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Maker: Design an Application Software for a 3D printer Based on MTConnect

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Abstract

Smart manufacturing technologies improve the productivity, efficiency, and competitiveness for U.S. industries. Key enabling technologies in smart manufacturing are to 1) acquire real-time heterogeneous data from IoTs, sensors, and machines tools, and 2) make decisions from the data using analytics. This Maker project discusses the development of a prototype Application software for a 3D printer based on MTConnect protocol. This Application is able to collect, visualize, and store data from additive manufacturing processes. This project aims to train students about 1) MTConnnect on Adapter, Agent, and Application development, 2) additive manufacturing, 3) database, and 5) communication protocols, for manufacturing operations. The results developed through this project potentially can be used in the "Manufacturing Automation" course to teach students concepts related to the MTConnect.

1 Introduction

Data is the foundation for the smart manufacturing. It drives manufacturing activities such as monitoring health status of equipment, scheduling, prediction and optimization of processes and systems. Nevertheless, data collection at shop floor is a challenge due to the variety of machines with different types of interfaces and communication protocols, which leads to issues related to complexity and interoperability. If data collection is inconsistent, it causes extra difficulties for analytics to generate valuable information and profitable decision for manufacturing operations. In addition to this, many Small- and medium-size manufacturers (SMMs) do not have access to a cost-effective method and expertise on data collection and analysis from their manufacturing equipment. Thus, much of the data generated in their production operations goes in vain. In the context of Smart Manufacturing and Industry 4.0, SMMs need 1) light weighted efficient ways and 2) skillful workforce to collect and analyze the data generated in their operations. To address the complexity issue in data collection, the recent advancement in loyalty-free middleware such as MTConnect and OPC UA (OPC Unified Architecture) allows the development of a unified data collection system that does not rely on proprietary and expensive commercial software. Additionally, these middlewares are open-source, which allows users to freely modify the software for their applications.

Virginia State University (VSU) recently received a subaward from Virginia's NIST-MEP Center (GENEDGE) helping SMMs at Virginia adopt smart manufacturing technologies. In addition to this, the University uses the technology developed through this project to train next generation of Engineers. Equipping engineering students with the knowledge on MTConnect and OPC UA is to prepare them on the necessary skillset related to Smart Manufacturing and Industry 4.0. This paper introduces a Maker project at VSU on developing a MTConnect-based Application software for a Stratsys™ F370 3D printer. With this software, various real-time machine data were collected, visualized, and archived from the printer controller and different sensors such as thermocouple, voltage meter, and current meter. MTConnect was implemented as the communication standard as well as the information modelling technique to realize unified connection, integration, and management in the software. Experimental results validated the feasibility and advantages of the proposed MTConnect-based Application software for the 3D printer.

The rest of this paper is organized as follows: Section 2 presents a brief introduction to the background of MTConnect. Section 3 introduces the system architecture, information model, and key coding techniques of MTConnect-based Application software. Section 4 presents the results of software development. Section 5 concludes the research and outlines the future direction.

2 Background of MTConnect

MTConnect is an open, free communication protocol based on Extensible Markable Language (XML) and Hypertext Transfer Protocol (HTTP) [1]. MTConnect defines the vocabulary and semantics of the information model, which can be retrieved from devices. It serves as a middleware, which enables a unified system connection to avoid the complex driver setup and vendor specific connection. In order to build a MTConnect solution, a developer needs to work on the elements including devices, Adapter, Agent, and Application.

Devices are machine tools, robots, sensors, etc. in manufacturing activities. Adapter is a software component that enables communication between the device and the Agent. The users need to develop Adapter for legacy machines, but many of latest machines already have Adapter enabled for the MTConnect. Agent implements the HTTP protocol, XML generation, and MTConnect protocol. Application accesses the MTConnect Agent and parses the agent's XML output to perform specific tasks such as data visualization, storage, and analytics etc.

To develop an Application, the Agent should provide data items associated with each component in a device [2]. The data item that MTConnect can retrieve from components includes status, failures/faults, process/tooling/machine, energy usage, sensor data, quality data/inspection output etc. With these data, the users can formulate machine information for specific Applications such as utilization, overall equipment efficiency (OEE), energy consumption, maintenance, quality/inspection results, and verifying simulation with real data.

```
<MTConnectStreams xmlns:m="urn:mtconnect.org:MTConnectStreams:1.5" xmlns="urn:mtconnect.org:MTConnectStreams:1.5" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:schemaLocation="urn:mtconnect.org:M
  <Header creationTime="2025-01-15T16:45:23Z" sender="f370D32439" instanceId="1720744529" version="1.4.0.12" bufferSize="131072" nextSequence="165605373" firstSequence="165474301" lastSequence="165605372"/>
  <Streams>
    <DeviceStream name="f370" uuid="D32439">
      <ComponentStream component="Controller" name="Controller" componentId="controller">
        <Events>
          <SerialNumber dataItemId="swBuildVersion" timestamp="2024-07-12T00:35:04.822867Z" name="Build" sequence="179">5976</SerialNumber>
          <SerialNumber dataItemId="swVersion" timestamp="2024-07-12T00:35:04.822867Z" name="Version" sequence="181">2.6</SerialNumber>
        </Events>
      </ComponentStream>
      <ComponentStream component="Enclosure" name="Cover" componentId="cover">
        <Events>
          <DoorState dataItemId="coverOpenState" timestamp="2024-11-12T19:01:39.247197Z" name="OpenState" sequence="108038681">CLOSED</DoorState>
        </Events>
      </ComponentStream>
      <ComponentStream component="Device" name="f370" componentId="dev">
        <Events>
          <Availability dataItemId="avail" timestamp="2024-07-12T00:35:04.822867Z" name="Availability" sequence="266">AVAILABLE</Availability>
          <AssetChanged dataItemId="dev_asset_chg" timestamp="2024-07-12T00:35:04.081592Z" sequence="7" assetType="">UNAVAILABLE</AssetChanged>
          <AssetRemoved dataItemId="dev_asset_rem" timestamp="2024-07-12T00:35:04.081592Z" sequence="8" assetType="">UNAVAILABLE</AssetRemoved>
          <SerialNumber dataItemId="printerSerial" timestamp="2024-07-12T00:35:04.822867Z" name="SerialNumber" sequence="180">D32439</SerialNumber>
        </Events>
      </ComponentStream>
      <ComponentStream component="Enclosure" name="Door" componentId="door">
        <Events>
          <ActuatorState dataItemId="doorLockState" timestamp="2024-11-20T06:58:44.350994Z" name="LockState" sequence="115466783">INACTIVE</ActuatorState>
          <DoorState dataItemId="doorOpenState" timestamp="2024-11-20T19:04:47.400727Z" name="OpenState" sequence="115907181">UNLATCHED</DoorState>
        </Events>
      </ComponentStream>
      <ComponentStream component="Linear" name="ModelExtruder" componentId="m1">
        <Samples>
          <Amperage dataItemId="m1AxisCurrent" timestamp="2024-11-20T06:58:22.874805Z" name="AxisCurrent" sequence="115466409" subType="TARGET">0</Amperage>
          <Amperage dataItemId="m1AxisExtCurrentAvg" timestamp="2024-11-20T06:58:16.689301Z" name="ExtrusionCurrentAverage" sequence="115466188" subType="TARGET" statistic="AVERAGE">0.4194767773</Amperage>
          <DepositionRateVolumetric dataItemId="m1FlowRateAct" timestamp="2024-11-20T06:58:22.874805Z" name="FlowRateActual" sequence="115466408" subType="ACTUAL">0</DepositionRateVolumetric>
          <DepositionRateVolumetric dataItemId="m1FlowRateCom" timestamp="2024-11-20T06:58:22.874805Z" name="FlowRateCommanded" sequence="115466407" subType="COMMANDED">0</DepositionRateVolumetric>
          <Angle dataItemId="m1Follow" timestamp="2024-11-20T06:58:22.874805Z" name="FollowingError" sequence="115466410" subType="ACTUAL">0</Angle>
          <Amperage dataItemId="m1LowerHeatCurrent" timestamp="2024-11-20T06:58:22.874805Z" name="LowerHeatCurrent" sequence="115466412" subType="TARGET">0</Amperage>
          <Temperature dataItemId="m1TAct" timestamp="2025-01-15T16:45:22.792203Z" name="ActualTemperature" sequence="165605366" subType="ACTUAL">83</Temperature>
          <Temperature dataItemId="m1TCom" timestamp="2024-11-20T06:58:22.874805Z" name="CommandedTemperature" sequence="115466397" subType="COMMANDED">0</Temperature>
          <VolumeSpatial dataItemId="m1TipOdometer" timestamp="2024-11-20T06:58:46.130912Z" name="Odometer" sequence="115466820" subType="ACTUAL">832035</VolumeSpatial>
          <Amperage dataItemId="m1UpperHeatCurrent" timestamp="2024-11-20T06:58:22.874805Z" name="UpperHeatCurrent" sequence="115466411" subType="TARGET">0</Amperage>
        </Samples>
```


Figure 1. An Example on Current in MTConnect

The data item can be extracted using commands of /Current and /Sample to the IP address of the device in an HTTP web browser [1]. Current provides the most recent value for each data item.

An example on /Current outputs on a 3D printer is shown in Figure 1. Sample provides a stream of changes from a certain point in time. An example on /Sample outputs on a 3D printer is shown in Figure 2. Current plus Sample provide XML data stream for the device on initial state plus all sample stream in SHDR (Simple Hierarchical Data Representation) format. This data stream can be aligned with timestamps and context.


```xml
<MTConnectStreams xmlns:m="urn:mtconnect.org:MTConnectStreams:1.5" xmlns="urn:mtconnect.org:MTConnectStreams:1.5" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:schemaLocation="urn:mtconnect.org:M
  <Header creationTime="2025-01-15T16:47:05Z" sender="f370D32439" instanceId="1720744529" version="1.4.0.12" bufferSize="131072" nextSequence="165475517" firstSequence="165475417" lastSequence="165606488"/>
  <Streams>
    <DeviceStream name="f370" uuid="D32439">
      <ComponentStream component="Linear" name="ModelExtruder" componentId="m1">
        <Samples>
          <Temperature dataItemId="m1TAct" timestamp="2025-01-15T13:22:19.928647Z" name="ActualTemperature" sequence="165475444" subType="ACTUAL">82</Temperature>
          <Temperature dataItemId="m1TAct" timestamp="2025-01-15T13:22:21.210268Z" name="ActualTemperature" sequence="165475454" subType="ACTUAL">83</Temperature>
          <Temperature dataItemId="m1TAct" timestamp="2025-01-15T13:22:27.364455Z" name="ActualTemperature" sequence="165475510" subType="ACTUAL">82</Temperature>
        </Samples>
      </ComponentStream>
      <ComponentStream component="Enclosure" name="Oven" componentId="oven">
        <Samples>
          <Amperage dataItemId="oven1CurrentAct" timestamp="2025-01-15T13:22:17.402044Z" name="Oven1Current" sequence="165475424" subType="ACTUAL">0.1943999976</Amperage>
          <Amperage dataItemId="oven1CurrentAct" timestamp="2025-01-15T13:22:19.928647Z" name="Oven1Current" sequence="165475447" subType="ACTUAL">2.81159997</Amperage>
          <Amperage dataItemId="oven1CurrentAct" timestamp="2025-01-15T13:22:21.210268Z" name="Oven1Current" sequence="165475457" subType="ACTUAL">2.83679986</Amperage>
          <Amperage dataItemId="oven1CurrentAct" timestamp="2025-01-15T13:22:22.400166Z" name="Oven1Current" sequence="165475467" subType="ACTUAL">2.797199965</Amperage>
          <Amperage dataItemId="oven1CurrentAct" timestamp="2025-01-15T13:22:23.712489Z" name="Oven1Current" sequence="165475478" subType="ACTUAL">0.1871999949</Amperage>
          <Amperage dataItemId="oven1CurrentAct" timestamp="2025-01-15T13:22:24.907128Z" name="Oven1Current" sequence="165475488" subType="ACTUAL">0.1763999909</Amperage>
          <Amperage dataItemId="oven1CurrentAct" timestamp="2025-01-15T13:22:26.188203Z" name="Oven1Current" sequence="165475500" subType="ACTUAL">0.1907999963</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:17.402044Z" name="Oven1CurrentCom" sequence="165475418" subType="TARGET">0.1835999936</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:18.776352Z" name="Oven1CurrentCom" sequence="165475431" subType="TARGET">0.1979999989</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:19.928647Z" name="Oven1CurrentCom" sequence="165475440" subType="TARGET">2.804399967</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:21.210268Z" name="Oven1CurrentCom" sequence="165475452" subType="TARGET">2.81159997</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:22.400166Z" name="Oven1CurrentCom" sequence="165475464" subType="TARGET">2.782799959</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:23.712489Z" name="Oven1CurrentCom" sequence="165475474" subType="TARGET">0.1943999976</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:24.907128Z" name="Oven1CurrentCom" sequence="165475485" subType="TARGET">0.1907999963</Amperage>
          <Amperage dataItemId="oven1CurrentCom" timestamp="2025-01-15T13:22:27.364455Z" name="Oven1CurrentCom" sequence="165475506" subType="TARGET">0.2016000003</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:17.402044Z" name="Oven2Current" sequence="165475425" subType="ACTUAL">0.06480000168</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:18.776352Z" name="Oven2Current" sequence="165475434" subType="ACTUAL">0.06120000035</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:19.928647Z" name="Oven2Current" sequence="165475448" subType="ACTUAL">2.840399981</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:21.210268Z" name="Oven2Current" sequence="165475458" subType="ACTUAL">2.865599871</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:22.400166Z" name="Oven2Current" sequence="165475468" subType="ACTUAL">2.818799973</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:23.712489Z" name="Oven2Current" sequence="165475479" subType="ACTUAL">0.05759999901</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:24.907128Z" name="Oven2Current" sequence="165475489" subType="ACTUAL">0.04320000112</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:26.188203Z" name="Oven2Current" sequence="165475501" subType="ACTUAL">0.03240000084</Amperage>
          <Amperage dataItemId="oven2CurrentAct" timestamp="2025-01-15T13:22:27.364455Z" name="Oven2Current" sequence="165475512" subType="ACTUAL">0.05399999768</Amperage>
          <Amperage dataItemId="oven2CurrentCom" timestamp="2025-01-15T13:22:17.402044Z" name="Oven2CurrentCom" sequence="165475419" subType="TARGET">0.05399999768</Amperage>
          <Amperage dataItemId="oven2CurrentCom" timestamp="2025-01-15T13:22:19.928647Z" name="Oven2CurrentCom" sequence="165475441" subType="TARGET">2.840399981</Amperage>
          <Amperage dataItemId="oven2CurrentCom" timestamp="2025-01-15T13:22:22.400166Z" name="Oven2CurrentCom" sequence="165475465" subType="TARGET">2.807999849</Amperage>
          <Amperage dataItemId="oven2CurrentCom" timestamp="2025-01-15T13:22:23.712489Z" name="Oven2CurrentCom" sequence="165475475" subType="TARGET">0.05759999901</Amperage>
          <Amperage dataItemId="oven2CurrentCom" timestamp="2025-01-15T13:22:24.907128Z" name="Oven2CurrentCom" sequence="165475486" subType="TARGET">0.03599999845</Amperage>
          <Amperage dataItemId="oven2CurrentCom" timestamp="2025-01-15T13:22:26.188203Z" name="Oven2CurrentCom" sequence="165475495" subType="TARGET">0.03240000084</Amperage>
          <Amperage dataItemId="oven2CurrentCom" timestamp="2025-01-15T13:22:27.364455Z" name="Oven2CurrentCom" sequence="165475507" subType="TARGET">0.05759999901</Amperage>
```


Figure 2. An Example on Sample in MTConnect

3 System Development

The Application software was developed on a Stratasys™ F370 3D printer, the overall architecture for the system is as Figure 3. The 3D printer has integrated sensors to measure temperatures, electrical current, electrical voltage, material flow rate, and work axis position etc. It also provides the MTConnect Adapter and Agent to collect machine status and controller data as well as sensory data in XML format.

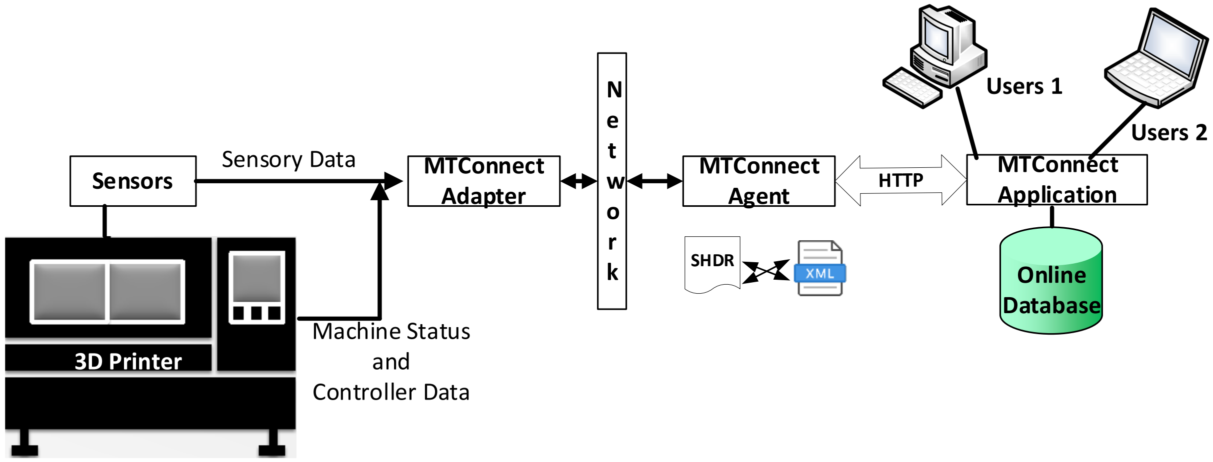


Figure 3. Overall Architecture for the MTConnect Application Software for the 3D Printer

The information model, which includes components and its associated data items, provides a logical structure to extract information from physical asset. The information model for the 3D printer is as Figure 4. The components include axes, extruders, material bays, drive blocks, power, oven, etc., in the 3D printer. The data items enabled for each component is also presented in the model.

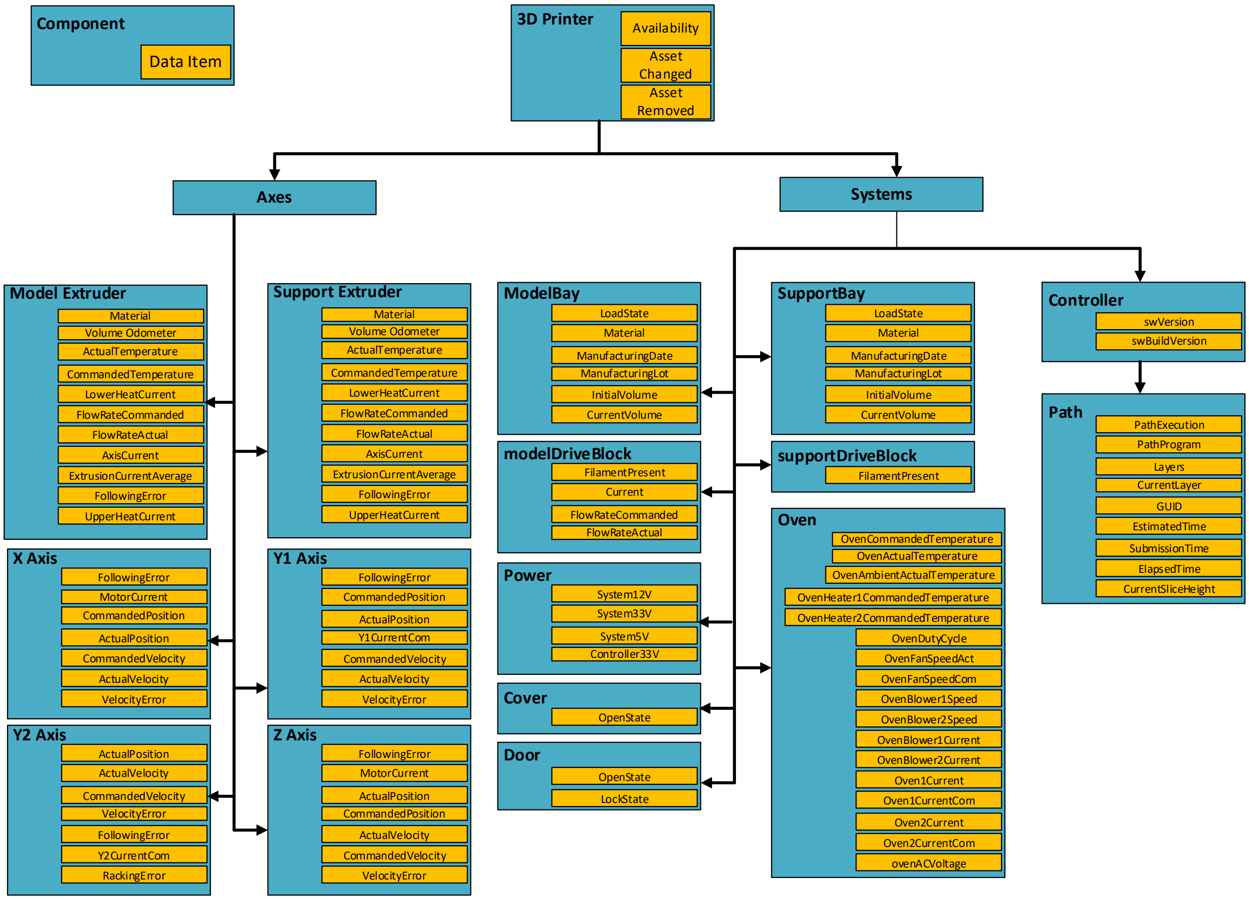


Figure 4. Information Model for the Software

The Application software was developed using Python, because it is a free and open-source with well-designed built-in libraries as well as many third-party open-source libraries and modules available. The MTConnect Application was developed in a Client-Server model. The Sever collects real-time data from the networked 3D printer by sending HTTP requests for access to the MTConnect Agents of the machine. The HTTP requests were performed using Requests library in Python [3] to the XML data illustrated in Figures 1 and 2, then use the parse function in the library of xmltodict [4] to get the current data. The Application sample code to request and parse data from the MTConnect Agent XML page as shown in Figures 5. After the data is parsed, the sever also automatically store and insert the relevant pieces of information into an SQL database using the PyMySQL library [5].

```python
# Attempts to retrieve data of an MTConnect Agent
def requestMTConnectData(debug: bool, machineInfo):
    global lastRequestData
    global nextSequence
    global all_machine_data
    global this_machine_data

    successful = False

    currentDataURL = DEVICE_URL + "/current"
    sampleURL = DEVICE_URL + "/sample?"

    # Go through our recorded machines and collect data for them
    for machine in machineInfo.values():
        machine_data = machine.get_data()
        machine_url = "http://" + machine_data['ip'] + ":" + machine_data['port']

        machine_base_sample_url = machine_url + "/sample?"
        machine_name = machine_data['name']

        if not machine_name in all_machine_data:
            all_machine_data[machine_name] = {
                'name': machine_name,
                'status': 'UNKNOWN',
                'samples': {},
                'sequences': {}
            }

        # Request for each machine
        for i in range(RETRIEVE_RETRY_MAX):
            try:
                this_machine_data = all_machine_data[machine_name]

                current_sequence = this_machine_data['sequences'].get('current_nextSequence')

                # Sequence
                sequence = "from=" + current_sequence if current_sequence else ""

                current_response = requests.get(machine_url + "/current?" + sequence)
                current_data = xmltodict.parse(current_response.content, attr_prefix="")

                this_machine_data['sequences']['current_nextSequence'] = current_data['MTConnectStreams']['Header']['nextSequence'] or current_sequence
                checkForError(current_data, machine_name)

                this_machine_data['current_data'] = current_data
                this_machine_data['components'] = current_data['MTConnectStreams']['Streams']['DeviceStream']['ComponentStream']
```

Figure 5. Sample code on the Server to Get and Parse data from MTConnect Agent

The Client sends commands to the Server to get up-to-date time-series data and append them in categories, and then display the data in different machine views. A sample code for getting and appending the time series data in categories is as below Figure 6.

```python
        data_items = data[machine_name]['samples']['SupportExtruderTemperatures']['Samples']['Temperature']

        for sample in data_items:
            y_axis.append(float(sample['#text']))

        for entry in y_axis:
            x_axis.append(x_axis_count)
            x_axis_count += 10 # ms
```

Figure 6. Sample Code on the Client to Append Categories Data from MTConnect Server

4 Experiment and Results

After the prototype Application software was implemented, a test experiment was conducted on 3D printing dog bone samples in ABS (Acrylonitrile Butadiene Styrene) plastics. Data from machine and sensors is generated using MTConnect adapter, transmitted to MTConnect data in the MTConnect Agent. The sampling rate was every 10 milliseconds (ms).

Figure 7 is a snap shot on the Commanded and Actual Positions on axis in X, Y and Z.

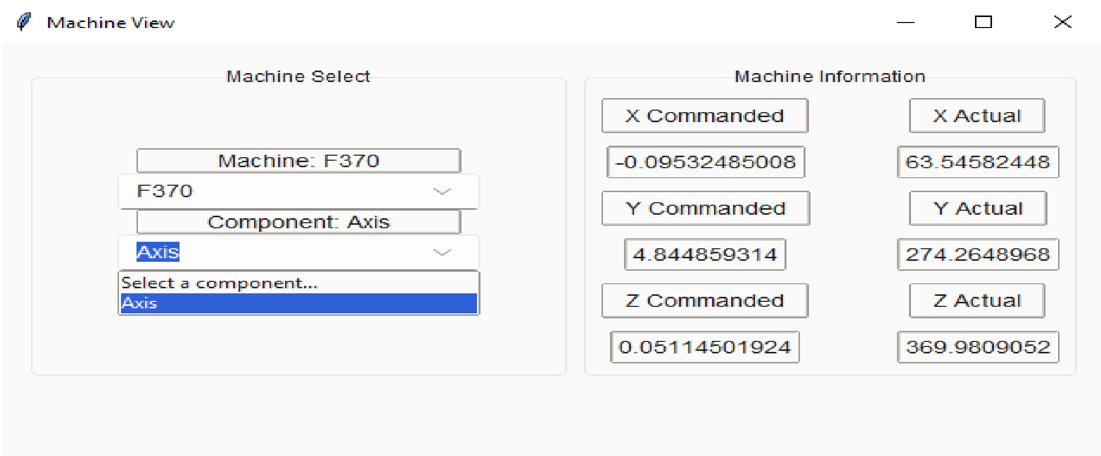


Figure 7. Machine View on the Commanded and Actual Positions on Axis in X, Y and Z

Figures 8 and 9 are the temperatures on the model extruder and support extruder. In Figure 8, the model extruder was in the working state to print the model layer, and temperature is about 260 to 270 Celsius. Please note that when printing ABS materials, the nozzle temperature ranges from 200 to 250 Celsius [6]. In Figure 9, the printing of support layer was finished, the extruder was in the idle state, so the extruder was cooled down and temperature is about 170 Celsius. The results displayed in Figures 8 and 9 are consistent with the additive manufacturing process. These results validate the data collected through the Application software.

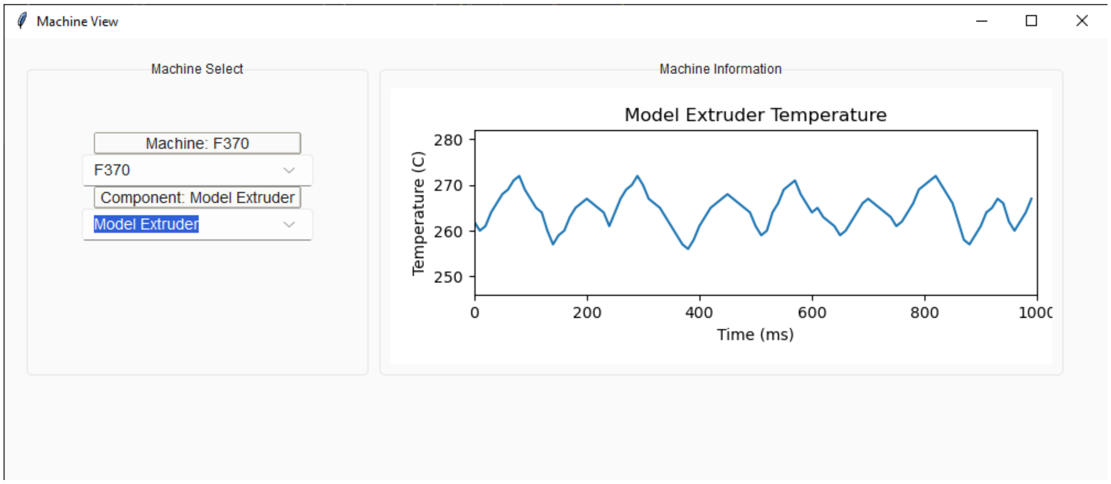


Figure 8. Machine View on the Model Extruder Temperature

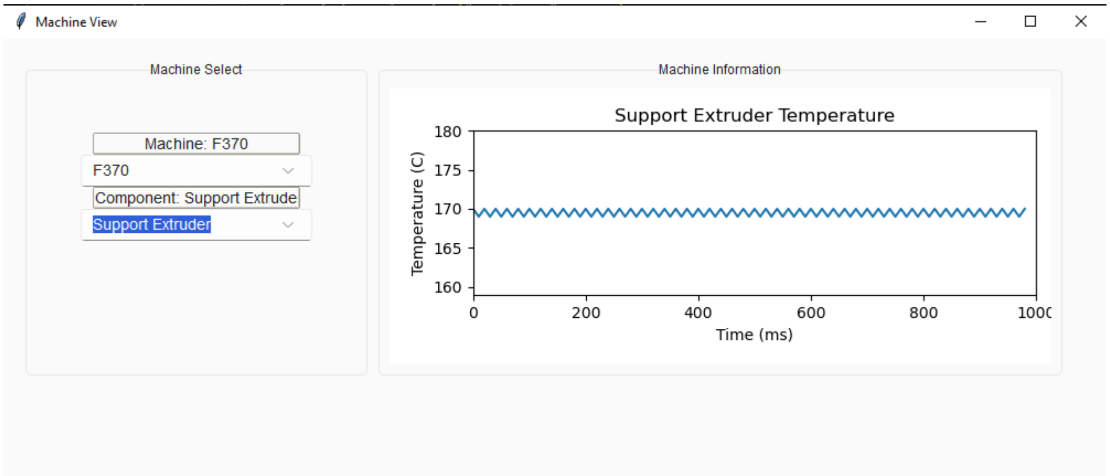
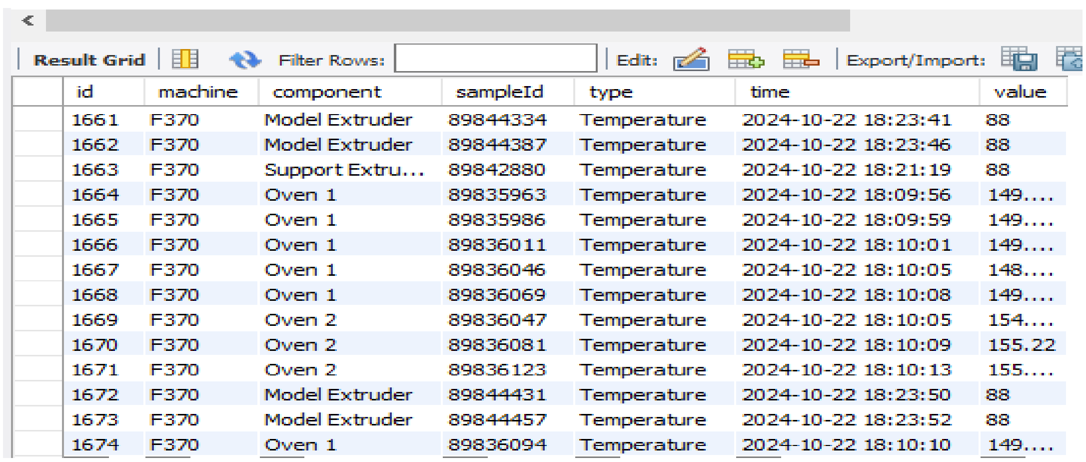


Figure 9. Machine View on the Support Extruder Temperature

Figure 10 shows the interface on the data being stored in a SQL database. These archived data can be used later for analyzing the 3D printing process.



id	machine	component	sampleId	type	time	value
1661	F370	Model Extruder	89844334	Temperature	2024-10-22 18:23:41	88
1662	F370	Model Extruder	89844387	Temperature	2024-10-22 18:23:46	88
1663	F370	Support Extru...	89842880	Temperature	2024-10-22 18:21:19	88
1664	F370	Oven 1	89835963	Temperature	2024-10-22 18:09:56	149....
1665	F370	Oven 1	89835986	Temperature	2024-10-22 18:09:59	149....
1666	F370	Oven 1	89836011	Temperature	2024-10-22 18:10:01	149....
1667	F370	Oven 1	89836046	Temperature	2024-10-22 18:10:05	148....
1668	F370	Oven 1	89836069	Temperature	2024-10-22 18:10:08	149....
1669	F370	Oven 2	89836047	Temperature	2024-10-22 18:10:05	154....
1670	F370	Oven 2	89836081	Temperature	2024-10-22 18:10:09	155.22
1671	F370	Oven 2	89836123	Temperature	2024-10-22 18:10:13	155....
1672	F370	Model Extruder	89844431	Temperature	2024-10-22 18:23:50	88
1673	F370	Model Extruder	89844457	Temperature	2024-10-22 18:23:52	88
1674	F370	Oven 1	89836094	Temperature	2024-10-22 18:10:10	149....

Figure 10. Data Storage to Online SQL Database

5 Conclusion and Future Direction

This paper presents a successful Maker project on developing an Application software, which is able to extract the information from a 3D printer based on MTConnect protocol, visualize the data in different machine views, and automatically store data to an SQL database. From this project, we conclude that students successfully learned knowledge on: 1) communication protocols including MTConnnect and OPC UA, 2) using Python to develop MTConnect Adapter, Agent, and Application, 3) additive manufacturing, and 4) database, for manufacturing operations. The results developed through this project potentially can be used in the "Manufacturing Automation" course to teach students concepts related to the MTConnect.

The research team plans the future research as follows. 1) To further develop the software with data analytics capabilities for other applications such as quality control, system monitoring, etc. 2) To scale up the current system from a single machine to a fleet of machines such as a combination additive and subtractive manufacturing machines. Ideally, the team visions to have all the CNC machines and 3D printers in the School machine shop to be integrated using MTConnect and/or OPC UA standards. Such an integration provides a prototype of "Smart Factory", which provides not only an excellent pedagogy resources to educate next generation of engineers on concepts related Industry 4.0., also an outstanding research infrastructure for Smart Manufacturing.

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