SMAR 2019 – Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

SMAR 2019

A hybrid optical fiber/wireless monitoring system for permeable pavements

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ABSTRACT: This paper presents the development and assessment of a novel hybrid optical fiber/wireless monitoring system for permeable pavements. The real-time hybrid fiber optic/wireless permeable pavement monitoring system can be used to simultaneously measure flow discharge, temperature, flow velocity, and water level using the advantages of Mach-Zehnder interferometer (MZI) and Arduino-based sensing technologies. There were two types of water-flow velocity simultaneous measurements: inflow and drainage processes. For the inflow and drainage processes, the differences between the MZI-based water-flow velocities and the Arduino-based wireless water-flow velocities were found in the range of 3.6—4.4%. We have demonstrated the feasibility of the novel hybrid optical fiber/wireless monitoring system for permeable pavements simultaneously for water level, flow discharge, temperature, and flow velocity measurements without modifying MZIs or coating chemical compounds. Hopefully, the findings of this study can be utilized to establish the real-time multiplexing hybrid optical fiber and Arduino-based monitoring system for different types of permeable pavements.

1 INTRODUCTION

Optical fiber sensors exhibit many advantages such as resistance to corrosion, real-time multiplexing, low-cost, robustness, low insertion losses, relatively simple fabrication, compact, ease of use, immunity to electromagnetic interference. The strengths of wireless sensors include the capability of node deployment and space distribution, ease of use, wide varieties of wireless sensors, and compatibility with mobile devices. The potential benefits of permeable pavements would help reestablish a more natural hydrologic balance and reduce runoff volume, reduce the concentration of some pollutants either physically, chemically, or biologically, cool down the temperature of urban runoff, reduce the stress and impact on the stream or lake environment, as well as control the runoff at the source. Thus, the goal of this project aims at the establishment and development of a real-time multiplexing structural health monitoring for a two-layer permeable pavement using the hybrid optical fiber Mach-Zehnder interferometer (MZI) and Arduino-based wireless sensing technologies. The real-time multiplexing hybrid fiber optic and wireless permeable pavement monitoring system can be used to simultaneously measure water level, flow discharge, temperature, and flow velocity using the advantages of MZI interferometer and Arduino-based sensing technologies. Hopefully, the final results and findings of the project can be utilized to establish the real-time multiplexing hybrid fiber optic and Arduino-based monitoring system for permeable pavements as well as to evaluate the structural health of permeable pavement performance.

Optical refractometer sensors based on waveguide technology are promising for chemical and biotechnological applications. The advantages of this type of sensor are their compactness, relatively simple construction, low cost, ease of use, immunity to electromagnetic interference, and high sensitivity to the external refractive index (RI). Several types of optical wave-guide sensors or optical fiber-based refractometer have been proposed, including long-period fiber gratings, Fabry-Perot interferometers, and Mach-Zehnder interferometers (MZI). The interferometers utilizing a pair of lateral offset zones separated by a few centimeters are suitable for sensing applications for they offer many advantages such as low cost, robustness, low insertion losses and relatively simple fabrication [Jha et al. (2008), Jha et al. (2009), and Wang et al. (2012)].

For the two-layer permeable pavement, top layer (layer 1) is a 10-cm permeable pavers (see Figure 1) and layer 2 is a 15-cm single size aggregate material (see Figure 1), respectively. In this paper, we present the development and assessment of a novel hybrid optical fiber/wireless monitoring system for a two-layer permeable pavement using the hybrid optical fiber MZI and Arduino-based wireless sensing technologies.

2 EXPERIMENT

2.1 Optical fiber Mach-Zehnder interferometer monitoring system

According to the interference theory, the value of the fringe period (Λ) of the MZI at any λ can be expressed as follows [Villatoro et al. (2007), Wang et al. (2012)]:

$$\Lambda = \frac{2\pi\lambda}{(\beta_1 - \beta_2)\cdot L} \tag{1}$$

where λ is the central wavelength of the light source; β_1 and β_2 are propagation constants of the modes involved in the interference, and L is the length of the interferometer. The fringe period is inversely proportional to propagation constant deviation $\Delta\beta = \beta_1 - \beta_2$ and the interferometer length L. The sensing principle is usually based on that as the surrounding environment or the external refractive index changes, the wavelength shift or fringe period of the MZI varies [Villatoro et al. (2007), Wang et al. (2012)].

The fiber-optic sensing system used to measure the transmission spectrum of the sensor consists of a broadband light source (λ = 1520—1620 nm), two homemade sensing MZI interferometers, a lift platform system, and a personal computer with LabVIEW–GPIB system connected with a high-resolution OSA (HP 71450B) for data acquisition. The interference spectra and the relationship between wavelength shift and transmission were used to characterize the Mach-Zehnder interferometers. The two fiber-optic MZI interferometer sensors were placed and a small fixed magnitude of tension was applied to minimize bending of the fiber. The proposed fiber-optic MZI interferometer sensor consisting of two MZIs (MZI 1 and 2 at 5-cm and 30-cm water levels, respectively) in series was fusion spliced and shown as Figure 1, which was used to measure water level and optical fiber-based water-flow velocity (between 5-cm water level and 30-cm water level). There was an 80 cm-long diameter, 50 cm-width, and hollow storage tank having at least a 60-cm water level capacity (see Figure 1). For precise measurement, we kept the experimental setup and sample materials at a constant ambient temperature (within 1°C fluctuation). Therefore, the results reported here were not influenced by the effects of temperature, strain and bending.

2.2 Arduino-based wireless monitoring system

Arduino is an open-source hardware and software project [D'Ausilio (2012)] and our proposed Arduino-based wireless monitoring system consisting of Arduino UNO microcontroller board, programmable with the Arduino IDE (Integrated Development Environment) via a type B USB cable, Arduino Bluetooth module, two DS18B20 temperature sensors, and two water-flow volume sensors. The Arduino-based wireless sensors are two temperature sensors and two flow volume sensors and used to measure the temperature, flow discharge, and flow velocity for two-layer permeable pavement structure at the laboratory. The Arduino-based wireless monitoring system is shown in Figure 1 and this wireless system is proposed to measure the temperature, water-flow volume, and Arduino-based wireless water-flow velocity (between 5-cm water level and 30-cm water level).

Thus, a hybrid optical fiber/wireless sensing system in structural health monitoring for permeable pavements has been proposed to measure water level, optical fiber-based water-flow velocity, temperature, water-flow volume, and Arduino-based wireless water-flow velocity.

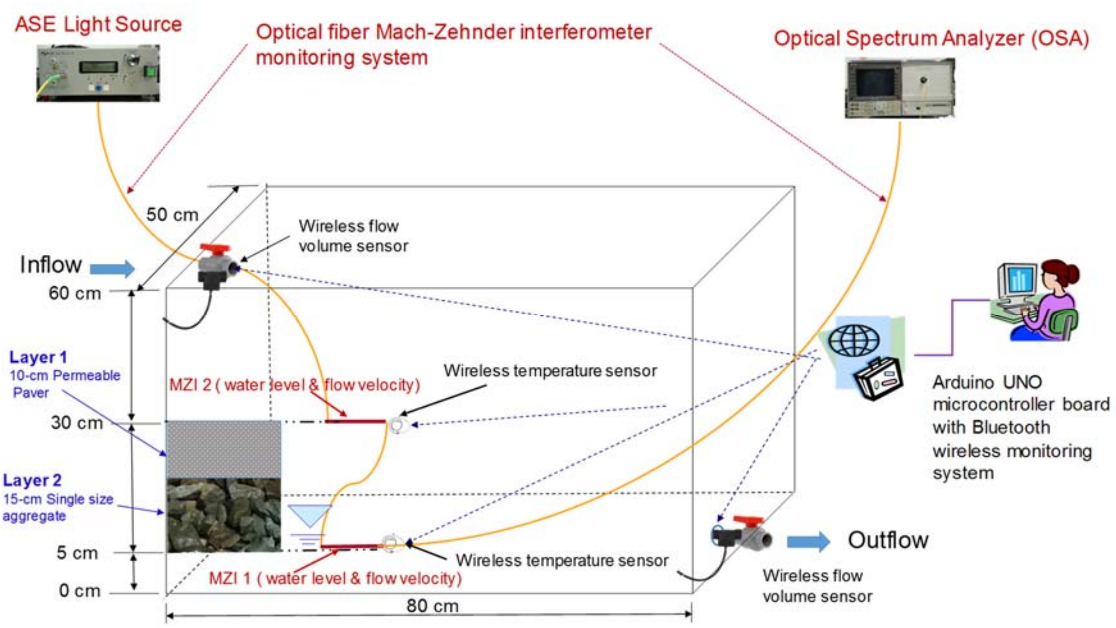

Figure 1. Experimental setup for a hybrid optical fiber/wireless monitoring system for permeable pavement.

3 RESULTS AND DISCUSSION

3.1 Optical fiber Mach-Zehnder interferometer monitoring system

The transmission spectra of the two MZI sensors (MZI 1 and 2 at 5 cm and 30 cm water levels, respectively) during inflow phase is shown in Figure 2 as well as the transmission spectra of the two MZI sensors (MZI 1 and 2 at 5-cm and 30-cm water levels, respectively) during discharge phase is displayed in Figure 3, respectively. It is clear for both Figures 2 and 3, the transmission spectra exhibited different for three water conditions, respectively. Figures 4 and 5 shows the transmission spectra of two MZI sensors for peak 3 during inflow and discharge phases and it is feasible to recognize this three water conditions based on the transmission losses or wavelength shifts, respectively.

3.2 Arduino-based wireless monitoring system

Figures 6 and 7 show the temperature variation of Arduino-based wireless temperature sensor at 5-cm and 30-cm water levels during inflow and discharge phases, respectively. The Arduino-based wireless water-flow velocity (between 5-cm water level and 30-cm water level) can be calculated based on Figures 6 and 7 using the water level difference divided by the time difference between inflow and discharge phases. For flow volume measurements, Figures 8 and 9 shows the inflow and discharge volumes of Arduino-based wireless flow volume sensor during inflow and discharge phases and the accumulated water inflow and discharge volumes was 136.99 L and 135.36 L, respectively.

3.3 Comparison of the hybrid optical fiber/wireless monitoring system

There were two types of water-flow velocity simultaneous measurements: inflow and drainage processes. Table 1 summarizes both water-flow velocities for a hybrid optical fiber/wireless sensing system using optical fiber MZI-based water-flow velocities and the Arduino-based wireless water-flow velocities. For the inflow and drainage processes, the differences between the optical fiber MZI-based water-flow velocities and the Arduino-based wireless water-flow velocities were found in the range of 3.6—4.4%.

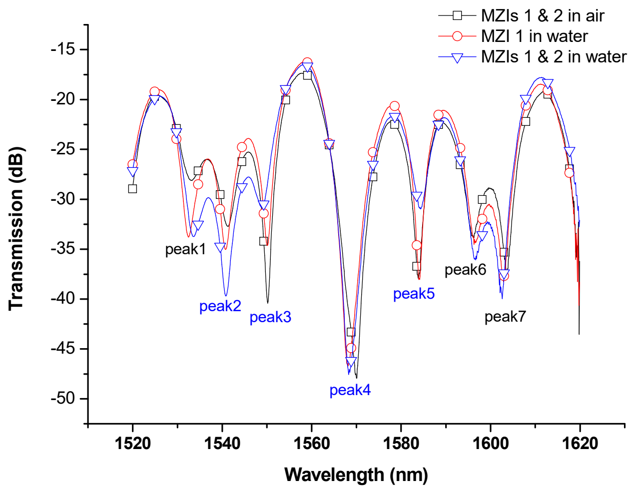

Figure 2. Transmission spectra of the two MZI sensors (5 and 30 cm water levels) during inflow phase.

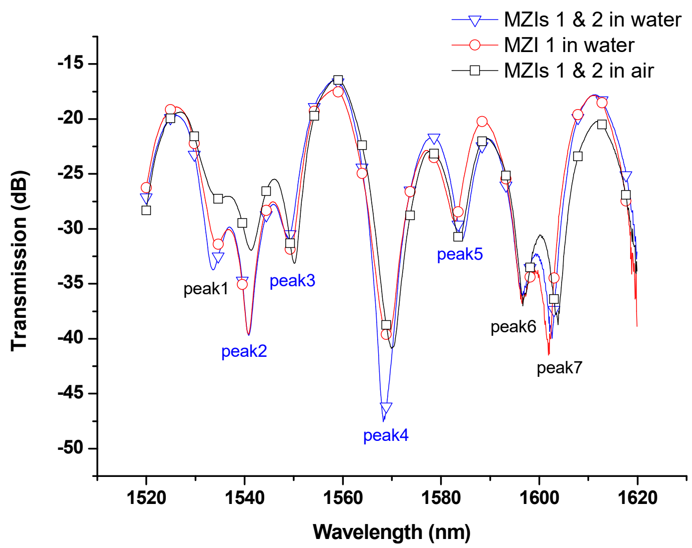

Figure 3. Transmission spectra of the two MZI sensors (5 and 30 cm water levels) during discharge phase.

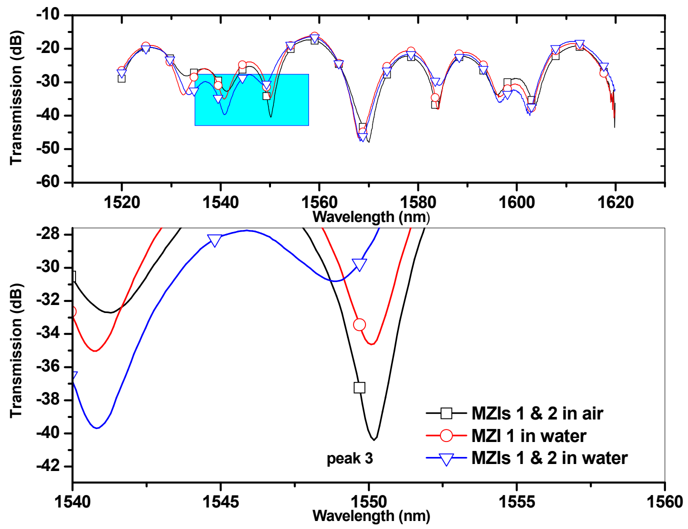

Figure 4. The transmission spectra of two MZI sensors for peak 3 during inflow phase.

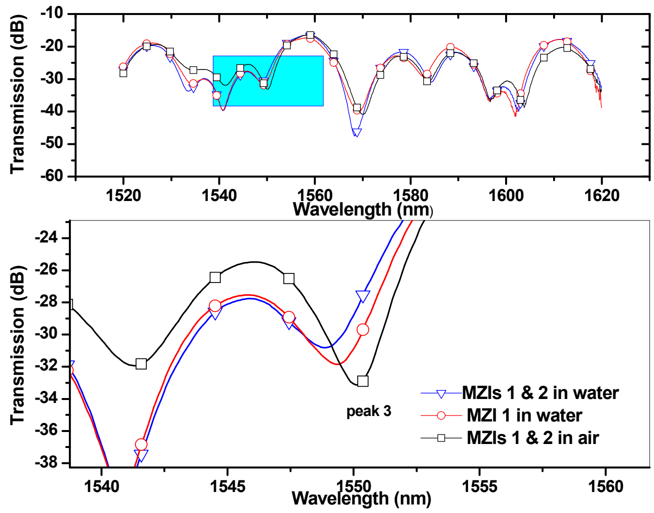

Figure 5. The transmission spectra of two MZI sensors for peak 3 during discharge phase.

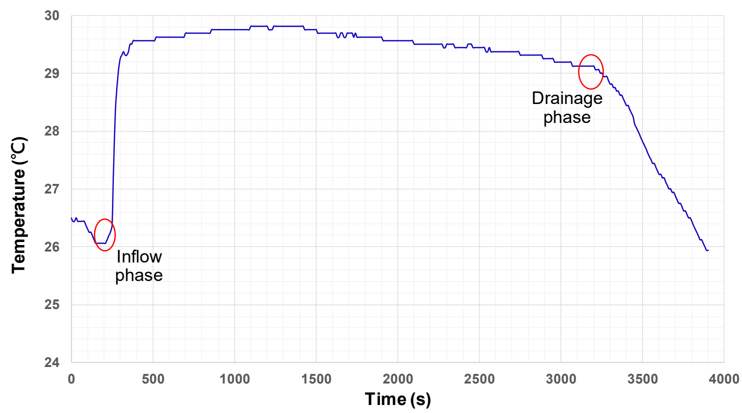

Figure 6. The temperature variation of Arduino-based wireless temperature sensor at 5-cm water level during inflow and discharge phases.

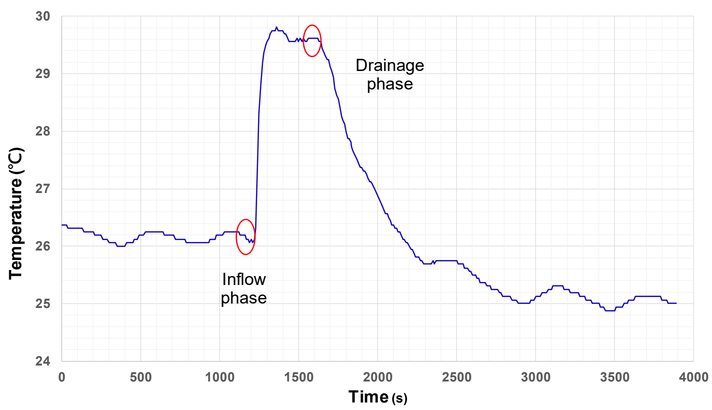

Figure 7. The temperature variation of Arduino-based wireless temperature sensor at 30-cm water level during inflow and discharge phases.

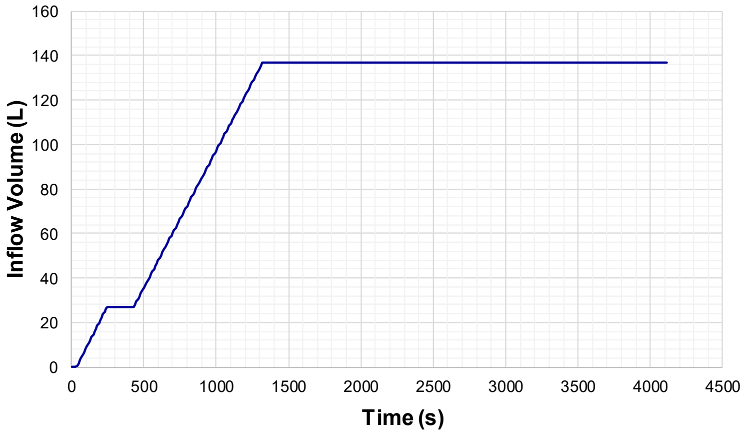

Figure 8. The inflow volume of Arduino-based wireless flow volume sensor during inflow phase.

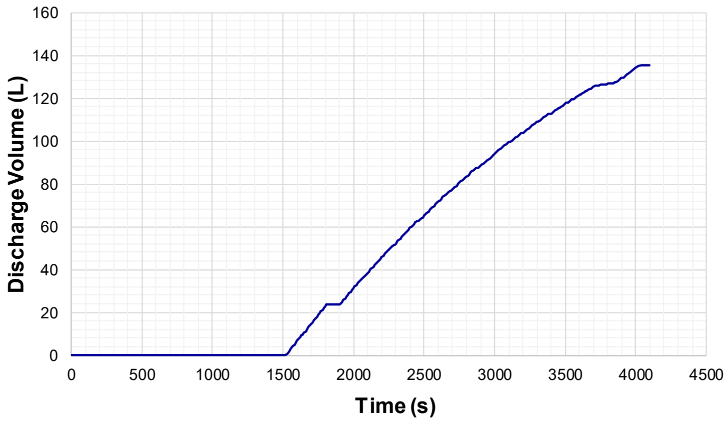

Figure 9. The discharge volume of wireless Arduino-based flow volume sensor during discharge phases.

Table 1. Summary of water-flow velocities for a hybrid optical fiber/wireless monitoring system

Water-flow velocity (cm/s)		
Inflow Phase		
Optical fiber Mach-Zehnder interferometer measurement (cm/s)	0.02388	0.02612
Arduino-based wireless sensing measurement (cm/s)	0.02475	0.02632
Difference (%)	3.6	0.7
Discharge Phase		
Optical fiber Mach-Zehnder interferometer measurement (cm/s)	0.01392	0.01522
Arduino-based wireless sensing measurement (cm/s)	0.01453	0.01520
Difference (%)	4.4	1.4

4 CONCLUSIONS

We have successfully demonstrated the feasibility of a hybrid optical fiber/wireless monitoring system for a two-layer permeable pavements and simultaneously measured flow discharge, temperature, flow velocity, and water level using the advantages of MZI interferometer and Arduino-based sensing technologies. The MZI-based optical fiber sensor was fusion-spliced a cascade of different length MZIs and used to simultaneously measure the water level and flow velocity for two-layer permeable pavement structure at the laboratory. The Arduino-based wireless sensors are two temperature sensors and two flow volume sensors and used to measure the temperature, flow discharge, and flow velocity for two-layer permeable pavement structure at the laboratory. There were two types of water-flow velocity simultaneous measurements: inflow and drainage processes. For the inflow and drainage processes, the differences between the MZI-based water-flow velocities and the Arduino-based wireless water-flow velocities were found in the range of 3.6—4.4%. We have demonstrated the feasibility of the novel hybrid optical fiber/wireless sensing system in structural health monitoring of permeable pavements simultaneously for water level, flow discharge, temperature, and flow velocity measurements without modifying MZIs or coating chemical compounds. Hopefully, the findings of this study can be utilized to establish the real-time multiplexing hybrid optical fiber and Arduino-based monitoring system for different types of permeable pavements.

5 ACKNOWLEDGEMENT

The partial support of the Ministry of Science and Technology (Taiwan) through grant numbers: MOST 106-2218-E-027-007 and MOST 107-2221-E-224-023 is gratefully acknowledged.

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