ARTICLE IN PRESS

Manufacturing Letters xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Manufacturing Letters

journal homepage: www.elsevier.com/locate/mfglet

Letters

Embedded fog computing for high-frequency MTConnect data analytics

Roby Lynn *, Ethan Wescoat, Dongmin Han, Thomas Kurfess

George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

A R T I C L E I N F O

Article history:
Received 5 September 2017
Accepted 27 November 2017
Available online xxxx

Keywords:
Fog computing
CNC
MTConnect
Embedded systems
Machine monitoring

A B S T R A C T

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.

1. 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].

1.1. 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 configured 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.

1.2. 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

* Corresponding author.
E-mail address: roby.lynn@gatech.edu (R. Lynn).

https://doi.org/10.1016/j.mfglet.2017.11.002

[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 vibration spikes produced by a machine tool spindle [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 [17]; Lee et al. used MTConnect to implement a system to enable continuous process improvement by analyzing machine tool energy consumption [18]; 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 [19]. However, there is a deficiency of works that explore MTConnect-based fog computing for high frequency acquisition and analysis using embedded platforms.

2. 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, package, and transmit the data 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. 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.

2.1. Vibration analysis

The PRUs on the BBB were configured for a sampling rate of 1825 Hz with a sample size of 2048 [20]. 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 [21]. The frequency resolution *df* of the FFT can be calculated by

$$df = \frac{f_s}{N} = \frac{1825}{2048} = 0.891\ \text{Hz} \quad (1)$$

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

$$T = \frac{N}{f_s} = 1.122\ \text{s} \quad (2)$$

2.2. 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 Fig. 1. The MTConnect

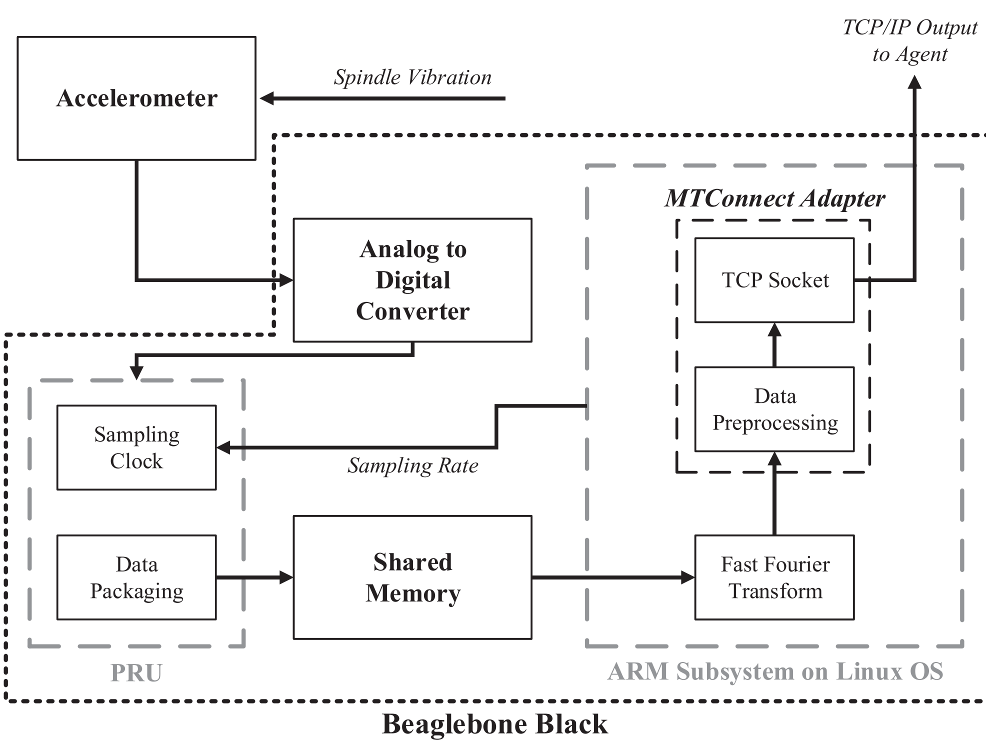

Fig. 1. Vibration analysis and MTConnect conversion on the fog compute node.

Please cite this article in press as: Lynn R et al. Embedded fog computing for high-frequency MTConnect data analytics. Manuf Lett (2017), https://doi.org/10.1016/j.mfglet.2017.11.002