would be to implement the workflow for training and qualification of personnel. By providing a step-by-step workflow for sensor installation, we can ensure a standardized working procedure is implemented and followed. This helps to avoid any non-conformity.

One other added advantage of using an AR-based workflow is the possibility of feeding in the information captured during the installation/inspection/training processes and generate automated reports following a standard template. Although this is not part of the study proposed in this work, possibilities of report generation would be part of our future work.

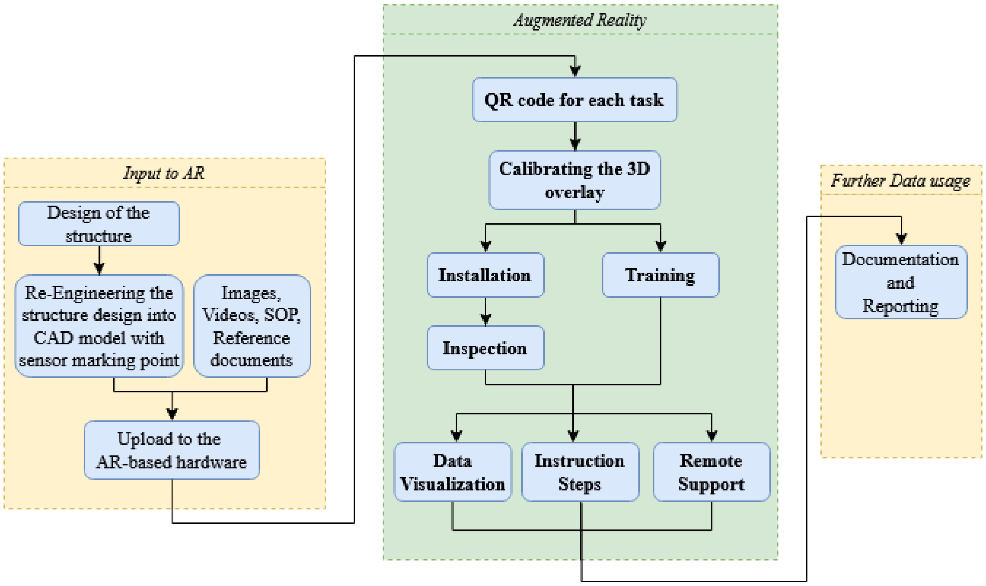
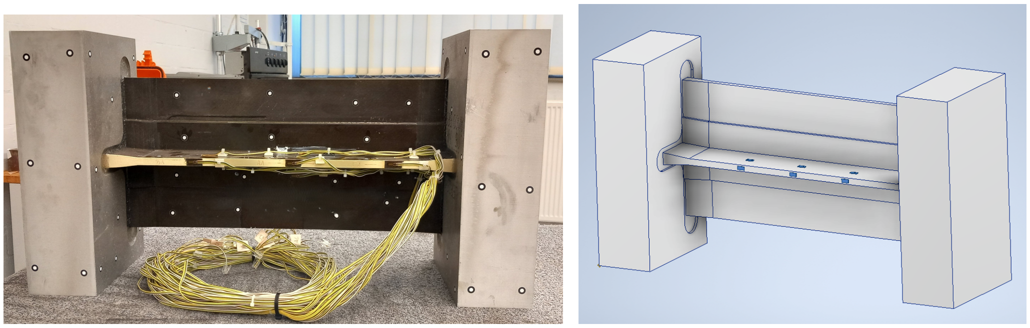


Figure 2. Proposed AR Solution for SHM workflow

TEST BENCH AND TEST CAMPAIGN

To validate the practical applicability of the above described workflow, a moderately complex test structure, as illustrated in Figure 3 was selected. This structure presents more geometric complexity than a simple flat plate, yet is not as complex as an aircraft fuselage panel with stringers or a large structure, like a brige or a wind turbine blade, making it an ideal test bench to assess AR performance.

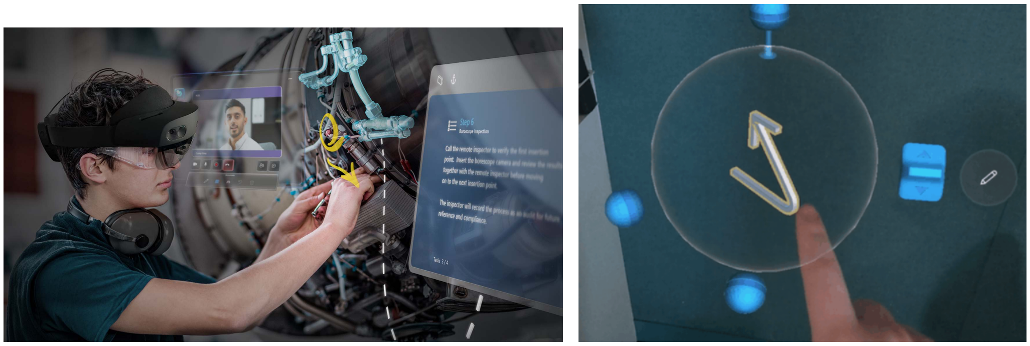


(a)

(b)

Figure 3. Structure under Test. (a) Physical Structure; (b) Re-engineered CAD model of the test structure with marked sensor points

To leverage the use of AR-based workflow for SHM, selection of compatible hardware is critical. AR hardware are generally classified into head-worn displays, hand-held devices, and projector systems. Among these, head-worn devices—such as AR headsets (Microsoft HoloLens) and smart glasses (Vuzix, Realware etc.) —are most suitable for SHM applications due to their hands-free capabilities. Additionally, their integrated sensor fusion supports natural hand–head–eye coordination, spatial awareness by perception of virtual elements in the real-world environment and improving the overall immersive experience.



(a) (b)

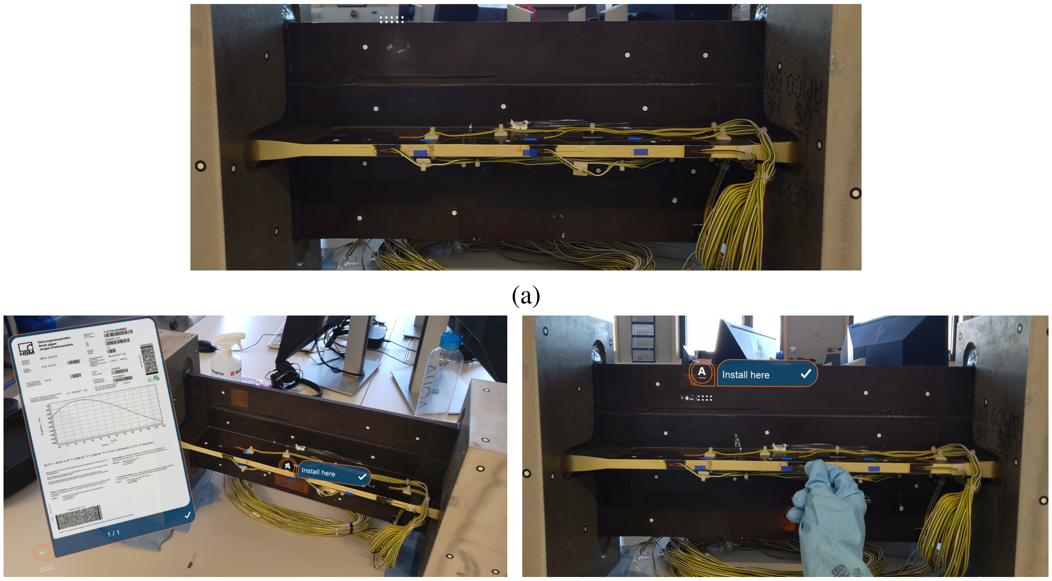
Figure 4. (a) Microsoft HoloLens-2; (b) Touch gestures viewed through a Holo-Lens [6]

Test Campaign: To evaluate the efficacy of proposed AR-based solution, a test campaign was conducted including multiple installation engineers. The engineer selected had little or no experience with sensor implementation. The scope of the test was focused on providing AR-based training and installation assistance and compare their performance in comparison with the conventional installation protocols. The goal here was to evaluate the proposed AR-methodology for training and installation assistance.

The objective of the test campaign was to estimate the effectiveness of the AR-based solution workflow in comparison to the standard working procedure, which uses two dimensional drawings and installation sheets. In order to do this, we choose two metrics, time taken and accuracy of the marked installation points on the selected structure. These metrics are estimated for both the said cases, with and without AR, and are compared. The tests were carried out in a controlled laboratory environment to ensure a common working environment for all the test takers. The room was well lit providing optimal visibility with the Holo-lens. The structure was placed on a stable platform about 80 cm above the ground level; a favorable height to complete the task either sitting or standing. Each participant was asked to install sensors on the test structure using the two approaches previously defined. The time and accuracy metrics are thereafter calculated. Further information about the two methodologies are provided below for reference,

Conventional Method: A printed out 2D drawing of the structure, annotated with required measurements and exact position and dimension of the sensor is provided to the user. Using a measuring scale, participants are asked to manually locate and mark the sensor positions.

AR-Assisted Method: Using the HoloLens 2, the participants first calibrate the 3D model until perfectly aligned to the test structure, followed by the sequential AR-guided procedure to visualize and place sensors as per the sensor guides on the CAD model.



(a)

(b)

(c)

Figure 5. (a)View through the Holo-lens with the visual guides for the sensor points on the structure; (b) A reference document viewed along with the step-wise instructions; (c) An attempt by the sensor installer to place a sensor on the visual guides

DISCUSSION AND COMPARISON

The time metric, in percentage, was estimated based on the time taken by the engineers using the AR-based method (including calibration) relative to the conventional method. The observation of the time metric for different users is shown in the table I. On an average, **41%** of time for marking the sensor positions can be saved by using a AR-based solution over an conventional approach.

TABLE I. Relative time reduced on using AR-based solution

Tests	**Conventional (mm:ss)**	**AR-based (mm)**	**Relative % time reduced**
User 1	28:43	12:24	57%
User 2	6:20	3:09	50%
User 3	4:00	3:02	24.5%
User 4	4:54	3:09	32%

We observe that the calculated time metric depends on two key factors, namely, the complexity of the structure and the experience of the engineers. In our initial study, since we focused on training as the primary use-case, we had conducted the experiment with engineers having little/no experience and used a structure that had a simple geometry (in this case, all sensors are located in the same plane and have the same orientation). We believe that by increasing the complexity of the structure and/or by increasing the experience of the engineers, the time metric may vary. For example, if an experienced engineer ought to have performed the same task (prior discussed), he/she would have completed the same faster with the conventional approach rather than with an AR-based approach. On the contrary, an engineer with little or no experience working on complex geometries would have completed the installation task potentially faster using the AR support than without.

One may also argue about the experience of the user with the AR environment. This is a valid concern and we believe, based on our observation, with repeated usage and custom calibration, one can adapt quickly to the same. For this study, since none of the users had any experience with an AR environment and having observed that the learning curves were rather quick, we ignore the effect of this factor in our studies for now.

The accuracy metric, is estimated based on the error in positioning the sensors based on the given instructions (either paper or AR-based). The accuracy metric, being based on the sensor position, is affected by the calibration step. An erroneous calibration could result in a less precise 3D overlay, which would in turn reduce the accuracy metric. The first results of the and accuracy metric can be seen in the table II.

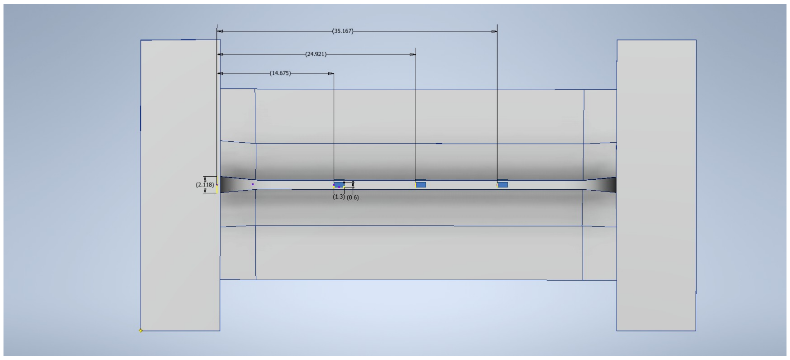


Figure 6. Position of each sensor point considered during the test campaign, measured from a reference point

TABLE II. Sensor position observations and error of the test campaign

Tests	**Conventional (cm)**			**AR-based (cm)**		
	Sensor 1	**Sensor 2**	**Sensor 3**	**Sensor 1**	**Sensor 2**	**Sensor 3**
User 1	14.6 (Err: 0.08)	25.0 (Err: 0.08)	35.1 (Err: 0.07)	15.1 (Err: 0.42)	25.0 (Err: 0.08)	35.0 (Err: 0.17)
User 2	14.6 (Err: 0.08)	24.9 (Err: 0.02)	34.9 (Err: 0.27)	14 (Err: 0.68)	24 (Err: 0.92)	34 (Err: 1.17)
User 3	14.6 (Err: 0.08)	24.9 (Err: 0.02)	35.1 (Err: 0.07)	14.5 (Err: 0.18)	24.5 (Err: 0.42)	34.6 (Err: 0.57)
User 4	14.4 (Err: 0.28)	25 (Err: 0.08)	35 (Err: 0.17)	14.2 (Err: 0.48)	24.8 (Err: 0.12)	35 (Err: 0.17)

In order to calculate the absolute error in sensor position marking, a reference point is considered from the CAD model. The sensors, as in figure 6, are located from a reference point at a distance of 14.68 cm, 24.92 cm and 35.17 cm respectively. The error is then determined as the absolute difference in marking from these defined distances. On the basis of our previous experiences with sensors and installation, we considered an acceptable error range within 0.5cm. In table II, the values exceeding the limits (highlighted in gray), are mainly due to misalignment between real-world coordinates and virtual calibration point. Such misalignment are usually caused due to movements of human body.

CONCLUDING REMARKS

The AR-assisted workflow has demonstrated added value in the installation of SHM sensors. It significantly reduces the time required for installation, which is one of the most time consuming step in a typical installation, especially for complex and larger structure. The accuracy that the AR-based solution depends on the quality of initial calibration. Where most sensor placements remained within acceptable limits, validating the reliability of AR for SHM installation, a few sensor position error exceeded the threshold. One of the identifiable reason is variability, induced due to human body movements for finger-tip calibration method. These findings affirm the potential of AR as a practical and scalable tool for improving installation accuracy and reducing operational bottlenecks in real-world SHM applications.

The accuracy is also anticipated to improved with user proficiency with AR technology and the hardware. Reducing the error in accuracy of the solution by refining the calibration process is to be carried out in future study. The current workflow can be further extended to maintenance processes by including features like real-time data visualization and AR-aided remote connectivity.

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