Implementation and validation of a low-cost IoT-enabled shake table system

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ABSTRACT

Shake tables are essential tools for validating structural health monitoring (SHM) systems. However, commercially available shake tables are relatively expensive and often hardly affordable for research and teaching institutions. Moreover, the widespread adoption of remote working and online teaching, fostered by the COVID-19 pandemic, often prevents researchers and students from physically accessing laboratories to conduct experiments. Research and teaching institutions would benefit from using low-cost shake tables with Internet-of-Things (IoT) capabilities for remotely conducting shake table experiments on test structures equipped with SHM systems. This paper presents the implementation and validation of a low-cost IoT-enabled shake table system (IoT-STS). The IoT-STS is composed of off-the-shelf components and builds upon a four-layer architecture. A smartphone application is devised to send periodic or random excitations, i.e. displacement time histories, through an IoT-based cloud service to a microprocessor, which, via actuators, imposes excitations on the shake table. Vice versa, the microprocessor sends the output displacement data, representing the motion reproduced by the shake table, to the cloud for remote access and visualization. To validate the IoT-STS, displacement time histories, remotely entered through the smartphone application, are compared with output displacement data, recorded by a potentiometer. The results demonstrate that the low-cost IoT-STS is capable of accurately imposing periodic and random excitations on test structures, thus showcasing the compatibility of the IoT-STS with remote working and online teaching in light of the COVID-19 pandemic.

INTRODUCTION

Civil infrastructure is exposed to a broad variety of dynamic excitations, such as traffic, wind, and seismic loading [1]. Dynamic excitations, depending on the intensity, may trigger rapid loss of structural integrity or accelerate fatigue-induced structural degradation [2]. The impact of dynamic excitations on civil infrastructure has fueled research towards investigating the structural dynamic behavior via laboratory tests using downscaled structures and shake tables [3]. In this context, research and teaching institutes have been integrating laboratory shake table testing into research approaches and teaching colloquiums, focusing primarily on validating structural health monitoring

(SHM) systems, which are typically used for monitoring the structural dynamic behavior [4]. However, the cost of commercially available shake tables may be relatively high, rendering shake tables hardly affordable by research and teaching institutes. Moreover, the need for remote solutions for laboratory testing is coming to the forefront, due to the extensive lockdowns of research and teaching institutes as a consequence of the COVID-19 pandemic [5]. As a result, research and teaching institutions may benefit from using low-cost shake tables with Internet of Things (IoT) capabilities that allow remotely conducting shake table experiments in a cost-efficient manner.

Research efforts towards developing low-cost shake tables have been reported in [6]. In [7], the authors have developed an Arduino-based low-cost shake table capable of inflicting excitations on structures up to 120 kg with a maximum frequency of 17 Hz for a total price of EUR 650. A low-cost shake table at a price of EUR 2,500 has been presented in [8], equipped with a feedback controller system that ensures precise displacements of the shake table in real time. Furthermore, approaches towards developing shake tables with remote-control capabilities have also been reported, including remote shake-table laboratories for mobile learning modules [9], frameworks for remotely accessible shake tables [10], and programmable shake tables with IoT-based interfaces [11]. Notwithstanding the aforementioned works, approaches towards IoT-enabled low-cost shake tables have been scarce, and prices of commercially available shake tables may be prohibitive for research and teaching institutes.

In this paper, the implementation and validation of a low-cost IoT-enabled shake table system (IoT-STS) is presented. The IoT-STS is composed of off-the-shelf components and builds upon a four-layer architecture, including a smartphone application and an IoT cloud service. The smartphone application sends excitation parameters, i.e. displacement time histories describing periodic or random excitations, to a microprocessor through an IoT-based cloud service, which imposes the excitations on the shake table via actuators. Vice versa, the microprocessor sends the output displacement data, representing the motion reproduced by the shake table, to the cloud for remote access and visualization. The IoT-STS is validated in laboratory experiments, in which the displacement time histories are compared to the output displacement data, recorded by a potentiometer. The remainder of the paper is organized as follows. First, the implementation of the IoT-STS is described, followed by the validation. The paper ends with a summary and conclusions, and an outlook on future research is provided.

IMPLEMENTATION OF THE LOW-COST IOT-STS

The IoT-STS builds upon a layered IoT architecture, in which the different layers connect the physical world and the digital world. Figure 1 shows a schematic representation of the IoT architecture, based on the four-layer architecture proposed in previous work [12], including (i) an application layer, (ii) a middleware layer, (iii) a sensing layer, and (iv) a security layer. The *application layer* supports remote control and data visualization via user interfaces facilitated by smartphone applications. The IoT *middleware layer* comprises an IoT-based cloud service, used as a database for processing, storing, and retrieving data. The *sensing layer* encompasses the IoT-enabled low-cost shake table, which includes a low-cost microprocessor with IoT communication capabilities, sensors, and actuators that interact with the real world. The *security layer* provides authentication and encryption protocols for complying with data security requirements.

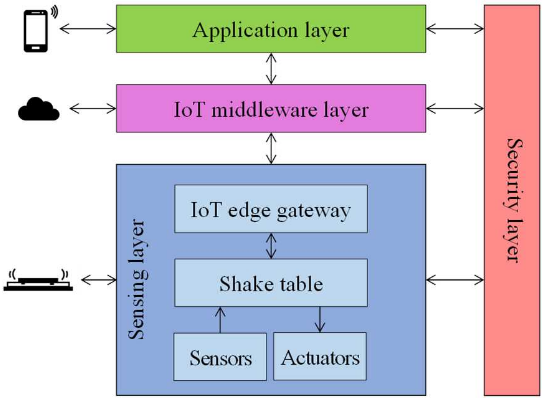

Figure 1: Schematic representation of the four-layer IoT architecture of the IoT-STS.

The components of the IoT-STS are illustrated in Figure 2, which shows the readily implemented IoT-STS. The IoT-STS consists of (i) an ***ESP32 microprocessor***, controlling the excitations via a control algorithm as well as ***sensors/actuators*** and the elements of the ***IoT-enabled low-cost shake table***, which primarily include (ii) a ***stepper motor*** that is connected to the microprocessor through a step-servo driver for converting electrical pulses into rotary motion, (iii) a ***linear ball screw*** attached to the stepper motor that converts the rotary motion into translational motion, and (iv) a ***moving platform*** comprising a stage plate connected to the linear ball screw that rests on four ***linear bearing blocks*** that slide along two ***linear guide rails***. In total, 15 items are purchased for building the low-cost shake table with the total cost of EUR 341.83.

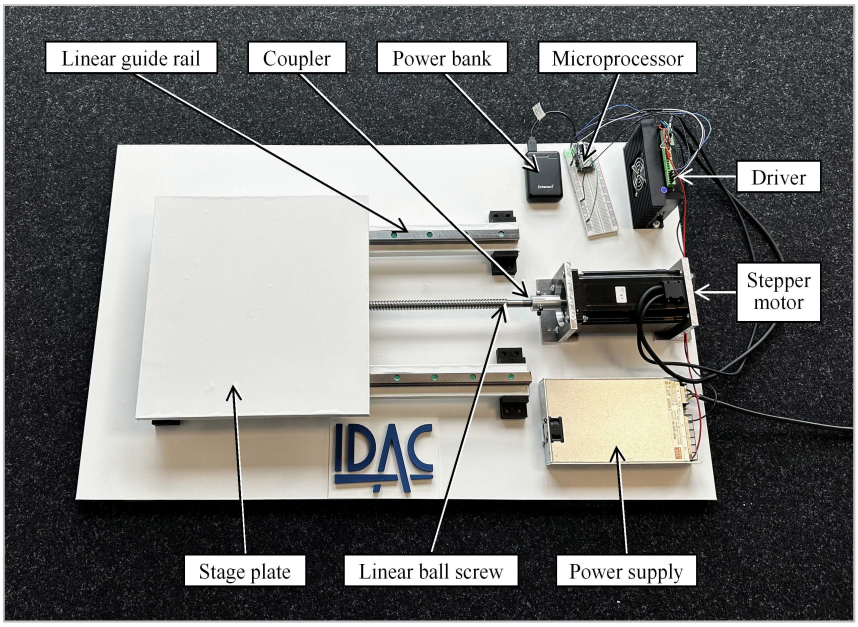

Figure 2: Hardware components of the shake table, as part of the sensing layer of the IoT-STS.

The control algorithm, embedded in the microprocessor, retrieves excitation parameters to produce periodic and random excitations from the database of the IoT-based cloud service. The parameters for periodic excitations include amplitude A, angular frequency ω, time step Δt and total duration T_{tot}, while the parameters for random excitations are displacements $\Delta \mathbf{x} = [\Delta x_1, \Delta x_2, \ldots, \Delta x_n]^T$. Technically, the parameters are uploaded as text files together with the time step Δt and the total duration T_{tot}. To reproduce the excitations, in the ith time step ($\Delta t_i = t_i - t_{i-1}$), the displacement Δx_i is converted into rotary motion that is produced by the stepper motor, which depends on the type of excitation. Exemplarily, Figure 3 presents the control algorithm for periodic (sinusoidal) excitations, where the displacement Δx_i of a periodic excitation with an amplitude A and a frequency ω is computed by Equation 1.

$$\Delta x_n = A(\sin 2\pi\omega t_i - \sin 2\pi\omega t_{i-1}) \qquad (1)$$

The rotary motion necessary for inflicting Δx_i corresponds to the number of electrical pulses NP sent from the microcontroller to the stepper motor. The NP value is defined as the ratio of the displacement Δx_i over the unitary displacement of the shake table Δx_{unit} ($NP = \Delta x_i / \Delta x_{unit}$). The unitary displacement Δx_{unit} is the distance that the linear ball screw moves when one pulse is sent to the stepper motor. Specifically, for the IoT-STS, the Δx_{unit} value is equal to 0.0125 mm. The stepper motor is set to rotate either clockwise or counter-clockwise, depending on the sign of displacement Δx_i. The time delay t_d corresponding to each pulse is estimated by the ratio of the time step Δt_i over the number of pulses ($t_d = \Delta t_i / NP$). For producing the displacement Δx_i, the microcontroller sends the NP electrical pulses sequentially to the stepper motor, ensuring adequate time delay between successive pulses to maintain time t_d. After all NP pulses have been sent, the actual advance in time is compared with the time step Δt_i, and, if necessary, extra delay is applied. Upon ensuring that the time step has been correctly maintained, the control algorithm proceeds with the next displacement Δx_{i+1}.

The smartphone application is implemented in Java programming language. Preventing insecure access and possible misuse of the shake table, the application requires users to log in with credentials to operate the shake table remotely. Once logged in, the application offers options for calibrating the shake table and for defining excitation parameters to be sent to the microprocessor. The application is connected to the database of the IoT-based cloud service, which enables the application to send excitation parameters to the microprocessor and to receive and visualize output displacement data from the microprocessor, corresponding to the motion reproduced by the shake table. The next section describes the validation tests and discusses the results from using the low-cost IoT-STS.

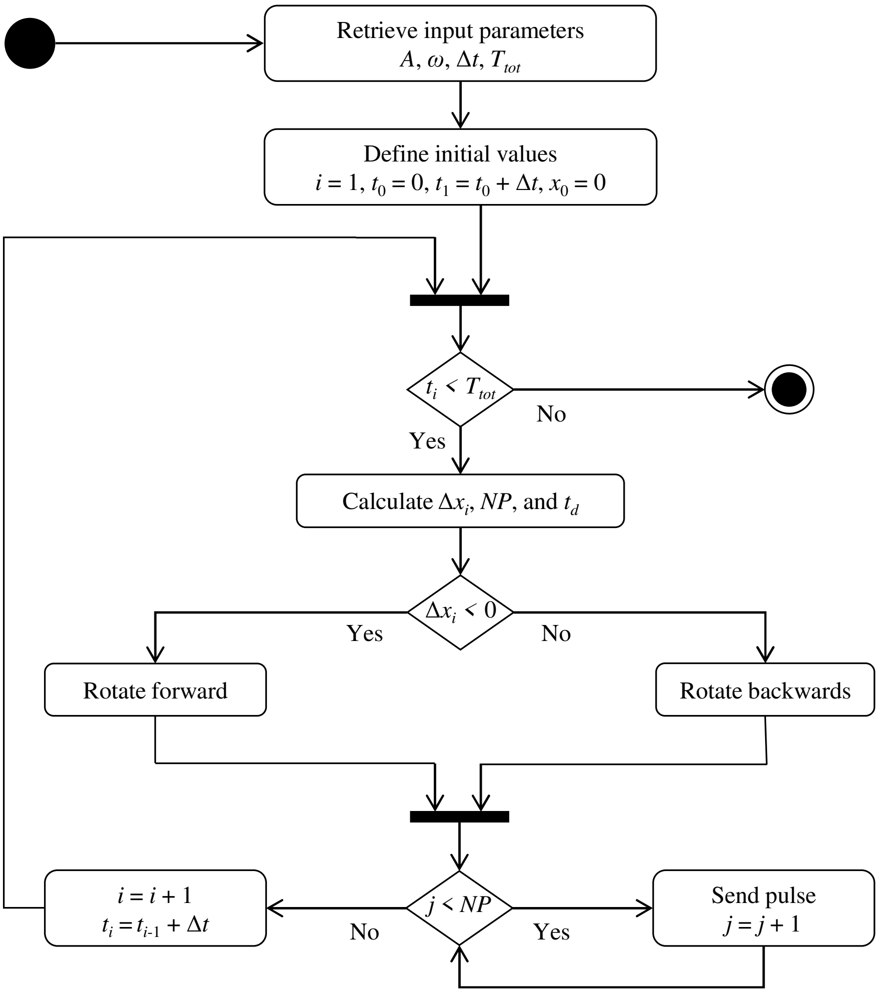

Figure 3: The control algorithm embedded in the microprocessor of the IoT-STS.

VALIDATION TESTS

In this section, the IoT-STS is validated via two tests. In the first validation test, periodic excitations are used as inputs for the IoT-STS, and the amplitude and the frequency of the output displacement data are independently evaluated by measuring the output displacement data using an external potentiometer. Similarly, in the second validation test, random excitations are used as inputs for the system, and the external potentiometer is deployed to record the output displacement and frequency. The potentiometer is installed parallel to the shake table, and has a measuring range of 10 cm, i.e. 5 cm in one direction and 5 cm in the opposite direction. The potentiometer is connected to an additional ESP32 microprocessor (i.e., not the same microprocessor controlling the shake table) that solely serves the validation purposes with the potentiometer.

In the first test, the ability of the low-cost shake table, as part of the IoT-STS, to reproduce periodic excitations is validated for a broad range of amplitudes and frequencies. In addition to merely validating the reproduction of periodic excitations, the objective of varying amplitudes and frequencies is to verify up to which amplitudes and frequencies the low-cost shake table can reproduce excitations accurately. The amplitudes tested in this study range from 1 to 20 mm, and the frequencies range from 1 to 5 Hz. Exemplary results obtained from the periodic excitations are shown in Figure 4 for two combinations of amplitudes and frequencies. As a result, when varying the frequency (considering a maximum amplitude of 20 mm), the shake table can accurately reproduce periodic excitations up to 5 Hz. In particular, for an excitation frequency equal to 5 Hz, the frequency of the output displacement data is 4.99 Hz, exhibiting a 0.2% error. When varying the amplitude for a constant frequency of 2 Hz, the shake table reproduces a maximum amplitude of 15 mm with a 3 % error between the excitation frequency and the frequency of the output displacement data.

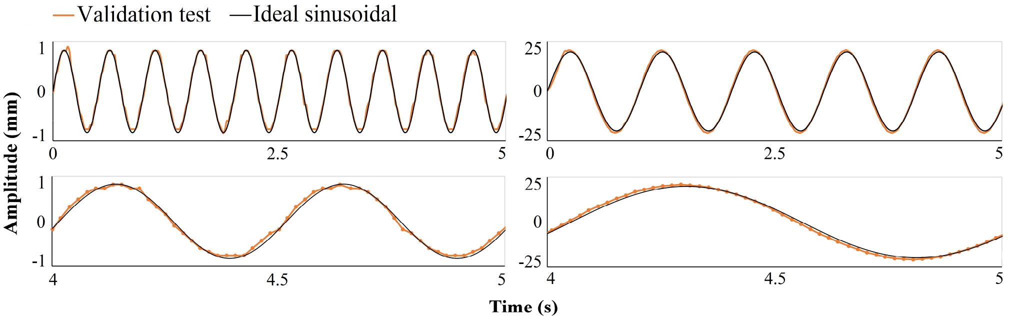

Figure 4: Results of the first validation test (periodic excitations) for 2 Hz with 1 mm (left) and for 1 Hz with 20 mm (right).

In the second test, the ability of the IoT-STS system to reproduce random excitations is validated. The random excitation parameters are sent to the shake table, represented by seismic displacements that are obtained from a ground motion (GM) record from the 2015 earthquake in Coquimbo (Chile). Prior to sending the random excitation parameters to the microprocessor, the GM record is scaled for adapting the displacements to the settings of the shake table. The displacements in the GM are scaled by a factor of 6, forming two tests cases (i) without scaling the time, and (ii) scaling the time by a factor of 36. The results obtained from the random excitations are shown in Figure 5, indicating that the random excitation is reproduced accurately when the time is not scaled. By contrast, when the time is scaled, a cumulative discrepancy is observed. In the microprocessor, the pulses *NP* and the delay t_d must be natural numbers and are, therefore, "truncated". The truncation involves rounding *NP* and t_d down to the closest positive integers. As a result, the cumulative discrepancy is attributed to the small increments in the displacement and time that are not properly captured by the truncated values of t_d and *NP*.

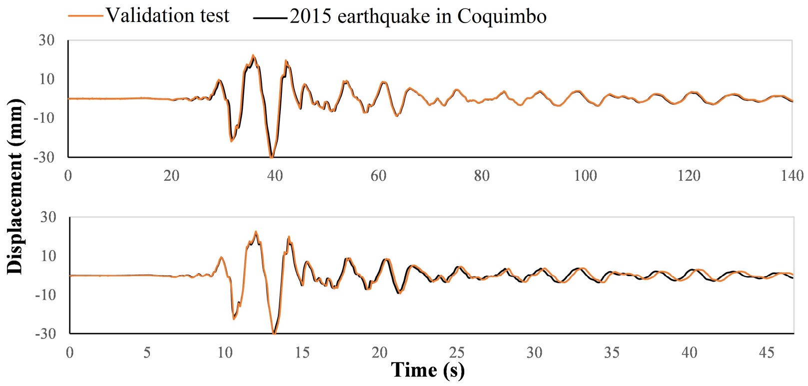

Figure 5: Results of the second validation test (random excitations), without scaling time (top) and with scaling time (bottom).

SUMMARY AND CONCLUSIONS

This paper has presented the implementation and validation of a low-cost IoT-enabled shake table system (IoT-STS). Contrary to similar approaches on low-cost shake tables, the implementation presented in this paper uses off-the-shelf components and enables remote access to the shake table using IoT technologies. The shake table consists of an ESP32 microprocessor, a stepper motor with a step-servo driver, a linear ball screw, and a moving platform on which test structures can be mounted. As opposed to commercial shake tables, the total cost of all components is less than EUR 350. A control algorithm has been embedded into the ESP32 microprocessor, which imposes excitations on the shake table, using user-defined excitation parameters. The shake table can be remotely accessed through a smartphone application. The excitation parameters are sent to the ESP32 microprocessor via an IoT-based cloud service from the smartphone application. The cloud service is also used for receiving and visualizing output displacement data from the microprocessor, corresponding to the motion reproduced by the shake table.

The validation of the IoT-STS has been performed by estimating the proximity of the motion reproduced by the shake table to the parameters sent via the application to the microprocessor both for periodic excitations and for random (seismic) excitations. The validation tests have showcased the capability of the shake table to impose periodic and random excitations, as well as the ability of the IoT-STS to be accessed and controlled remotely using IoT technologies. Future work may focus on coupling the shake table with a low-cost closed-loop motor control system.

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