Embedded Agent based on Cyber Physical Systems: Architecture, Hardware Definition and Application in Industry 4.0 Context

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Abstract: Industry 4.0 is promoting a new Industrial Revolution through the application of computer and communication technologies for the construction of Cyber Physical Systems (CPS), which can be considered a key component for the development of this new revolution. In this context, this article proposes to implement an architecture for embedded intelligent agents based on CPS. For this, it is proposed a classification of hardware suitable for boarding this agent. Through this classification a device and initial testing of the agent is selected using the MTConnect standard, which currently presents itself as a potentially efficient standard for this application given the guarantees of some communication requirements. The initial tests presented satisfactory results in the system against the requirements of communication, processing and storage. In addition, the benefits of the proposed architecture over traditional automation systems are presented. Finally, the possible scenario for validation of this architecture is presented.

1 INTRODUCTION

The evolution of the industrial environment is fundamental for the supply of human demands. And as new needs and challenges arise, technological innovations need to emerge to meet those demands. Throughout history, the industrial scenario underwent three major transformations: the 1st Industrial Revolution was characterized by the mechanization of production, with the invention of the steam engine. The introduction of electricity and creation of assembly lines, characterized the 2nd Industrial Revolution. The 3rd Industrial Revolution emerged in the 1970s, when the electronics and information technology industries were still developing the automation of production processes (Drath and Horch, 2014).

According to (Kagermann et al., 2013), the introduction of the German program called *Industrie 4.0* has given rise to the challenge that is presented as the 4th Industrial Revolution, in which intelligent machines and components can communicate autonomously. Thus, decisions on the shop floor can be made by the machines themselves, from information provided in real time. Another important feature, which can be highlighted from Industry 4.0, is the integration of various technologies related to the system, focusing on its cybernetic representation. Cybernetic representation can be seen as a digital representation of the real entity, so it is also called Digital Twin (Lee et al., 2015).

Within this new world that is being idealized, some concepts gain great prominence and direct influence for the development of the 4th Industrial Revolution. Cyber Physical Systems(CPS) (Jazdi, 2014) and Internet of Things (IoT) (Shrouf et al., 2014) are some of the concepts that have contributed to the already known and emerging technologies applied to industrial manufacturing.

For (Zhou et al., 2015), Industry 4.0 is a vision for the future, as it currently faces many difficulties and challenges, including scientific challenges, technological challenges, economic challenges, social problems and political issues. Examples of scientific and technological challenges include the development of intelligent devices, building the network environment, large data analysis and processing, and digital manufacturing.

The ability to communicate and transfer data between different devices (sensors and actuators) within an industrial environment emerges as one of the pro-

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blems to be solved for the new industry infrastructure. Several standards have emerged to ensure that equipment from different sources can collect and transmit data in a safe and efficient way.

Another point that has a great prominence in this scenario is the decentralization of control and increment of complexity for the accomplishment of all the operations. Thus the need to develop the autonomous behavior of the system through approaches such as multi-agent systems.

In this context, the present article proposes a classification of Single Board Computers (SBC) for industrial applications based on an intelligent agent based CPS architecture. Once the CPS architecture, based on 5C (Lee et al., 2015), was developed, it was necessary to define constraints for supported hardware to deploy it. The CPS architecture aims to meet most of the principles of Industry 4.0 using established technologies. The SBC classification indicates which levels of the CPS architecture on each device type are able to run on it.

2 OVERVIEW OF CONCEPTS AND TECHNOLOGIES FOR INDUSTRY 4.0

This section presents some concepts of techniques as well as technologies that are gaining prominence with the development of the next industrial revolution.

2.1 Industry 4.0 Principles

Industry 4.0 is based on six basic principles (Hermann et al., 2016):

- Real-time operation capability: consists of instant acquisition and processing of data, allowing decision-making within the constraints time of the environment;
- Virtualization: proposes the existence of a virtual copy of the intelligent factories, allowing the remote traceability and monitoring of all the processes through the numerous sensors spread throughout the plant;
- Decentralization: decision-making can be done by the cyberphysical system according to the needs of real-time production. In addition, machines will not only receive commands, but will be able to provide information about their work cycle;
- Service Orientation: Use of service-oriented software architectures coupled with the Internet of Services concept.
- Modularity: Production according to the demand, coupling and uncoupling of modules in the production, offering flexibility to change the tasks of the machines easily.
- Interoperability: The ability of machines, devices, sensors and humans to connect and communicate through the Internet of Things and the Internet.

2.2 Cyber Physical Systems

According to (Lee et al., 2015) the CPS is a system composed of the union of physical subsystems in network with the computation. The CPS is responsible for connecting the virtual world with physical reality, which integrates computing, communication and storage capacities, and can operate in real time in a reliable, secure, stable and efficient way.

According to (Barbosa et al., 2016) CPS is an essential aspect for the consummation of the 4th Industrial Revolution, ie, is the key point for the current industry transformation in Industry 4.0. Cyber Physical Systems aim to monitor and control industrial processes through a network of intelligent devices and sensors, using virtual models of processes that correspond to real processes models, through the combination of computational, communication and control elements (Kim and Kumar, 2012). With this it is possible to decentralize the decision making, that is, an intelligent device has the power to self-contro

The constitution of CPS may involve the use of various technologies, such as Multi Agent Systems (MAS), Service-Oriented Architecture (SoA), Cloud Computing, Big Data, Machine-to-Machine (M2M) and Visual Computing.

The integration between different technologies aims to contribute to the CPS facing challenges identified in the principles of Industry 4.0. Multi Agent Systems, for example, can contribute on flexibility, robustness, adaptation, configuration and distributed control of these systems.

In the context of Industry 4.0, intelligent agents and Multi Agent Systems share common ground with CPS. They can enable CPS with a myriad of capabilities to achieve complexity management, decentralization, intelligence, modularity, flexibility, robustness, and real-time responsiveness capabilities (Leitao et al., 2016).

2.3 5C Architecture for CPS

Among the CPS architectures, the architecture denominated 5C proposed by (Lee et al., 2015) has great prominence in the literature. It serves as a guide for developing and implementing CPS for industrial applications. This architecture is divided into five levels as seen in Figure 1:

(i) **Smart Connection:** this level is responsible to acquire accurate and reliable data from sensors, controllers and even ERP systems, with seamless and tether-free guaranties;

(ii) **Data-to-information Conversion:** this level is responsible for generating meaningful information from different data sources, which can be achieved using algorithms for prognostics and health management.

(iii) **Cyber:** Considering that this level must to gather massive information, it must use specific analytics to extract additional information about the status of individual components and machines;

(iv) **Cognitive:** This level must generate e provide knowledge of the monitored systems for other components and operators;

(v) **Configuration:** This level acts as a supervisory control since it can attribute self-capabilities for the system generating corrective and preventive decisions.

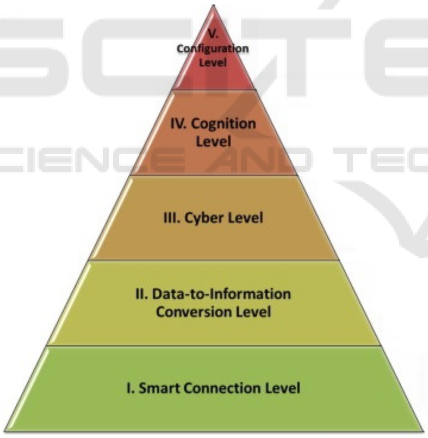

Figure 1: 5C Architecture for Developing a CPS for Industry 4.0 (Lee et al., 2015).

2.4 MTConnect

The ability to connect between different devices appears as one of the main challenges of Industry 4.0. Several standards and protocols have been developed in recent years, and the MTConnect Institute has developed a solution to this problem.

The MTConnect standard is based on standard Internet technologies such as HTTP (Hyper Text Transfer Protocol) and XML (Extensible Markup Language). A system that implements the MTConnect protocol has five fundamental components: Device, Adapter, Agent, Network and Application/Client, arranged according to Figure 2. The most important components are Agent and Adapter.

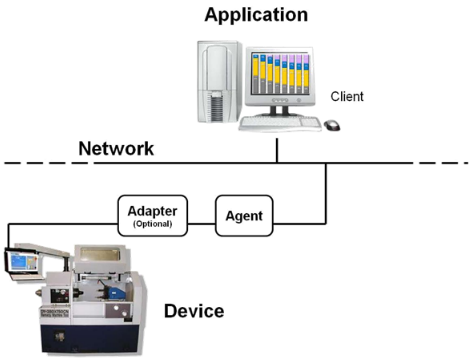

Figure 2: Basic architecture of device connected using MTConnect standard (MTConnect, 2008).

In the context of Industry 4.0 MTConnect emerges as a solver for connection between physical devices of a CPS, acting at the lowest level ensuring the acquisition of data independent of the format or protocol of communication.

3 PROPOSED ARCHITECTURE

This section aims to propose an architecture for the development of intelligent embedded agents based on Cyber Physical Systems. The CPS 5C architecture proposed by (Lee et al., 2015) is taken by reference. The intelligent agent design is based on the characteristics of this architecture and the theory of Multi Agent Systems, in order to enable the construction of intelligent environments compatible with CPS.

The embedded intelligent agent must be able to perceive and interact with the physical medium through sensors and actuators, as well as interact with virtual agents through the network. It can also present control elements, through algorithms such as PID (Proportional-Integral-Derivative Controller) and Artificial Intelligence, promoting distributed control and decentralization.

3.1 Agent Software Architecture

The proposed software architecture for agent development is organized into five modules: configuration, intelligence, cybernetic, conversion and communication.

Figure 3 presents the layout as well as the technologies and functionalities of the agent software architecture modules.

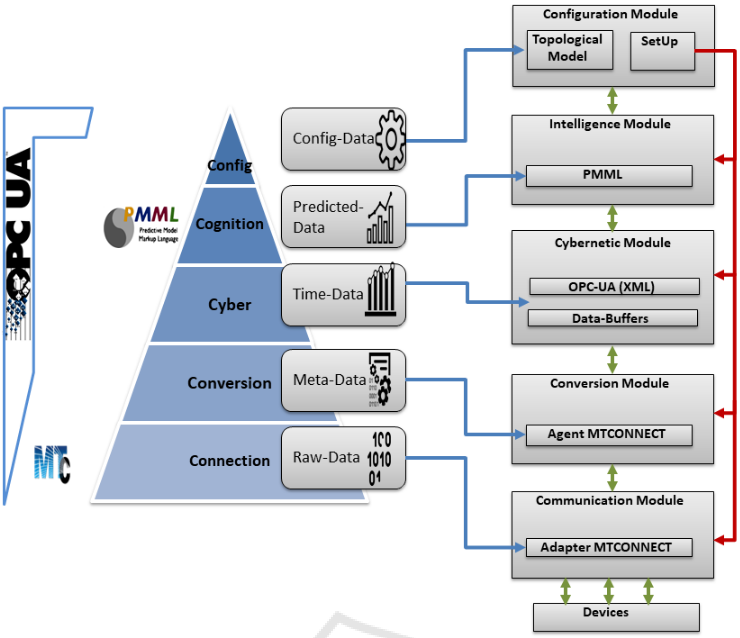

Figure 3: Software architecture in 5 modules.

- Configuration Module: responsible for the configuration interfaces of all the modules. In it are defined interfaces to access and define the properties of the topological model, properties of communication, control, intelligence and storage. The topological model is a hierarchical structure replete with information of the devices, components and systems that make up the agent-managed physical structure, when this is the case. This module requires a complete modeling of all components connected or managed by the agent.

- Intelligence Module: responsible for the mapping and tracking of patterns, behaviors and data quality control. It uses advanced algorithms to point out faults and promotes the predictive and cognitive behavior of the system. From this module emerge basic functions of manufacturing systems, such as control, monitoring, planning and scheduling.

- Cybernetic Module: responsible for the management of system information in order to represent them on a temporal scale through inferences and predictions. It consists of a buffer, which registers the agent data and a data adapter for external databases that enables data acquisition.

- Conversion Module: responsible for the conversion of data collected in the communication module into information for the system, assigning semantics and some type of treatment to guarantee the continuous provision of this information.

- Communication Module: responsible for adapting the different protocols of industrial networks to the standard adopted in the system and to enable interoperability through this standard. The module also provides the model with the topological description of the equipment for the other agents through the network.

The architecture described above imposes greater restrictions on communication and information manipulation for the first three layers, communication, conversion and cybernetics, and greater processing restrictions for the upper layers, intelligence and configuration. From these requirements it was necessary to establish a classification for SBC able to board this architecture. This classification is presented in the next section.

4 HARDWARE CLASSIFICATION

With the technological advancement of the advancement in the past few years, the Single Board Computers (SBC) had an increase of the capacity of processing and memory, reduction of cost and consequently its popularization. Faced with this, several projects have emerged that use this type of hardware for industrial applications.

An SBC is a computer shipped in a reduced form and ready for use. It can be considered as a generic solution in hardware and software that can be used in the development of embedded systems. It provides a complete platform for the development of end products for various applications such as medical, industrial automation, aerospace and robotics.

Thus, this section will be presented recent projects that use the Raspberry Pi platform in industrial applications. A classification of hardware devices will also be performed for the development and implementation of the CPS Agent modules.

4.1 Industrial Solutions using Raspberry Pi

An industrial computer based on Raspberry Pi meeting the IEC 61131-2 standard is shown in (RevolutionPi, 2017). This standard establishes hardware standards for any product in which the primary purpose is the function of industrial control equipment, including PLC (Programmable Logic Controller) or its associated peripherals for the purpose of control and command of machines. Depending on customer requirements, this device may be supplemented by digital or analog I/O modules as well as by appropriate fieldbus gateways to connect it to an industrial network. The base modules and expansion modules are shipped with 24 Volts which is the standard used in the industry.

The Strato Pi (SferaLabs, 2017) base empowers the Raspberry Pi Model B version 2 and 3 models with various hardware features to make it suitable for use in professional applications where reliability and continuity of service are essential requirements.

Modberry (ModBerry, 2017) is a universal controller built with the needs of the automated, telemetric and integrated systems markets in mind. It has several communication interfaces such as digital or analog I/O modules, GPS, Modbus and Wi-Fi.

NetPI (netIOT, 2017) is a Raspberry Pi 3 architecture-based platform for implementing custom industrial automation projects with Cloud, Internet of Things and Industry 4.0 features.

4.2 Hardware Classification for CPS Agent

According to (Newark, 2014), SBC today are basically divided into two categories: proprietary and open source. Proprietary is one who is usually designed for use in final application or as a reference for evaluation. They are industrial projects that go through the same tests that a final product requires. Open source SBCs give users access to the design and layout of hardware and the source code used on the board. This is ideal for all users because they can easily understand how software and hardware operate and adopt design to meet project requirements.

Considering the most popular open source SBC, a classification was created, analyzing characteristics such as: Processing capacity, available memory, I/O devices and connectivity. The classes in turn were defined using only the processing capacity and available memory information of each hardware, as seen in the Table 1.

The characteristics adopted to define the classes of hardware, processing capacity and available memory will serve as the basis for implementations of different types of applications. According to the established classes a set of characteristics such as levels of intelligence, cognition and control, compatible with the structure of the CPS agent module, will be added to each component of the class, or even how many layers of the 5C architecture will be contemplated in each device.

A survey of SBC corresponding to the *Odroid, Raspberry Pi, Banana Pi and Orange Pi* families was carried out and the following classes were defined:

- **Class A** - Devices with Quad Core Processors from 1GHz:

  Within this class are the devices with a large processing capacity, having processors with 4 cores that can reach up to 2GHz, and with different capacities of memories, ranging from 512MB to 2GB. Class A SBC are divided into the following subclasses:

  - **Subclass A1** - Quad Core from 1.2 GHz up to 2GHz and 2GB memory;
  - **Subclass A2** - Quad Core from 1.2 Ghz up to 1.5 GHz and 1GB memory
  - **Subclass A3** - Quad Core up to 1 Ghz and 1 GB memory;
  - **Subclass A4** - Quad Core from 1 Ghz up to 1.5GHz and 512 MB memory.

- **Class B** - Dual Core processors of 1 GHz and memory up to 1 GB:

  Class B is characterized by devices that have a considerable processing rate with 1GHz two-core processors, and a memory capacity of up to 1GB.

- **Class C** - Single Core processor with a maximum of 1 GHz and up to 512 MB of memory:

  The class C of SBC is characterized by devices that have a processing rate, can reach up to 1GHz, but only 1 core. Another characteristic point of this class is the low capacity of memory can reach up to 512 MB.

Table 1: Classification of SCB according to their processing and memory capacities.

Device	Processing	I/O	RAM	Connectivity	Class
Banana Pi R2	ARM Cortex-A7 (ARMv7) 1.2GHz Quad Core ARMv7	2x USB 2.0 40pin header	2GB DDR3 RAM	Wi-Fi 802.11n Bluetooth 4.1 Ethernet port	A1
Odroid XU4	Samsung Exynos5422 ARM Cortex-A15 Quad 2.0GHz	2x USB 3.0 1x USB 2.0 30Pin: GPIO/IRQ /SPI/ADC 12Pin: GPIO /I2S/I2C	2GB LPDDR3 RAM PoP stacked	Ethernet port WLAN Antenna	A1
Odroid C2	Amlogic ARM Cortex-A53(ARMv8) 64 bits 1.5Ghz Quad Core	4x USB 2.0 1x USB OTG 40pin GPIOs 7pin I2S GPIO]/I2C/ UART/ADC	2GB 32bit DDR3 912MHz RAM (512MByte x4pcs	Wi-Fi adapter Ethernet RJ-45	A1
Odroid C0	Amlogic S805 SoC ARM Cortex-A5 (ARMv7) 1.5GHz Quad Core ARMv7	2x USB 2.0 40pin (GPIO/UART/ SPI/I2C/ADC) 7pin port (I2S)	1GByte DDR3 32bit RAM (512MByte x 2pcs) 792Mhz	WLAN with Antenna	A2
Raspberry Pi 3	Broadcom BCM2837 4 x ARM Cortex-A53 1.2Ghz 64bit ARMv7	4x USB 2.0, 40 pin port GPIO / UART / SPI / I2S	1GB 32bit LPDDR2 450MHz	Wi-Fi 802.11n Bluetooth 4.1 Ethernet port	A2
Raspberry Pi 2	Broadcom BCM2836 4x ARM Cortex-A7 900MHz ARMv7	4x USB 2.0, 40pin port (GPIO/UART/ SPI/I2C/I2S)	1GB 32bit LP-DDR2 400MHz	Ethernet port	A3
Odroid C1+	Amlogic S805 SoC 4x ARM Cortex-A5 1.5GHz ARMv7 Architecture	4x USB 2.0 1x USB OTG 40pin GPIO/UART/ SPI/I2C/ADC) 7pin port (I2S)	1GB 32bit DDR3 792MHz	Gigabit Ethernet WLAN with Antenna	A3
Banana Pi Zero	Cortex-A7 (ARMv7) 1.0 GHz Quad Core ARMv7	Micro USB 40pin GPIO	512 MB DDR3 RAM	Wi-Fi 802.11n Bluetooth 4.0	A4
Banana Pi M1+	A20 ARM Cortex-A7 (ARMv7) 1.0GHz Dual Core	2x USB 2.0 40pin (GPIO/UART/ SPI/I2C/ADC)	1GB DDR3	Wi-Fi 802.11n Ethernet port	B
Raspberry Pi 1	Broadcom BCM2835 ARM11 de 700Mhz Single Core	2x USB 2.0 40pin GPIO	512 GB 32bit LP-DDR2 400MHz	Ethernet port	C
Raspberry Pi 0 W	Broadcom BCM2835 ARM11 de 1GHz Single Core	Micro USB 40pin GPIO	512MB LPDDR2 SDRAM	Wi-Fi: 802.11n Bluetooth	C

5 INITIAL TESTS

This section will present the scenario in which the initial tests were carried out. After this the results obtained with these tests will be presented.

5.1 Methodology

For the initial tests, a Smar PD3 Industrial Didactic Plant, a Raspberry Pi 3 and a computer (Figure 4) were used. The industrial plant has several equipment and instruments such as temperature, flow and level transmitters. These devices in turn are connected to the Nexto3030 PLC from the Altus manufacturer.The algorithm to control the PLC was replaced by one that has a function that acquires and makes available the data from the equipment connected to it via Modbus TCP/IP communication.

With the PLC transmitting plant data via Modbus TCP/IP, a Modbus TCP/IP adapter was implemented in MTConnect. This adapter was implemented using C++ programming language. The adapter has the function of transforming the data obtained from the plant to the MTConnect standard. The

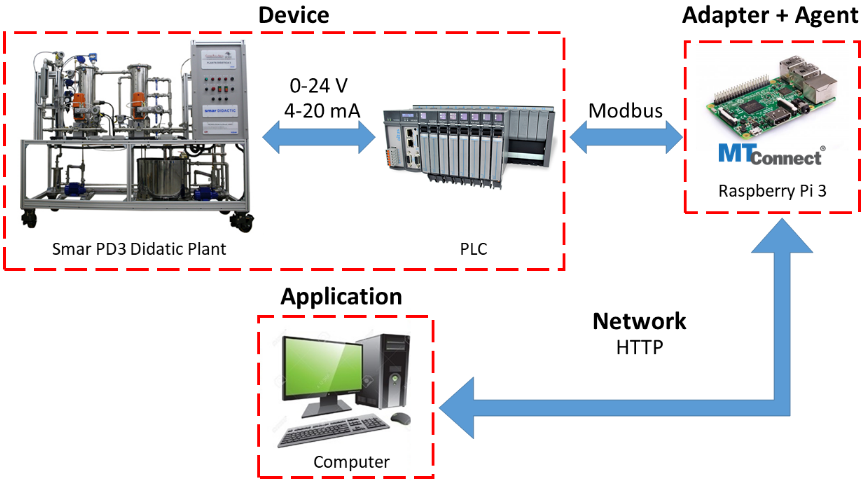

Figure 4: Arrangement and connection of the equipment used in the tests.

topological modeling of the plant was also done in the MTConnect XML standard. The default agent was used, which is also implemented in C++. This agent publishes the adapter data to a standard HTTP page. The adapter and agent run on a Raspberry Pi 3 connected to the Ethernet network of the PLC. An internet-connected computer was also used to access the page that provides the XML generated by MTConnect.

5.2 Results

From the implementation of the agent and adapter it is possible to access through a web browser the HTTP page that displays an XML generated by MTConnect. This XML comprises time series of all events, samples and conditions of the equipment running on the plant. A cut-off the agent response to the sample command can be seen in Figure 5. It is noted that the agent made available all the plant data according to the XML modeling previously done. A comparison with data read directly in the PLC proved the accuracy of the data. It has also been proven that MTConnect fully implements the communication and conversion modules, in addition to implementing part of the cybernetic module through buffer, thus justifying its use.

6 CONCLUSIONS AND FUTURE WORK

This article proposes an architecture of an intelligent embedded system to compose a Cyber Physical System. The embedded agent was based on the intelligent agent theories and based on the CPS architecture named 5C.

It has also been demonstrated the application of this architecture in industrial environments and partial results obtained in the laboratory. Advantages of this architecture include standardization of communication, promotion of distributed control, autoconfiguration, visibility and transparency of data as well as interoperability between agents and applications.

The proposed experiment was able to transform the Modbus TCP/IP data to the MTConnect standard. The MTConnect agent has full capability of executing the communication, conversion, and partial modules of the cybernetic module. These capabilities justify their choice for application of this architecture. The ability of Raspberry Pi 3 to run these modules has also been proven.

As seen in Section 4, SBC devices are increasingly common for applications in industrial solutions today. And the Raspberry Pi platform has been gaining ground due to its high performance, and a considerable cost compared to other platforms. Raspberry Pi devices present the desirable requirementes for the development of this work, as seen in Table 1.

As future work, we can mention the development of a connection interface for the industrial plant equipment to Raspberry, thus dispensing with the use of PLC. The implementation of the other modules, fundamental to the architecture presented in this article, must also be performed. Existing technologies such as OPC UA (Open Platform Communications Unified Architecture) and PPML (Predictive Model Markup Language) present themselves as possible solutions for the implementation of these modules because they have functions provided in them, besides being standards, thus allowing different tools to speak the same language.

In addition, it will be necessary to develop or

```
  <Header creationTime="2018-03-12T17:14:26Z" sender="raspberrypi" instanceId="1520874148"
version="1.3.0.18" bufferSize="131072" nextSequence="101" firstSequence="1" lastSequence="830"/>
  <Streams>
    <DeviceStream name="smar-device" uuid="1">
      <ComponentStream component="Sensor" name="TankFlow" componentId="">
        <Samples>
          <Flow dataItemId="" timestamp="2018-03-12T17:02:39.047062Z" name="tk1flow" sequence="4"
subType="ACTUAL">0</Flow>
        </Samples>
      </ComponentStream>
      <ComponentStream component="Sensor" name="TankTemperature" componentId="">
        <Samples>
          <Temperature dataItemId="" timestamp="2018-03-12T17:02:39.047062Z" name="tk1temp"
sequence="5" subType="ACTUAL">7167</Temperature>
```

Figure 5: Agent response to the Sample command.

adapt essential software for industrial automation such as SCADA (Supervisory Control Systems and Acquisition of Data), Distributed Control System (DCS), and AR-DCS (Augmented Reality Distributed Control System) (Rodrigues, 2016) for communication from the MTConnect standard. Finally, perform performance tests, functionalities and robustness of this system compared to traditional automation systems.

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