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Letters

An I2C based architecture for monitoring legacy manufacturing equipment

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ABSTRACT

The Industrial Internet of Things (IIoT) has the potential to improve manufacturing through increased productivity and decreased costs by collecting, processing, and acting upon process data. Recent manufacturing equipment can provide the necessary data needed by IIoT, but most legacy machines cannot. This severely limits IIoT implementation since most production machines are legacy equipment. To overcome this limitation, this paper describes a low-cost architecture based upon the Inter-Integrated Circuit (I2C) communication protocol that can support IIoT systems by collecting data from sensors placed on legacy equipment. The proposed system is designed, fabricated, and validated on a horizontal band saw.

1. Introduction

Applying IIoT towards manufacturing is predicted to have a large positive effect on productivity, costs, and traceability. As a result, equipment vendors are investing in controllers and instrumentation that can provide the necessary data to IIoT systems to support their customers [1–3]. Unfortunately, most legacy machines lack this capability, and replacing them is cost prohibitive. Thus, a cost-effective solution is needed to measure data from legacy equipment and transmit the results to IIoT systems.

A significant barrier to instrumenting legacy equipment is the lack of interoperability among devices. Though a sensor setup can be used towards a specific machine, there is no guarantee that the same sensor system can be applied towards other equipment. In addition, new sensor types are continuously being developed, but replacing existing sensors can be costly and time consuming. Furthermore, raw sensor signals are rarely of direct use to the manufacturer and therefore they need to be converted into an understandable result. To achieve the conversion, deterministic sampling and signal processing is needed, which can severely burden the capabilities of a microprocessor, especially if multiple sensors are involved.

I2C is a promising communication protocol for transferring processed data from local sensors to a single controller. The I2C communication protocol uses two bus lines to connect slave devices to a bus that enable a master device to ping slave devices by their particular address [4]. In contrast, the Universal Asynchronous Receiver/Transmitter (UART) protocol requires an additional two bus lines for each individual master-slave communication. Thus, I2C can collect data from many sensors by using four wires, where each sensor is addressed by a unique code. This allows I2C devices to be easily added, replaced or swapped. I2C also requires less overhead and cost than implementing protocols such as Ethernet for the exchange of data among devices in close proximity. I2C has been demonstrated in various applications, including environmental observation [5,6], healthcare monitoring [7,8], and image processing [9].

In this paper, a low-cost, flexible, and nonintrusive sensor architecture using I2C communication for enabling processing monitoring of legacy equipment is proposed. In the proposed system, sensors are connected to microcontrollers as sensor packages, which act as I2C slave devices that communicate to a single I2C master. In the following sections, the architecture is described in detail and then implemented on a legacy machine as a case study. The results of the case study are presented followed by conclusions.

2. Architecture description

A schematic of the proposed architecture is shown in Fig. 1. The retrofit sensing system consists of the following components:

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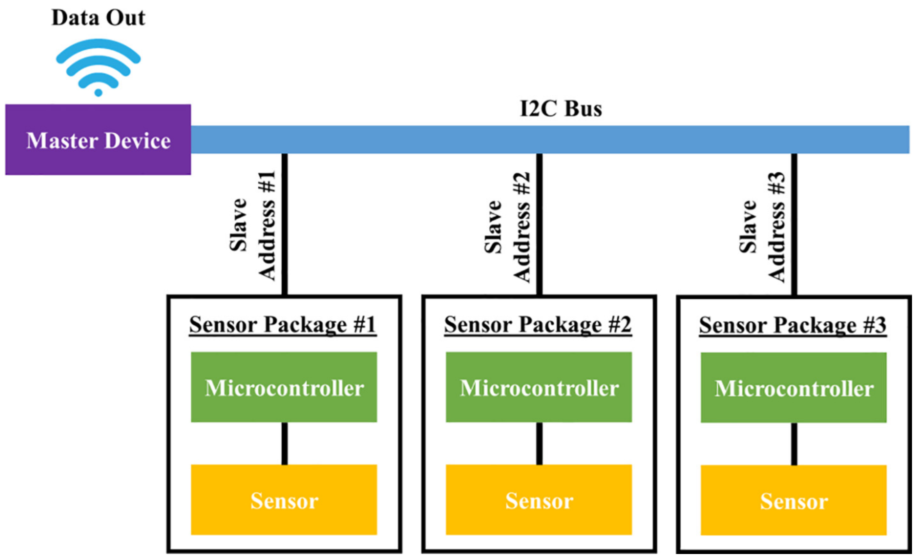

Fig. 1. Schematic of proposed architecture.

1. Sensor devices that can attach to the legacy equipment. As sensors are plentiful and becoming less costly, a variety of hardware is available to non-intrusively convert physical process parameters to digital signals. Such sensors include mechanical switches, acoustic emissions, vibration sensors, strain-based measurement systems, current sensors, and temperature sensors. Note that viable sensors' communication protocols include, but are not limited to, analog voltage, UART, SPI, I2C, and GPIO. For time series-based analog measurements, analog voltage is recommended due to its ability to enable signal processing.
2. Microcontrollers for processing the data and communicating to the master device. Due to recent advances in embedded electronics, low-cost options including Teensy [10], mbed [11], and Arduino [12] are available for processing sensor data. The significant results from the processed data are sent to the master device. Thus, transmitting only significant signal characteristics reduces the master device's requirements for power and sensor communication bandwidth. In addition, the microcontrollers can be placed near their corresponding sensors, thus reducing signal noise. Therefore, the microcontroller must support the sensors' communication protocol and be able to communicate with the master device.
3. Master device for data collection. The I2C master device receives the processed data from the microcontrollers. The master device can be configured to receive data from slaves when an event occurs or ping devices at specific intervals. The master device can then process the packages into a standard protocol formats, including Message Queue Telemetry Transport (MQTT) and Representational State Transfer (REST), for sending to higher level systems.

Note that the proposed architecture can easily integrate multiple sensors as stated previously. However, the architecture's efficiency decreases with the number of sensors. Thus, if using only one or two sensors, the I2C bus protocol can be replaced with UART.

3. Case study and results

The proposed system architecture was fabricated and implemented in the following case study. The goal of the case study was to monitor the status of a horizontal band saw machine tool over the span of machining 4 parts. The experimental setup is shown in Fig. 2. A Beaglebone Black was used as the master device, which is a low-cost (~$50) Linux-based single board computer with 65 General Purpose Input Outputs that can implement three I2C busses [13]. During this case study, multiple devices were connected to a single I2C bus. To monitor the machine tool status, three sensors were used: a 3-axis accelerometer (Memsic MXR9500MZ), an electret microphone (Challenge Electronics CEM-C9745JAD462P2.54R), and a magnetic switch set (Little Fuse 59145-030). The magnetic switch was mounted on the moving arm of the band saw to determine when a cut was complete. The magnetic switch was wired to a Teensy 3.2, which transmitted a running count of manufactured parts via I2C to the Beaglebone. The number of cuts over time indicates the throughput of the machine.

The accelerometer and microphone were each connected to a Teensy 3.2. The Teensies, using their 16-bit analog-to-digital converters, measured the output voltage from the sensors at a rate of 2048 Hz. A Fast Fourier Transform (FFT) running on the Teensies were used to generate a 1024 bin frequency decomposition. The sum of the magnitudes as a measure of the total system energy

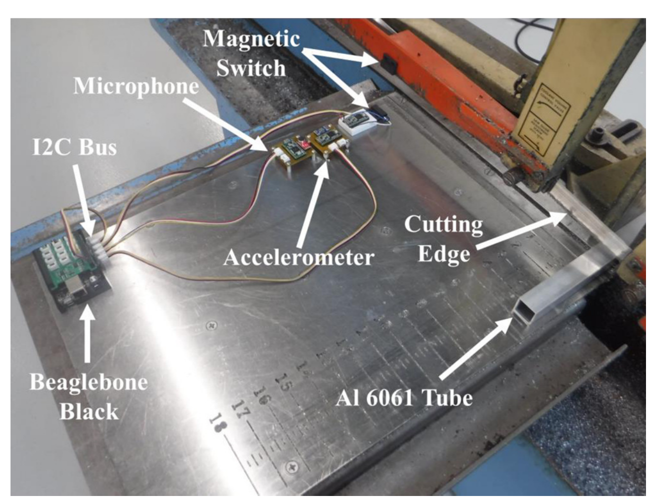

Fig. 2. Experimental setup for architecture demonstration.

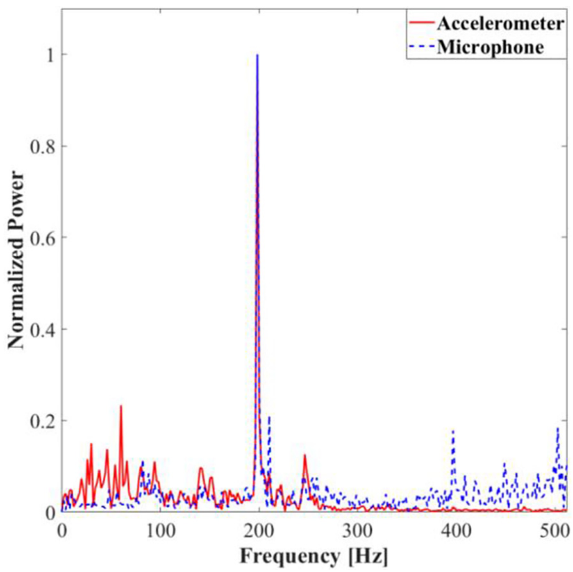

Fig. 3. Accelerometer and microphone FFT output.

was sent to the Beaglebone using I2C. The total system energy was used to demonstrate the processing capability of the proposed architecture, though other processed results, including the most dominant harmonics, could have been transmitted. Fig. 3 displays an example of the frequency decomposition that was produced by the accelerometer and the microphone.

To determine if the horizontal band saw was operational, a univariate control chart was implemented. The Upper Control Limit (UCL) and Lower Control Limit (LCL) of the chart was set as:

$$UCL = L_c\sigma, \quad LCL = -L_c\sigma \tag{1}$$

where L_c is chosen based on the allowable false alarm rate and σ is the standard deviation of the signal's FFT sum when the motor is running and no material is being cut. This state was chosen as the control variable because the upper control limit can indicate that the band saw is cutting while the passing of the lower threshold can indicate that the motor is off.

Because the sum is assumed to be a Gaussian distribution, L_c can be determined as:

$$Z_c(z \leqslant L_c) = 1 - \alpha_f/2 \tag{2}$$

where $Z_c(z)$ represents the cumulative distribution function of a standard Gaussian distribution and α_f is the false alarm frequency [14]. For this case study, L_c is set to 4, which corresponds to a false alarm rate of 6E-5. Thus, if the sum of the accelerometer/microphone's FFT magnitudes is larger than 4 σ of the control variable (indicating that the system energy has increased), the band saw was considered to be cutting. If the sum is less than 4 σ of the control variable, then the system energy has decreased, thus signaling that the motor is turned off and the saw is not cutting. If the state of the motor has changed, the Teensy sends a message to the master device indicating the change.

The data sent to the Beaglebone Black is sent to an external computer using serial communication for data storage and representation. Fig. 4 shows the operational state output of accelerometer and magnetic switch sensor packages using the proposed architecture. In addition, the proposed architecture is shown to accurately track the number of parts manufactured. The total number of parts manufactured is shown to correlate with a decrease in total FFT power because the band saw's motor automatically stops after it has finished a cut. Thus, the I2C based architecture is demonstrated to appropriately monitor the machine tool state of a legacy machine.

4. Conclusion

An architecture to monitor legacy machines based on the I2C protocol that provides several benefits was proposed and validated in a case study. Benefits of I2C include: low-cost, minimal overhead, a small number of wires to implement and the support of many low-cost microcontrollers. I2C can also be used to greatly reduce sensor signal noise by digitizing analog sensor data and

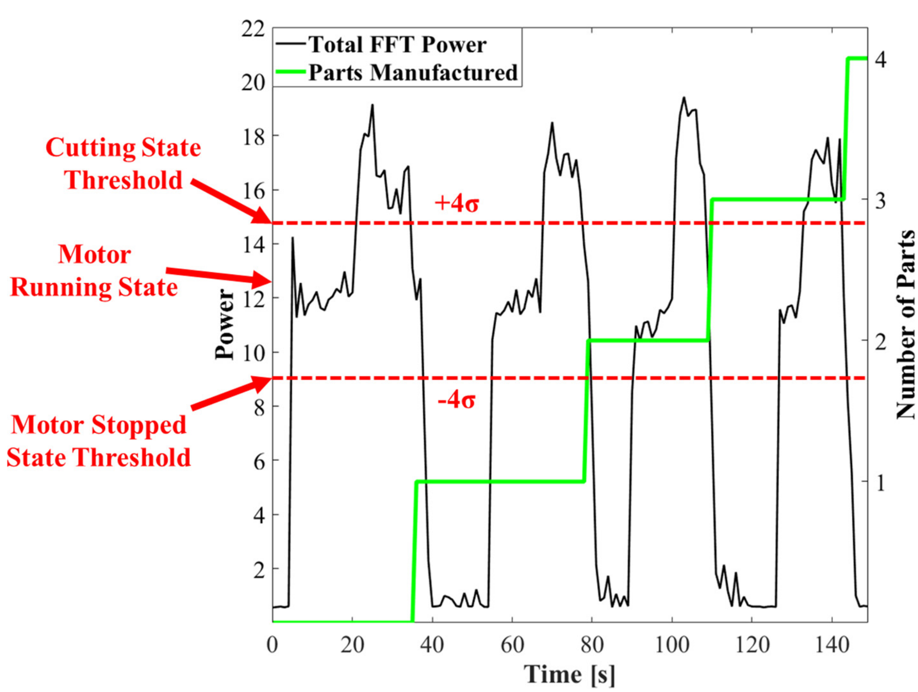

Fig. 4. Machine tool status output from the sensor system.

transmitting it via I2C, which is much less susceptible to noise, by using an enabled microprocessor located next to the sensor. The proposed I2C architecture has been demonstrated to combine and process a variety of sensor outputs into compressed and understandable results, demonstrating an effective and flexible solution for monitoring legacy equipment.

References

[1] Altintas Y, Erol N. Open architecture modular tool kit for motion and machining process control. CIRP Ann Manuf Technol 1998;47:295–300.
[2] Rober SJ, Shin YC. Modeling and control of CNC machines using a PC-based open architecture controller. Mechatronics 1995;5:401–20.
[3] Yamazaki K, Hanaki Y, Mori M, Tezuka K. Autonomously proficient CNC controller for high-performance machine tools based on an open architecture concept. CIRP Ann Manuf Technol 1997;46:275–8.
[4] Kalinsky D, Kalinsky R. Introduction to I2C. Embedded Syst Program 2001;14:1101–5.
[5] Liao Y, Mollineaux M, Hsu R, Bartlett R, Singla A, Raja A, et al. SnowFort: an open source wireless sensor network for data analytics in infrastructure and environmental monitoring. IEEE Sens J 2014;14:4253–63.
[6] Mainwaring A, Culler D, Polastre J, Szewczyk R, Anderson J. Wireless sensor networks for habitat monitoring. In: Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications, Association for Computing Machinery, 2002, pp. 88–97.
[7] Agnihotri A. Human body respiration measurement using digital temperature sensor with I2C interface. Int J Sci Res Publ 2013;3:1–8.
[8] Lo BP, Thiemjarus S, King R, Yang G-Z. Body sensor network–a wireless sensor platform for pervasive healthcare monitoring, (2005).
[9] Rahimi M, Baer R, Iroezi OI, Garcia JC, Warrior J, Estrin D, Srivastava M. Cyclops: in situ image sensing and interpretation in wireless sensor networks. In: Proceedings of the 3rd international conference on Embedded networked sensor systems, ACM, 2005, pp. 192–204.
[10] Teensy USB Development Board, PJRC, LLC., 2017.
[11] Arm Mbed, Arm Limited, 2017.
[12] Arduino Uno, Arduino, 2017.
[13] Beaglebone Black, Beaglebone.org, 2017.
[14] Univariate and multivariate control charts, NIST/SEMATECH e-Handbook of Statistical Methods, National Institute of Standards and Technology, 2013.