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Development of Modular Networked Multi Process Control System: Low-Cost NMAS Simulator

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***Abstract*—A multiple process control system testbed which represents Water Distribution System (WDS) consist of multiple water tanks, sensors, actuators, controllers and data acquisition modules is constructed. This testbed is specifically designed for experimental testing of the designed control algorithm and measurement of controller performance. A TCP/IP and serial communication are used for transmission of the control signals and sensors measurement. These communication channels are used to ensure for easy future modification and enhancement as a Network Multi-Agent System (NMAS) using Ethernet and Wi-Fi. The result of System Identification of the testbed is presented using ARX model.**

Keywords—Arduino, control system, process control, testbed development

I. Introduction

Process control system testbed is an important tool in conducting process control research and crucial in conducting interactive teaching activities related to control system fundamentals. Process control testbed such as networked process-control systems testbed allows the students to have hands-on exploration and exposed them toward progressive technologies in the field [1]. Due to this, a lot of commercial testbeds have been produced and marketed for this purpose. Unfortunately, process control systems testbed is typically very expensive and has a high degree of complexity as a platform. Furthermore, most of it is usually comes with proprietary software, constraining its capacities and ability to be extended and reconfigured. Hence, planning and designing a low-cost testbed utilizing open-source software has gained a significant interest from researchers within the control community [1]–[3].

In the related literature, even though theoretical and simulation works on networked control system (NCS) and networked multi-agent system (NMAS) has seen noteworthy progress, lab scale experimental works are limited. With the advancement in network communication technologies and explosion of the Internet of Thing (IoT) applications, open up opportunity toward practical applications involving NCS and NMAS. Among others, NCS and NMAS application are considered in large public utilities such as power network, air traffic management, and water distribution system (WDS). Utilization of NCS and NMAS control structure offers a lot of advantages compared to the conventional method in terms of modularity, distributed control capabilities, and lower operational and maintenance cost [4].

There are several testbeds are widely used in water level process control such as AMIRA DTS-200 and Quanser Coupled Tank. Several testbeds are commonly connected via communication channels to make them worked within NMAS environment such as in [5]. However, the group of testbeds that formed NMAS are quite expensive. The price can reach up to a few thousand dollars. Thus, this simulator is introduced with a lower cost of implementation.

For example, to enhance WDS operation in times of limited water resources during a disruption, integrated solutions using IoT is suggested [6]–[8]. WDS sustainability has been a growing concern in many developing countries [9]–[13]. With sensors are getting cheaper with the aid of the advancement in electronics, an affordable integrated system can be easily developed and deployed to get real-time information to enhance water management and their overall operations. Motivated by this opportunity, a modular NMAS testbed with Arduino open source package is proposed. The configuration of the testbed represents a generic WDS structure. Arduino microcontroller kit is chosen due to the fact that it has very comprehensive but simple to understand open source software, coupled with reliable and cheap plug and play hardware setup that comes at an affordable price. It also has numerous examples for controlling peripherals that have been preloaded in the open-source Arduino software. It also has wide-ranging completed open source projects that can be useful in the initial development of the testbed [14].

In this paper, a modular design of the testbed is proposed to enable it to represent multiple modes of the configuration of WDS such as branched and looped mode. Plus, the testbed forms the basic standard of WDS which can be easily extended to any arbitrary WDS configuration. The contribution of this paper is to provide a modular testbed as a NMAS experimental research platform within an affordable scale.

This paper is organized into four main sections. In Section Ⅱ, a methodology of constructing up the testbed is described. The approximated derived model using system identification and data collection method is explained in Section Ⅲ. Section Ⅳ describes the future goals of the on-going research while the conclusion of the work presented in Section Ⅴ.

II. Testbed Development

The testbed is designed as a multiple process control system to represent the structure and framework of basic WDS. It is composed of multiple water tanks, sensors, actuators, controllers, and data acquisition modules. Each tank is controlled by a designated microcontroller that capable to communicate with other microcontrollers. The communication between the controllers is established through serial communication which transmits control signals and sensor measurements.

A. Modularity of Testbed Setup

The fabricated tested is designed to be reconfigurable to represent various multi-agent control system setup. The overall dimension of the testbed is 55 cm x 40 cm x 81 cm. It is built with modular water tubes and communication network to vary the network topology and configuration of the whole systems. Each water tanks on the testbed represent as a single agent. The water tubes can be removed, added or connected to one another to represent the desired system.

B. Selection of Transducer

A differential pressure sensor MPX2010DP is attached to each tank on the testbed to quantify the level of the stored liquid (water). This pressure transducer is selected according to certain requirements. The rated pressure is 10kPa, which is equivalent to a meter depth of water. This pressure transducer has two inlet ports, a pressure port (P1) and vacuum port (P2) which consists of 4 pins for electronic connections. P1 contains silicone gel to isolate the die from the environment and produce positive differential pressure measurement if the pressure in P1 is greater than in P2. At equilibrium state, both ports transmit output voltage of 2.5V. When P1 asserted more pressure than P2, the voltage output on pin 2 will rise while the voltage output from pin 4 will drop. The difference of voltage measurement produced by this pressure sensor is varied up to 12.5mV. This measurement, however, is too small to be read by Arduino. Hence, the operational amplifier (op-amps) is utilized to amplify the signal before it was sent to Arduino hardware.

In this fabricated testbed, the LM324 operational amplifier is used. LM324 is ideally equipped with quad op-amps under one chip which share common power and ground connections. The raw signal in Figure 1 is filtered where the amplification of sensor voltage limits any swings from 1.5V up to 3V as can be seen in Figure 2.

C. Microprocessor

In this testbed, Arduino UNO microprocessor is used as it offers the most cost-effective and user-friendly solution. Digital Signal Processor (DSP) is a faster microprocessor, however, it is far too expensive compared to Arduino and has poor External Machine Interface (EMI) protection. The next generation of microprocessor after DSP is PIC microprocessor. It is considerably cheap, but slower than DSP and requires expensive compiler with a poor interface that relies on C programming. In recent years, Arduino is widely used as a microprocessor in control system due to its low-cost price and ability to use analog I/O.

Arduino is an open-source platform that provides digital and analog I/O and can be used to adopt the Processing/Wiring language for a certain enhancement in control. Arduino functions either as a stand-alone object or can be connected to available software on the host machine. Although it requires custom hardware for peripherals, it is capable to process advanced signals with build in the power management system.

Arduino UNO used in this testbed is the ATmega328 model that contains 14 digital I/O pins including 6 pins of 8-bits PWM outputs, 6 analog inputs, and serial that receives (RX) and transmits (TX) TTL serial data. It has a 16MHz crystal oscillator, USB connection, and a power jack. It operates within 5V and may hold up to 40mA. Arduino is connected to a computer that provides a power supply, to read the transmitted data and to process the received signals.

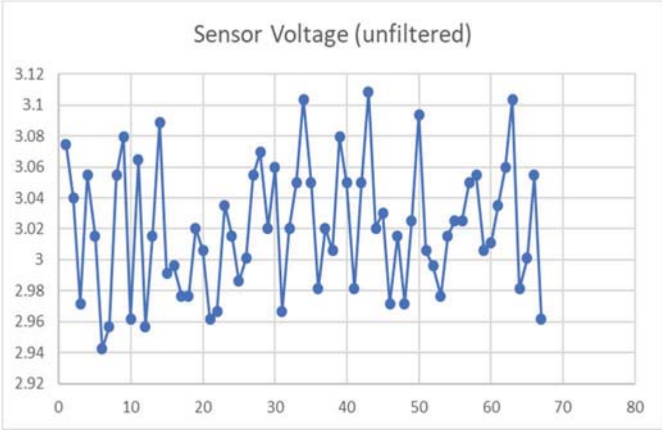

Fig. 1. Unfiltered sensor data

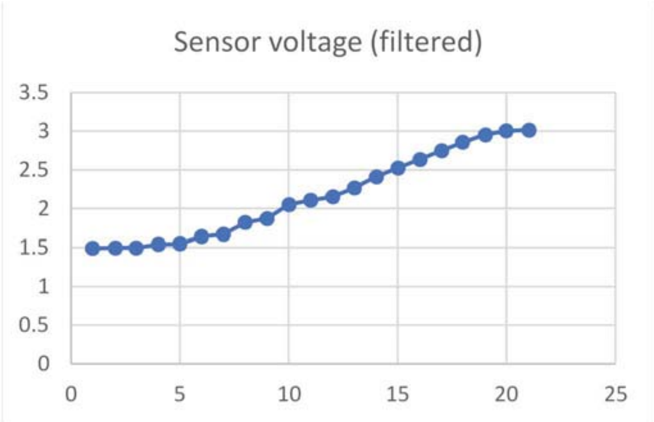

Fig. 2. Filtered sensor data

D. Data Acquisition (DAQ)

In a control system setup, DAQ equipment is critical equipment used for collecting and processing data. For this testbed, in addition to the microprocessor, Arduino UNO is also used as DAQ. The Support Package for Arduino Hardware in Simulink block library enables Simulink to produce executable arrangement and run it on the targeted hardware.

Data collection is performed when the Arduino board sends commands to the actuator (12V DC brushless motor pump) in voltage and the output of water level is received and recorded simultaneously through reading from the transducer (MPX2010DP differential pressure sensor). A Simulink model is developed to run the process. The host machine is continuously communicated with Arduino board to transmit and receive the data and conversion is generated through variations of gain to be read as the level in centimeter (cm).

Figure 3 shows the model that runs on the Arduino Uno board where the Voltage Command to Pins block receives data from the serial port and channels the voltage commands to the pins accordingly. Serial communication protocol enables the communication between the host computer and the Arduino board. An analog input pin on Arduino delivers a serial message of level in the *CreateMessage* subsystem. The model runs on the target hardware and ready to attain I/O data in real-time continuously by the host computer until the end of the execution time as shown in Figure 4.

The reference voltage is varied to excite the system, and then the corresponding outputs are recorded. At the end of the simulation, the signal logging feature in Simulink will create a data set in the workspace that contains the logged signals according to the duration settings. Next, the collected data is ready for estimation and validation. A few data sets are created to ensure adequate excitation of the system and to provide sufficient data for model estimation and validation.

E. Calibration

In order to increase the measurement accuracy, calibration of the sensor is done to get the best reading from the transmitted signal and to synchronize the value displayed with the actual reading of level in cm. It is performed by adjusting the multiturn variable resistor on the signal amplification circuit. Measurement of the output voltage and the actual level of water in the tank is tabulated in Table 1.

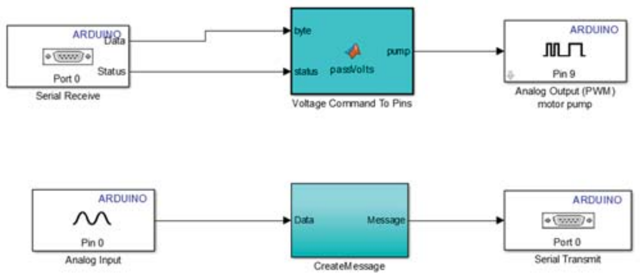

Fig. 3. Simulink model to run on target hardware

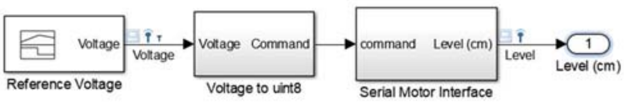

Fig. 4. Simulink model to run on host machine

TABLE I. TABLE OF SENSOR VOLTAGE

Water Level (cm)	***Sensor Voltage (V)***
0	2.04
2	2.07
4	2.11
6	2.15
8	2.18
10	2.22
12	2.26
14	2.31
16	2.35
18	2.39
20	2.43
22	2.47

a. cm = centimeter, V = volt.

F. System Identification

To model the water tank system, black-box system identification method is used. By using this method, the system's structure is assumed to be unknown parameters and the model is developed based on a set of data and observation from the system.

Through System Identification toolbox in MATLAB, the data obtained from the DAQ system is saved into *iddata* sets. Then, estimations and validations can be made to capture the response of the system. The data sets should be estimated using simple estimation, for instance, transfer function with low-order systems for simplicity of controller design. In this paper, the data is estimated using transfer function estimation with continuous-time. The data is estimated using two poles, no zero and without fixed delay on the input.

III. RESULTS

A. Model Identification

The testbed for a single tank system provides a best-fit response as the same input implemented. The results can be seen in Figure 5.

The Auto-regressive with eXogenous input (ARX) model is presented as ARX221 which has higher fit to data up to 90% of the original data with 7.536e-08 FPE and 7.534e-08 MSE. It focusses on prediction data.

The ARX221 model is a basis which can be extended to design a control algorithm with such equation produced above.

The equation of ARX221 model is given by,

$$A(z)y(t) = B(z)u(t) + e(t) \qquad (1)$$

where,

$$A(z) = 1 - 1.977z^{-1} + 0.9974z^{-2} \qquad (2)$$

$$B(z) = -1.469e^{-05}z^{-1} + 1.391e^{-05}z^{-2} \qquad (3)$$

In this model, the system of this work is represented by a mathematical equation in (2) and (3) which can be implemented in NMAS simulation research study.

Initially, 17 cm is set as the reference input of the system. It can be seen that the system reached the reference in 52 seconds with occurrence of some fluctuations.

B. Communication between Agents

Communication data transfer that communicates between one and another can be performed by plugging the Ethernet shield onto the Arduino. Then, the network connectivity is configured and set up for data transfer. Local Area Network (LAN) acts as a medium of transmission allowing one agent to send online data to another agent that receives the data. Transmission Control Protocol/Internet Protocol (TCP/IP) Ethernet and serial communications are used to communicate the agents. The architecture of data transfer is described as shown in Figure 6.

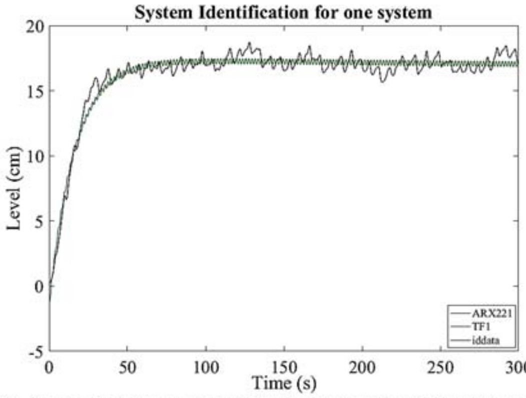

Fig. 5. Comparison of System Identification using transfer function and ARX model

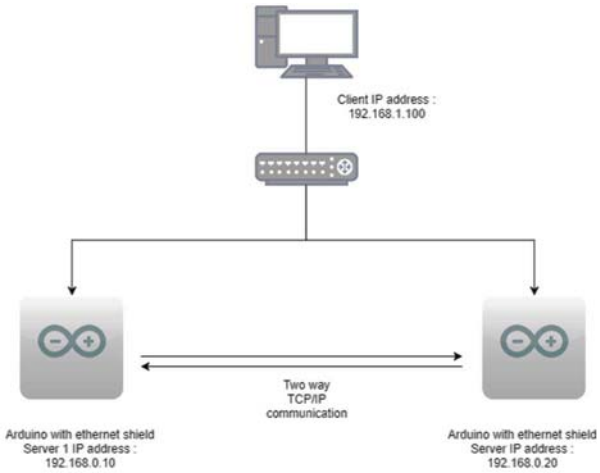

Fig. 6. Communication flow between agents

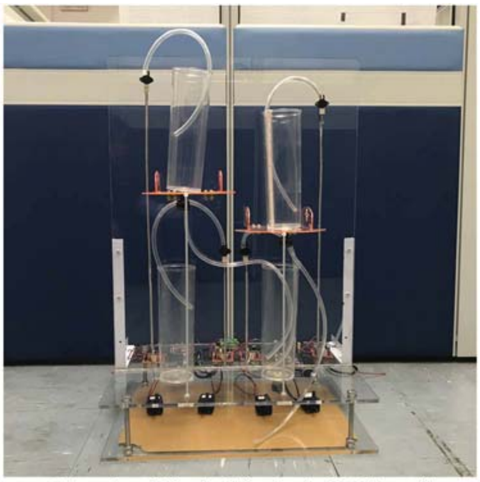

Fig. 7. Low-cost Educational Testbed for basic WDS configuration

IV. Future Directions

A. Control Strategy

After the system identification took place, a model will be developed to design an appropriate controller to achieve desired goals. For instance, the PI controller can be adopted for a simpler application of low-order control while Model Predictive Control can be modelled with some constraints.

B. Network Communication

Next, this testbed will be implemented with networks communication that will enable the systems to communicate with one another. With the presence of the Simulink Support Package for Arduino Hardware, it is easier to adopt network communication using ethernet or wi-fi for the control system integration.

C. Network Multi-Agent System (NMAS)

Fundamentally, a combination of numerous sensors, actuators, and tanks within a water supply facility creates a characteristically distributed and heterogeneous control system. The testbed can be developed within NMAS framework to represent the structure of basic WDS as can be seen in Figure 7.

Distributed consensus-based control has significant potential to efficiently manage this type of system. The water distribution can be governed by the consensus-based control according to the optimal network topology to establish a smart and resilient water distribution system.

There a many significant works can be found on consensus-based control strategies. Consensus means an agreement achieved depends on the state of all agents. Consensus protocol or algorithm defines the interaction between an agent and its neighbors that exchanging information over communication network in NMAS. Consensus is a part of fundamental problem in distributed control system. Prior research has suggested numerous types of consensus including average consensus, min-max consensus, consensus function, logical consensus and external or tracking consensus.

In addition, there are also various characteristics of NMAS to be explored. The studies of consensus problem can be conducted for either a homogeneous of a heterogeneous NMAS with constraints such as network delay and network data loss.

V. Conclusion

The structure of multiple process control system is presented by the testbed that composed of multiple water tanks, sensors, actuators, controllers and data acquisition module that approximately adopts the application of a WDS in a much affordable environment. This testbed is developed to apply numerous experiments that can be implemented in the control system. The ARX model has the best fit to estimation data which makes the system is suitable for prediction as the equation is ready to be implemented in MPC in the future. The serial communication is implemented for transmission of the control signals and for the transmission of the sensor measurement with some future goals that soon can be developed as NMAS using the ethernet and wi-fi as a communication medium. This work can be further extended by adding a consensus-based control to enhance the reliability of the testbed.

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