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Application of IoT for Concrete Structural Health Monitoring

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Abstract - Structural health monitoring (SHM) of built infrastructure ensures the durability and extended life without the need for major rehabilitation and maintenance strategies. Concrete structures are among the most applicable types of infrastructures that require a well-established SHM routine to ensure serviceability and longevity. The concept of Internet of Things (IoT) can be applied to enhance the SHM process by improved data collection, storage and transfer methods which was not feasible in the past. The frequency of data collection as well as the quality and accessibility of data ensure the durability of the infrastructure. This paper includes the details of a system development to estimate the strength of concrete structures by using IoT technology and embedded temperature sensors. The integration of sensors to collect performance data were evaluated and discussed. Preliminary results of this work showed promising results in terms of data collection frequency, accuracy and relevance to the broader goal of SHM for concrete structures.

I. Introduction

Infrastructure systems are under constant stress from different environmental conditions that cause deterioration over their life time. Concrete structures are among the most popular and mostly used for infrastructure applications. Structural Health Monitoring (SHM) is ensuring the durability of build infrastructure during their life span. One of the main factors in assessing the durability of concrete structures and ensuring their ability to endure applied loads, is estimating the strength of concrete samples at different stages after construction. The traditional method to determine the strength of concrete structures is to drill out core samples from the completed structure. This method is destructive and might affect the structural integrity of the structure. In the recent decades, the application of non-destructive methods in SHM and construction quality control have gained attention [1], [2], [3], [4]. Concrete maturity method is one of the non-destructive evaluation techniques to evaluate the performance of concrete structures. The maturity concept is based on the fact that concrete properties (including strength) is dependent of internal temperature and age [5]. The performance of concrete structure are usually evaluated 28-days after the initial construction. Since concrete production generates heat as a result of mixing water with cement, the magnitude of such hydration heat combined with age (after construction) can be defined as Maturity Index [6]. This index estimates the in-situ strength of concrete structure without the need for any destructive coring. According to the American Society for Testing and Materials (ASTM), the procedure to estimate maturity index is placing concrete samples in cylindrical molds and embedding the temperature sensors inside the fresh concrete [7]. A datum temperature should be defined for the calculation of maturity index. The selection of datum temperature as well as the accuracy of the temperature measurement sensor affects the results. Cylindrical samples are stored and cured under moist conditions so that the hydration process can continue throghout the testing process. The compressive strength of the cylindrical specimens are then recorded at different ages after the production of concrete until 28 days. The maturity index is estimated using the following equation [8]:

$$M(t) = \sum (T_a - T_0)\Delta t \qquad (1)$$

where $M(t)$ is the combined temperature-time factor at age t, Δt is the time interval in days or hours, T_a is the average internal temperature of concrete sample, and T_0 is the datum temperature. Another maturity index is used to estimate the equivalent age of the concrete structure using the following equation [9]:

$$t_e = \sum e^{-Q(\frac{1}{T_a} - \frac{1}{T_s})}\Delta t \qquad (2)$$

where t_e is the equivalent age at a specified temperature T_s in terms of days or hours, Q is the ratio of activation energy to the gas constant K, T_A is the average temperature of concrete sample during time Δt, T_s is a specified temperature and Δt is the time interval in days or hours. The estimated maturity index is then correlated to the strength of concrete samples at different ages to develop the maturity graph. Once the graph is the established, the strength of in-situ concrete structures at different ages can be estimated from embedded temperature sensors without the need for destructive core sampling. The maturity and temperature monitoring allows for the estimation of structural health and durability over its life span. In this paper, Internet of Things (IoT) approach was employed to monitor the internal temperature of laboratory concrete specimens at different ages using a series of embedded temperature sensors combined with a data collection system. The following sections include a brief summary of relevant studies in the literature followed by the details of system development as well as the preliminary results of collected data.

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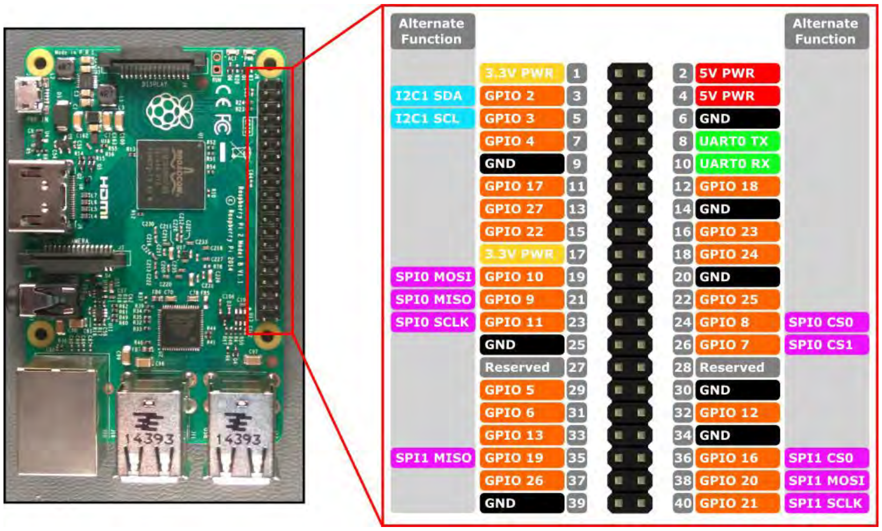

Fig. 1: Raspberry Pi 3

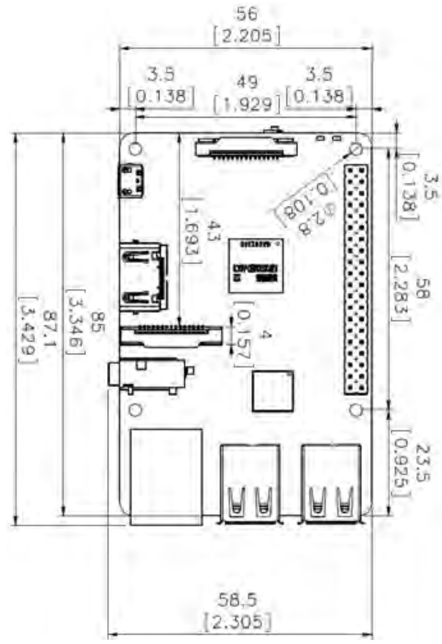

Fig. 2: Raspberry Pi 3 Dimension

Fig. 3: Temperature Sensors

II. System Requirements

Our goal was to build an IoT-based concrete Structural Health Monitoring (SHM) system that satisfies the following requirements:

(1) The system should continuously collect temperature data while the concrete is settling. To determine the structural health, continuous collection of temperature data is critical.

(2) The system should provide non-destructive evaluation methods in SHM. Hence, we embedded the temperature sensors inside concrete right after the initial construction.

(3) The system should be scalable. As the amount of data to collect grows rapidly, the system should provide robust data transmission method as well as data governance framework.

III. System Design

To satisfy these requirements, we developed IoT-based SHM system. The system consists of the following components.

(A) **Raspberry Pi B3+**. We use a Raspberry Pi 3B+ as our IoT edge device and sensor board. The collected temperature data is stored on on-board flash memory until the data is uploaded to the back-end server.

(B) **Temperature sensor module**. We use DS18b20 waterproof temperature sensors to collect temperature. The temperature sensors are embedded inside concrete right after the initial construction. Then, we collect the temperature inside the concrete while the concrete is cured.

(C) **Application**. We use Apache's NiFi and MiNiFi to control and secure data transmission from Edge device to back-end server. Also, we use an SQL database server for data storage.

A. Edge IoT Sensor Board

We use a Raspberry Pi 3B+, a single board microcontroller. Raspberry Pi 3B+ provides 1.4 GHz 64-bit quad-core ARM Cortex-A53 processor [11]. Also, Raspberry Pi 3B+ is equipped with 1GB of RAM as well as on-board flash memory. Also, Raspberry Pi 3B+ features dual-band IEEE 802.11b/g/n/ac WiFi, IEEE 802.15 Bluetooth 4.2, and 10/100/1000 Mbit/s Ethernet. In addition, Raspberry Pi 3B+ offers 40 pin General purpose input-output (GPIO) connectors. Figure 1 illustrates the GPIO layout of the Raspberry Pi 3B+. Moreover, a Raspberry Pi 3B+ weights 45g portable fully-equipped computer and its physical dimension is shown in Fig. 2.

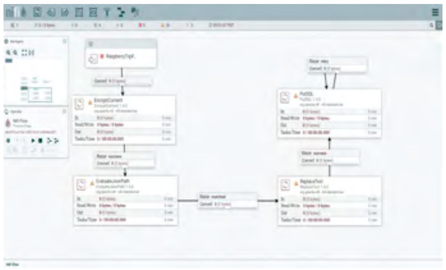

Fig. 4: Example of NiFi interface

Fig. 5: Example of Adding Processor

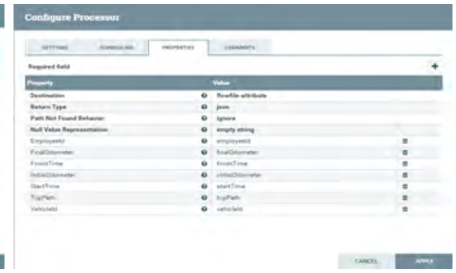

Fig. 6: Example of Properties Configuration

B. Temperature Sensor

As shown in Fig.3, DS18b20 water proof temperature sensors are embedded inside concrete. While the concrete is cured, we continuously collect temperature data.

C. Application

To provide robust and scalable data collection approach, we use a tool that allows us to monitor the data transmission flow, to identify any faults occurring during data transmission, and to handle the massive concurrent influx of new requests. Although there are numerous solutions, we wanted to utilize an open source tool so that we can extend the system as needed. To do so, we chose Apache's NiFi and MiNiFi, which is an open source data flow control software system built by the Apache Software Foundation [12]. This software provides data flow management, including data buffering, controlling the flow, prioritized queuing, flow specific quality of service (QoS), data recovery, and data encryption. MiNiFi is a light weight version of NiFi, which allows for simple NiFi integration of edge devices.

Apache NiFi provides a web-based user interface (UI) that allows one to build an automated data flow control system, It also provides visualizing, editing, monitoring, and administration of those data flows. The NiFi UI offers a components tool bar, navigation palette, operations palette, and status bar. Fig. 4 shows a small subset of the current project's data flow implementation.

Processors are the most common NiFi/MiNiFi component. They manage data inflow, outflow, routing, and manipulations. Processors provide numerous attributes that enable data source labelling, data streaming, data filtering, data modification, and data provenance tracking. Fig. 5 shows an example of adding a processor.

When a processor is added to the program, the next step is to configure its various properties. For example, Fig. 6 shows the properties that can be set up for the EvaluateJSONPath processor. This processor receives a JSON formatted text file and extracts specific data points from the file and ingests them into the JSON embedded data flow.

We built two data flow controls; MiNiFi Flow and Upload Flow. The MiNiFi agent on Raspberry Pi retrieves the temperature data acquired and transmit them to NiFi server. Upload flow parses the JSON files and constructs SQL insert statements. Then, the data acquired by the Raspberry Pi is

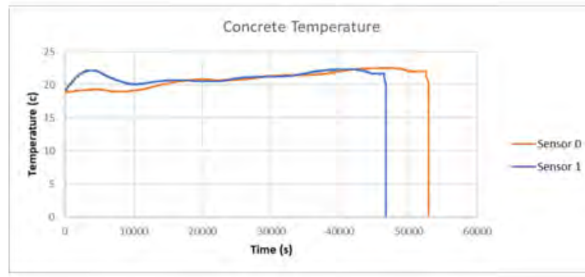

Fig. 7: Internal Temperature of two Self Consolidating Concrete

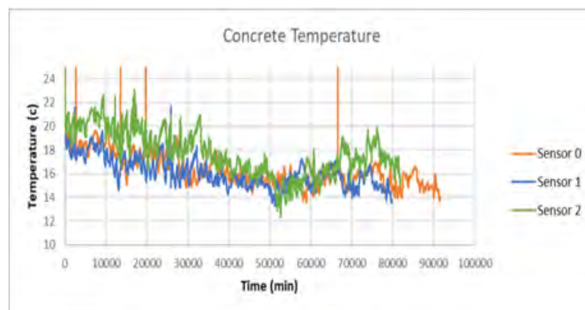

Fig. 8: Temperature Sensor Data

stored into the back-end database that we configured and implemented in SQL Database server.

IV. Experiments

During the curing process of concrete, which spans 96 days, temperature sensors were embedded into concrete samples to measure and record data. The temperature data in Figure 7 represents the internal temperature of two Self Consolidating Concrete (SCC) mixes for the first 28 days of curing. The temperature sensors collected data for 96 days which is presented in Figure7. The collected data along with measured concrete strength gain over time can be utilized to construct a concrete maturity index for each mix design. The maturity index gives a good estimate of the available strength performance of concrete during the curing process. In the concrete industry, formwork stripping and post tensioning methods are time sensitive and having an accurate measure of concrete strength development can help save time and money. Further testing is to be done in order to construct concrete maturity indexes for various SCC mix designs and evaluation of application to different curing processes.

V. Conclusion

A set of temperature sensors were embedded in concrete cylindrical specimens in the laboratory conditions to monitor the internal temperature variation. The heating of concrete materials can be correlated to their strength during the curing period. The maturity index represents the strength of the samples at different time periods after constructing the concrete structures. This can help avoiding the current destructive testing procedures where concrete cores are extracted from the structure to perform laboratory strength tests. In this study, we have developed a prototype that can measure and track the internal temperature of the concrete samples. Preliminary results showed that the data collection and transfer was efficient and user friendly. The extracted temperature data can be used to develop the maturity relationships and help predicting the strength of the concrete samples.

VI. Acknowledgment

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