Embedded Fog Computing for High-Frequency MTConnect Data Analytics

Roby Lynn, Ethan Wescoat, Dongmin Han, Thomas Kurfess

Abstract

Many modern machine tools are equipped with MTConnect implementations to manage data produced during machining. However, manufacturers still need access to data that may not be provided by the machines in the MTConnect format. The recent trend towards Internet of Things (IoT) and fog computing has paved the way for manufacturers to deploy low-cost, MTConnect-compatible embedded data acquisition and analysis devices at the shop floor level. This paper describes the development and validation of a fog compute node based on an embedded Linux computer that is capable of high-speed realtime sampling and analysis of spindle vibration from an accelerometer.

Keywords

Fog computing, CNC, MTConnect, embedded systems, machine monitoring

Introduction

As manufacturing operations become more sophisticated and rely more heavily on data collection for process monitoring and optimization, a need has arisen for systems that enable high-quality acquisition from both modern and legacy manufacturing equipment. While large scale manufacturers have created custom, proprietary systems needed for machine monitoring, many small manufacturing enterprises (SMEs) do not have the capital or personnel to develop such systems and instead must rely on affordable or open-source platforms [1]. Recent developments have focused on the creation of IoT devices that enhance data availability from the factory floor [2], [3]. Although some vendors have developed disparate systems for monitoring specific pieces of data, such as temperature or power consumption, there is a need for an integrated approach to monitoring a spectrum of data available from multiple sensors that can thoroughly describe the operating condition of a piece of manufacturing equipment [4]. Such a system should not only be deployable directly on the factory floor, but it should also be capable of acquiring data at a high enough frequency for analysis of rapidly changing process dynamics [5]. The concept of deploying IoT devices at the machine itself (as opposed to housing centralized monitoring systems in a remote location) is known as fog computing; the IoT devices, or fog nodes, reside between the factory floor and a cloud-based data management system to avoid sending large sets of raw data through the factory network to be analyzed elsewhere. A robust fog node suitable for machine monitoring should allow for the collection, analysis, and packaging of both low-frequency (e.g. temperature) and high-frequency (e.g. vibration) data without unnecessarily consuming valuable factory network bandwidth [6].

The MTConnect Standard

MTConnect is an open, royalty-free, and read-only standard for data transmission from manufacturing equipment [7], [8]. The MTConnect standard defines eXtensible Markup Language (XML) schema to govern the format of various data items that a certain machine can transmit. A complete MTConnect system consists of two essential components: an adapter, which is a machine specific component responsible for converting data into a standardized format; and an agent, which collects and stores data from one or more adapters and serves them via the Hypertext Transfer Protocol (HTTP) to other networked devices. Although many modern machine tools are set up to provide some MTConnect-compatible data through adapters that are provided by the machine builder, access to data not provided by the machine requires deployment of additional MTConnect-compatible devices. In this case, the fog compute node represents an additional adapter that collects data, specifically Samples, from external sensors. The combination of MTConnect data from both the machine itself and from the fog compute node can be written to a single agent that provides the data to clients.

Manufacturing Data Analytics

As manufacturing industries move towards a service-oriented approach, many researchers have sought to increase the availability of data from a manufacturing operation to enable factories to respond more quickly to rapidly-changing market conditions [9]–[12]. While some of these works rely on proprietary-architecture DAQ systems, others have demonstrated that disparate fog compute nodes built on open-architecture platforms can be used as an alternative. Narayanan, *et al* showed a successful implementation of low-cost and open-source platforms to monitor machine health [13]; Suprock, Nichols, and Fussell created a high-bandwidth, low-cost Bluetooth-enabled toolholder for milling vibration measurement [14], [15]; and Lynn, *et al* developed a variety of disparate low-cost systems for wirelessly monitoring a machine tool that could detect spikes in vibration amplitude [16]. Other researchers have relied on data availability directly from a machine tool in the form of MTConnect to perform both production control and machine monitoring. Vijayaraghavan and Dornfeld developed a framework for machine tool energy consumption and analysis using various frequencies of data acquisition with a cloud-based system [18]; Lee, *et al* used MTConnect to implement a system to enable continuous process improvement by analyzing machine tool energy consumption [19]; and Lynn, *et al* developed web applications with open-source tools to track machine utilization and production from multiple pieces of equipment using MTConnect data [20]. However, there is a deficiency of works that explore MTConnect-based fog computing for high frequency acquisition and analysis using embedded platforms.

Development of a Fog Compute Node for High-Frequency Data Acquisition

Acquisition of accelerometer data for the purposes of vibration analysis requires realtime sampling of an analog signal at sufficient frequency to avoid aliasing. This requirement implies that a suitable DAQ system must be able to not only sample the signal at regular time intervals, but also process and package the signal to transmit it to an MTConnect agent. The Beaglebone Black (BBB) was selected as the platform for the fog node; it provides multiple analog ports, Ethernet connectivity, realtime acquisition capabilities using two onboard Programmable Realtime Units (PRUs), and the ability to perform Fast Fourier Transforms (FFTs) using open-source libraries [21]. A high sensitivity accelerometer (Analog Devices ADXL203) with adjustable bandwidth, sensitivity of 1.0 V/g, and ±1.7 g measurement range was used to detect spindle vibration.

Vibration Analysis

The PRUs on the BBB were configured for a sampling rate of 1825 Hz with a sample size of 2048 [22]. A Python application using the NumPy module was created to calculate the real-valued FFT and extract the spindle speed by finding the frequency with the largest magnitude [23]. The frequency resolution *df* of the FFT can be calculated by

$$df = \frac{f_s}{N} = \frac{1825}{2048} = 0.891 \text{ Hz} \tag{1}$$

where f_s is the sampling frequency and N is the length of the FFT. Considering the trade-off between the sampling time and the frequency resolution, the sample size was kept close to the sampling frequency to ensure that data could be updated at a reasonable rate with acceptable frequency resolution. The total acquisition time T can be expressed by

$$T = \frac{N}{f_s} = 1.122 \text{ seconds} \tag{2}$$

MTConnect Integration

Upon completion of sampling and analysis, the resulting data were timestamped and written as Samples to an MTConnect adapter at a user-determined update rate that must be chosen to limit network bandwidth consumption. The MTConnect adapter was implemented within the Python application running on the BBB and communicated with an external MTConnect agent using a Transmission Control Protocol (TCP) socket. A diagram describing the operation of the fog compute node is shown in Figure 1. The MTConnect agent used for the node was implemented as an IOx application on a Cisco IE4000 industrial Ethernet switch

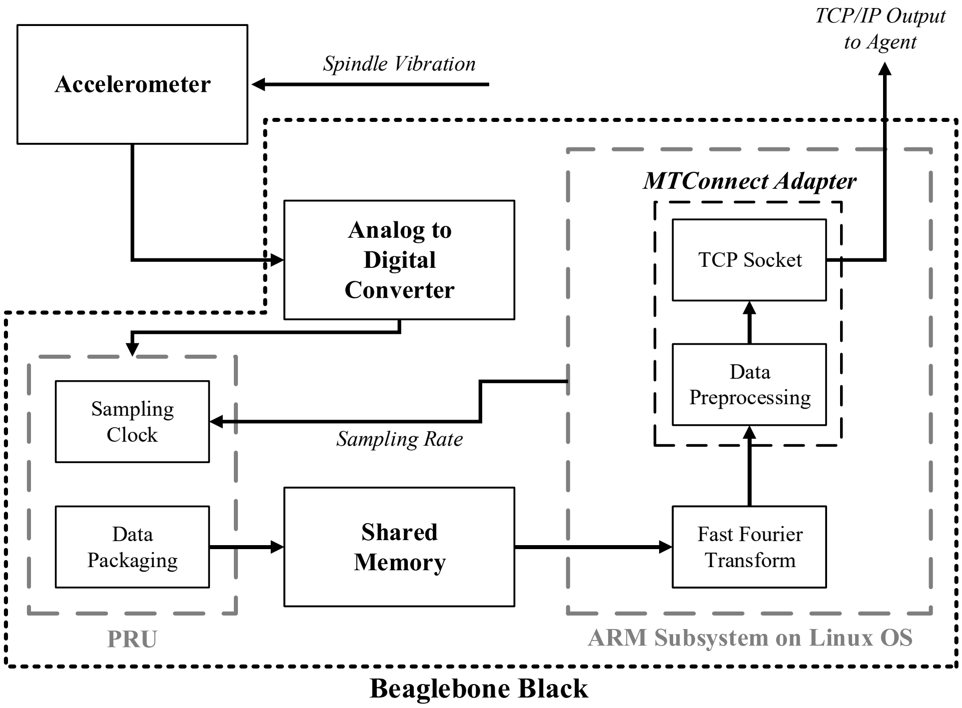

Figure 1. Vibration Analysis and MTConnect Conversion on the Fog Compute Node

within a Mazak SmartBox. The completed system is shown in Figure 2. The accelerometer used for recording spindle vibration is shown mounted on the spindle of a vertical machining center in Figure 2a and the fog node mounted in the SmartBox cabinet is shown in Figure 2b.

a. Accelerometer Mounted to Machine Tool Spindle

b. BBB (Bottom Left) and IE4000 (Top) Mounted in SmartBox Cabinet

Figure 2. Accelerometer and Assembled Fog Compute Node

Spindle Vibration Monitoring

Validation was performed on an Okuma vertical machining center to determine the capability of the fog compute node to analyze spindle vibration. The machine was loaded with a milling tool and the spindle frequency was measured by both the fog node and a National Instruments myDAQ at a series of programmed speeds. The fog node calculated the FFT and transmitted the resulting spindle speed to the MTConnect agent every five seconds, while the myDAQ served to validate the results of the fog node. Data were collected from the agent using an Excel application [24]. The five second update rate, although modifiable by the user, was chosen to allow the accelerometer to account for changes in spindle speed, limit network bandwidth consumption, and ensure that the fog node was capable of maintaining the deadline for data transmission. Data update rates below five seconds caused the BBB to occasionally miss the transmission deadline. Table 1 presents the numerical results of the spindle speed calculation experiment. The entire data set with samples spaced every five seconds is shown in Figure 3. Each horizontal line on

Table 1. Programmed and Calculated Spindle Speed as Measured by BBB System

Programmed Spindle Frequency (Hz)	***Spindle Frequency Calculated by Fog Node (Hz)***
3000	2994.14
3900	3903.08
4500	4491.21
5400	5400.15
6000	5988.28

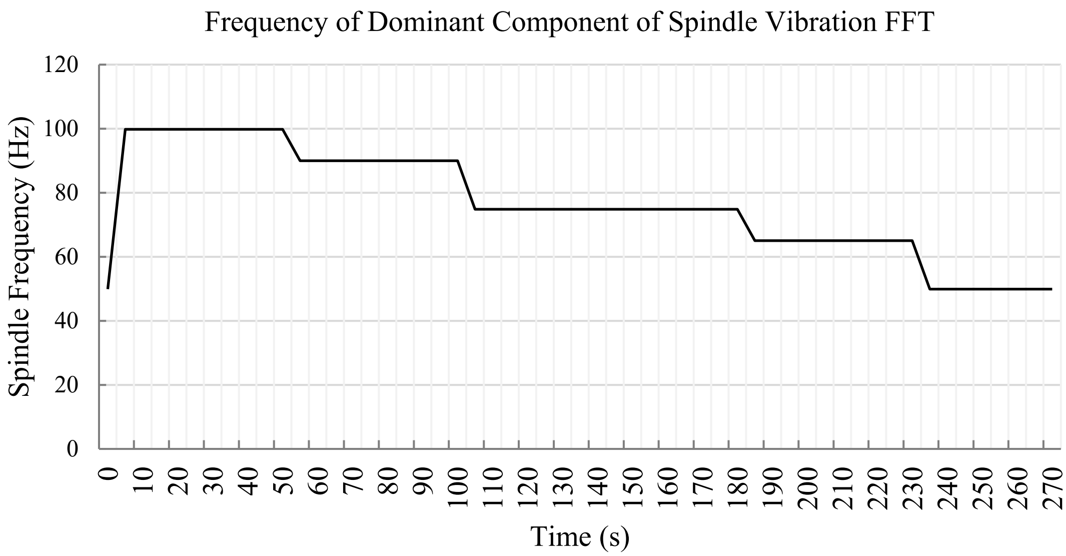

Figure 3. Spindle Frequency Measurement from the Fog Node

the graph represents a different programmed spindle speed at which the calculated speed stabilized. The system could quickly account for the changes being made to the speed and thus no miscellaneous data points between changes in speed were observed.

Conclusions

Data analytics applications in manufacturing frequently require access to signals that must be sampled at a high frequency for accurate results. A popular solution to acquire these signals is to use an expensive off-the-shelf DAQ system; however, for some manufacturing operations, this may be out of reach. Recent interest has been shown in fog computing, which relies on networkable computation using IoT devices on the shop floor. This research described an implementation of a fog compute node for spindle vibration analysis that relies on an inexpensive embedded Linux computer. Time domain acceleration data were acquired by the fog node from a high-bandwidth analog accelerometer in realtime and analyzed in the frequency domain using an FFT. The results demonstrate that a fog node based on the BBB can measure vibration at the relevant frequencies where a machine tool spindle would operate. Monitoring of the data provided by the fog node can enable identification of spindle problems before catastrophic spindle failure occurs; for instance, if dominant frequencies were to appear that did not match the programmed spindle speed, the spindle could be scheduled for inspection or repair. Specific areas of interest for future work include coolant concentration, fluid temperature, metrology, and machine position measurement.

Acknowledgements

This research was supported by NSF grants IIP-1631803, CMMI-1646013, DGE-1650044, and UI Labs Contract Number 0320170002.

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