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DMDII
a UI LABS Collaboration
DIGITIZING AMERICAN MANUFACTURING

DMDII FINAL PROJECT REPORT

STREAMING IN-PROCESS MACHINE DATA FROM A MILL-TURN MACHINING OPERATION TO THE DIGITAL MANUFACTURING COMMONS	
Project Team Lead	Binil Starly
Project Designation	15-16-08
UI LABS Contract Number	0220160017
Project Participants	Yuan-Shin Lee
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Project Team Cost Share	$203,689
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Completion Date	July 24th 2017

SPONSORSHIP DISCLAIMER STATEMENT: This project was completed under the Cooperative Agreement W31P4Q-14-2-0001, between U.S. Army - Army Contracting Command - Redstone and UI LABS on behalf of the Digital Manufacturing and Design Innovation Institute. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Department of the Army.

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I. EXECUTIVE SUMMARY

a. Problem Challenge: The Digital Manufacturing Commons (DMC) aims to be a collaborative platform connecting individuals, academia, small, medium and large scale businesses on digital data and models within the paradigm of integrating product lifecycle processes with the digital thread. The specific problem addressed in this project is the question of the methods through which we can stream data from physical manufacturing machines to servers maintained by the DMC infrastructure and have that data made available to authorized DMC users.

b. Solution Strategy: The digital factory of the future will be driven by the integration of physical smart machine tools and cyber-enabled software, working seamlessly to increase manufacturing intelligence, flexibility, agility and production efficiency. The objective of this project is develop and demonstrate a middleware software architecture to interface physical machines on a shop floor with client manufacturing applications. We have connected both legacy and modern 'smart' machines to a highly scalable database capable of storing streaming time-series data generated by on-board sensors and machine controllers. Three client applications were developed to demonstrate the mechanism through which third-party apps can be written without direct physical communications with machines on the shop- floor. The first, is an application that resides within the Digital Manufacturing Commons (DMC) which demonstrates the ability to query data from any physical machine on the floor; the 2nd application demonstrates a python app which compares digital product data with machine generated data; and the
3rd application demonstrates building a LabView app built to interface with the middleware service.

c. Project Outcomes and Recommendations: This proposed architecture enables an ecosystem of smart manufacturing applications to be built and deployed on the shop-floor through open-sourced software and hardware devices thereby reducing cost of manufacturing software development. a solution to interface machines on a shop floor towards a digital factory solution through a middleware architecture has been proposed. High granular streaming data from the machines can now be efficiently stored, archived and retrieved. This pilot solution can be replicated for all machines on the shop-floor. Machine monitoring apps are deployed to the DMC, opening the possibility of integrating a variety of machines on the shop-floor. We believe this can be a strong solution to helping manage data generated by academic laboratories throughout the world. A prototype application to verify a part's geometry by comparing original data with the coordinates obtained from the actual machine coordinates is also demonstrated. This will help to optimize part probing during machining and also provide an initial verification pathway for part tested. The project essentially bridges the machine and the digital platform at the back-end and explores manufacturing intelligence at the front. The ultimate goal of this project is to create a digital network which would replicate the above described system for all the machines in the ISE lab at NCSU. This would introduce the academic world to digitalization. One could use the data to build any number of back-end and front-end applications, from manufacturing intelligence, robotics to other fields. Understanding machine data and its significance could train the next generation of manufacturing engineers to improve production efficiency and low cost to production.

The middleware solution enables hardware abstraction layer which reduces software development costs. These apps demonstrate a low cost solution to obtaining data from manufacturing machines on the shop-floor including legacy manufacturing machines that may not have sophistical machine controls or PLCs to extract data from. The solution demonstrates how incoming streaming data can be stored into a next generation structured SQL database, such as PostgreSQL. This is in contrast to using traditional SQL type databases such as Access, ORACLE or MySQL. PostgreSQL, an open source database is well suited for fast writing of streaming time-series based data.

II. PROJECT REVIEW

a. Project Scope and Objectives

The main goal of digital thread in manufacturing is to provide industry with better insight about the product at any stage from inception to final disposal to avoid significant and costly errors and at the same time gain efficiencies. Several challenges exist that prevent the implementation of the digital thread. This section highlights few of the problems surrounding the digital thread implementation. This will further serve to highlight the need for the specific technical objectives in this project.

<u>Problem 1: Connecting Legacy Machines:</u> While many modern machine tools possess sensing and control systems, the data communications and digital interfaces are frequently complex and/or proprietary. The lack of plug-and-play type digital integration is an obstacle to achieving seamless digital operation of these machines within the manufacturing enterprise. Technologies such as MT-CONNECT (MTC) allow the standardization of data streaming out of the manufacturing. While new machines may be MTC enabled, many manufacturing machines in use today simply lack the necessary adaptors to communicate with the digital network. Therefore, the first problem to tackle is can we come up with relatively cheap methods to enable machines to communicate over the network.

<u>Problem 2: Data Storage and Retrieval:</u> For the digital thread to be meaningful, machines must stream its in-process data during the fabrication of the part for later retrieval and analysis. Many of the MTC enabled solutions are intended to only store discrete points of data. Time-series data, particularly when sensors are mounted on the machine can bog down traditional SQL database schemas. While proprietary plant historians exist for the continuous manufacturing space, the discrete manufacturing typically contain conventionally siloed solutions that fail to integrate across the lifecycle of the product. Any database solution must be scalable to handle 'Big Data' type characteristics when machines are streaming out lots of data that must be captured. A database system which stores this machine data and presents both static as well as real-time of machine shop floor as well as company specific data was necessary. This database can then act as an efficient and secure platform for front-end users to perform different analysis or serve data to other enterprise level systems.

<u>Problem 3: Enabling Information Sharing through Cloud Manufacturing:</u> Consider a case where product designers find it difficult to search and find a potential manufacturer to make their product. Current practice of identifying suppliers through the Internet, social media, and trade shows can be time consuming and in most cases not optimal. It is significantly challenging to land the right manufacturer who has the right set of machines with the required specifications to make the product. It is not feasible for designers to share their design and manufacturing process files across the job shops in the country. Privacy and security of the data can be threatened. In addition, the same piece of information must be shared by the product designer to multiple job shop companies before the right one is selected. Therefore, to circumvent this problem, can a cloud manufacturing setup be utilized for designers to share their data with a middleware, which then extracts relevant pieces of data to compare it against services, capabilities and capacities offered by the job vendor. This middleware, which would basically be an automated algorithm 'hides' information across the two sides. How would such a middleware architecture look like, particularly through the use of a cloud computing infrastructure. The middleware architecture in a well- defined cyber-physical setup can act as a direct link between the machine back end and the customer.

b. Technical Approach and Planned Benefits

This project addresses two technical objectives with respect to integrating manufacturing machines to a digital network. The first objective demonstrates how we can connect machines, specifically CNC machines to the local university network and then to the cloud. This project demonstrates specific apps that were created through a variety of third-party vendor applications. In the second objective, we address a case scenario through which we demonstrate how a cloud enabled middleware architecture can help connect designers with manufacturing shops across the country. The technical objectives are:

Technical Objective 1: To develop a middleware architecture which connects manufacturing machines, such as CNC machines, to a university wide network and then made accessible globally to any authorized user.

The approach taken demonstrates several innovative use of technology. First, low cost computing platforms such as the Raspberry Pi, were utilized to network connect various types of CNC machines to the network infrastructure. Second, we show data streaming from the manufacturing machines can be collected into advanced databases built to handle time-series data. Third, we show how our middleware architecture can enable an eco-system of third-party app to broaden how the digital thread can be leveraged by a variety of engineering and non-engineering disciplines.

Technical Objective 2: To demonstrate a cloud manufacturing framework to connect product designers with manufacturing machines while maintaining information asymmetry.

This objectives will show a cloud computing framework leveraging various services offered through the Amazon Cloud. This app framework demonstrates a user case in which a product designer can check to see whether a manufacturing process plan is compatible with the capabilities of a manufacturing job shop. The framework demonstrates how details of the process plan are hidden from the specific job shop until a match is made. In the same line, critical information from a manufacturing job shop – such as core technical capability and capacity information is hidden from the outside world. The two objectives eventually lead to building the foundation for a manufacturing cyberinfrastructure that can perhaps connect all manufacturing machines in a global network.

III. KPI'S & METRICS

Metric	Baseline	Goal	Results	Validation Method
Enter Metric	Enter Baseline	Enter Goal	Enter Results	Enter Validation Method
Data Analysis Apps made available on the DMC	None	5	3	Tested as of June 16th 2017. The remaining 2 app code has been uploaded but is yet to be in the marketplace.
Physical connection of Machines at NC State to the DMC Cloud	0	3	3	Tested and Operational as of Sept 15th 2017

Physical connection of Machines at UI Labs facility to the DMC Cloud	0	3	1	Operational as of June 16th 2017

IV. TECHNOLOGY OUTCOMES

a. System Architecture

The machine set-up in the NC State laboratory is shown in Figure 1 and Figure 2. Process related machine data from a HAAS VF2 is stored in System Variables or MACROS as defined by HAAS. These MACROS are then read by an MTConnect hardware Adapter. Alongside machine data, sensor data is also collected through a Hall sensor measuring spindle power consumption and a three-axis accelerometer installed within the workpiece holding fixtures within the machine. As seen in the Figure 2, a local system or a raspberry-pi can be used as the MTConnect Adapter in combination with corresponding machine hardware available at the HAAS machine. There are possibly two modes of enabling legacy machines to be Ethernet compatible. First, a low cost <$100 computer through the machines' RS232 port. Second, when there is no PLC or any compatible ports to pull data from, a low cost system-on-chip board such as a Raspberry Pi or a Beagle Bone Black, to directly interface with the machine control boards. In both cases, the machine data formatted through MTConnect standards was streamed through the university ethernet infrastructure to the local DB maintained within the university. The software side of the adaptor is a python script which runs a series of multiple queries and extracts relevant machine data as requested by the database. The local computer system at the HAAS runs its own agent within the board. The data collected by the adapter is filtered and stored in specific tags as defined by MTConnect. Using the TCP/IP connection via the NCSU server, the data is collected at the central system where it is produced as an MTConnect agent output (XML file format). This agent is then used to extract and push data into relevant tables within the database.

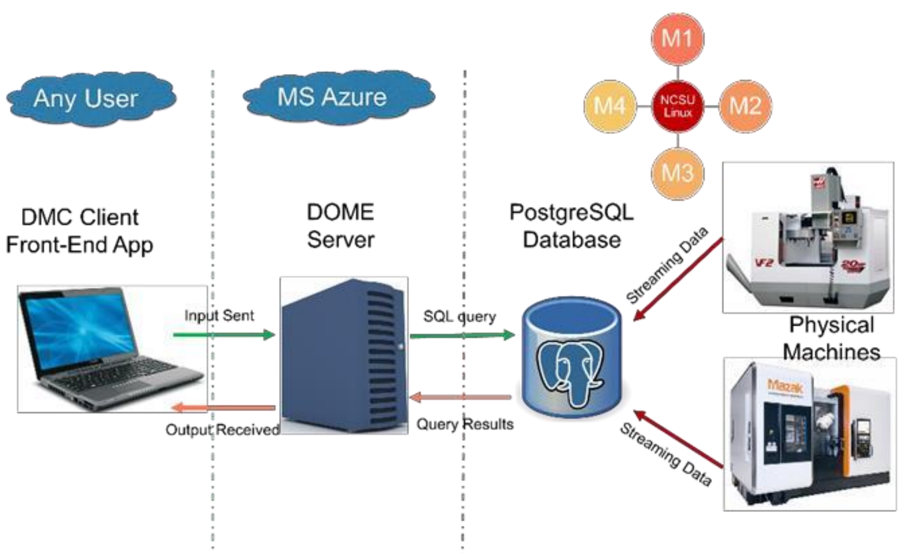

Figure 1: Information Flow from Physical Machine to Client Applications

Many such set-ups can be replicated for different machines across a shop-floor. Another implementation is directly connecting a preconfigured MTCONNECT enabled MAZAK Integrex i-100ST as shown in Figure 2. The MAZAK and HAAS along with any other machines will stream data through its respective agent to the local DB. The external hardware setups, as demonstrated at the HAAS, allow legacy machines to be interfaced for digital communication. Besides which, 'smarter machines' i.e. MT-CONNECT enabled, like MAZAK Integrex can also stream the data generated during machine operations to the local database.

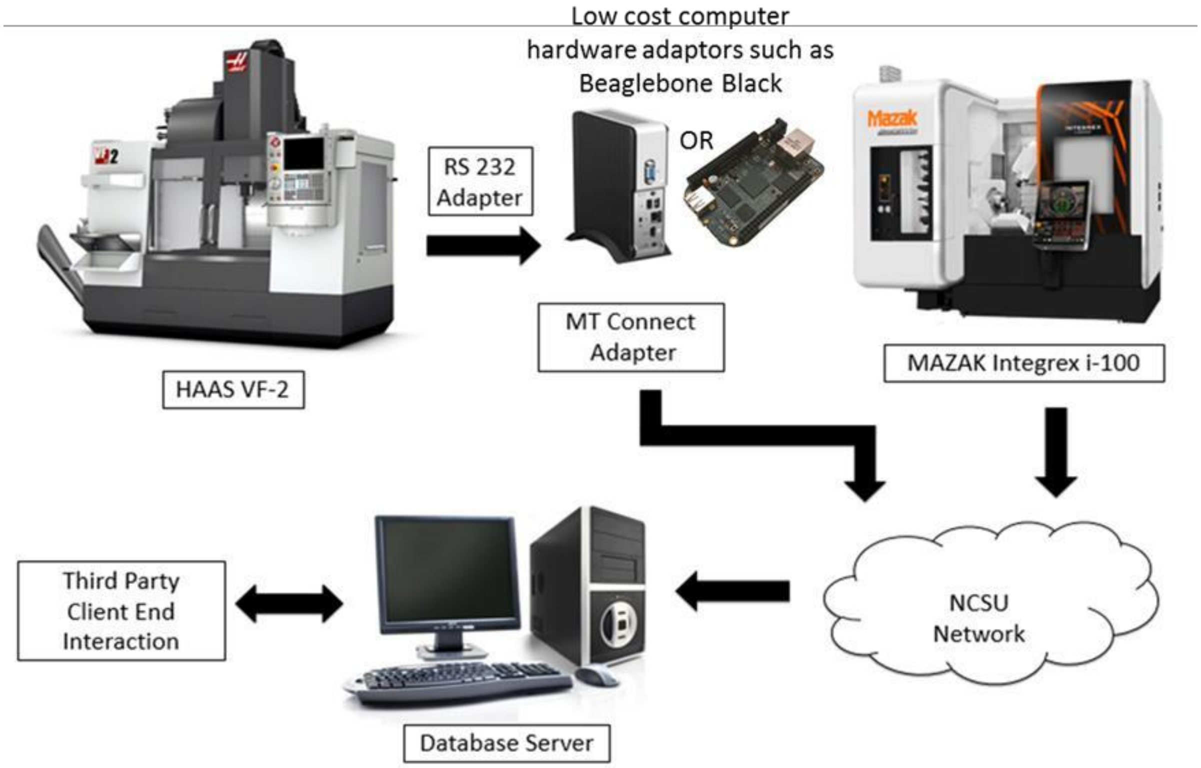

Figure 2: Detailed information flow from physical machine through hardware and software adaptors to third party client, such as Digital Manufacturing Commons (DMC) client.

Figure 3 shows the MTConnect adapter interface at the Benchman 4000 machine in the ISE lab. The Benchman 4000 is a low level 20-year-old legacy machine incapable of interacting with the NC State network. As seen in the Figure 3, various sensors; current, IR, press and light sensors, had to be installed to extract or sense the data out of the machine. The major difference here with the HAAS VF2 or the MAZAK discussed above is that it does not have any active ports for communication. This called for installation of sensors. Here, the Arduino serves as the MTConnect adapter and streams the Agent onto the NC State network from where it is streamed into the local PostgreSQL database.

The information from the MTConnect agents is stored in structured tables in the database. Each data point is associated with many elements that characterize the capabilities of the machine type. A python script reads each of the attributes of the element in the xml tree that the Agent generates and sends it to the database. Some of the key elements of a component are its timestamp, type, id, sequence and its value. PostgreSQL was chosen primarily because of its capability of writing high frequency time series based data. It uses a multiple row data storage strategy called MVCC (Multi Version Concurrency Control) to make PostgreSQL extremely responsive in high volume environments. MVCC is the method PostgreSQL uses to handle data consistency when multiple processes are accessing the same table. It is particularly suited for Big Data type applications. Yahoo, Instagram and Myspace are few of its prominent users.

For the purposes of this study, data is streamed to the PostgreSQL DB at rates of 100ms. For example, when the MAZAK machine is performing a cutting operation, the MTCONNECT data stream page is refreshed every 100ms or at 10Hz. At each 100ms refresh rates, scripts read the XML page and stores relevant data from the file. When data from the sensors were generated, we took an alternate approach, where data is first collected into a local file first and then at the end of the operation, the file is written to the DB tables. This approach is far more superior and efficient than directly writing sensor data to the disk. This allows multiple machines to stream data whenever a process operation is complete. Any filtering maybe done at the machine level to save on disk space and computation time.

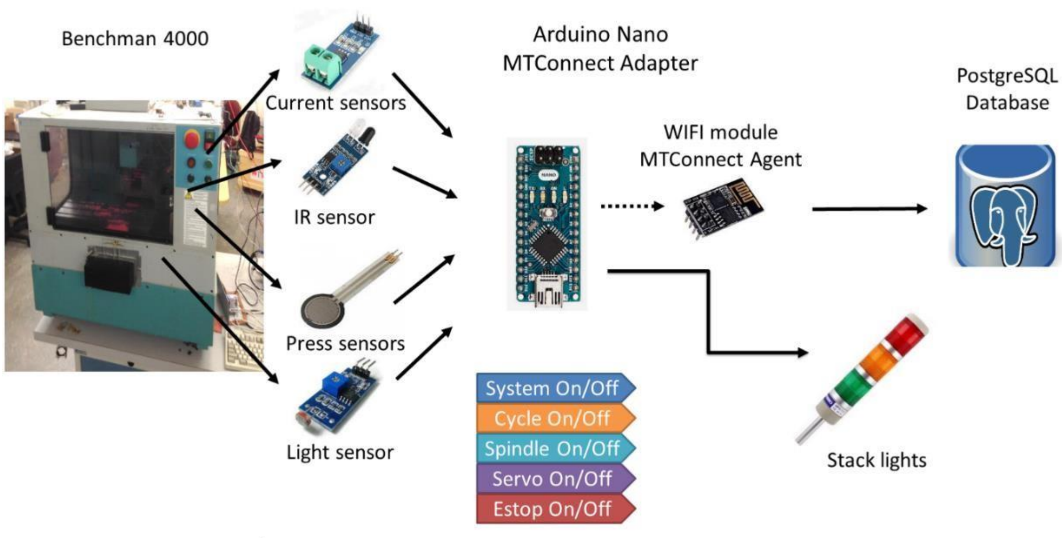

Figure 3: MTConnect Adapter Setup for Benchman 4000

b. Features & Attributes

Adaptor that connects to the HAAS machine and collect process data generated during the machining of a part.

A server that runs on the raspberry Pi system, which projects MT-CONNECT based XML data with regards to the process data.

An XML reader that parses through the MTCONNECT XML file and stores the data into the PostgRESQL data.

Apps that can query the database and display relevant metrics regarding machine utilization, machine status, part count can be retrieved.

c. Users & Use Cases

Streaming Machine Data to Digital Manufacturing Commons (DMC)

As discussed earlier, DMC is a free and open-source software project to develop a collaboration and engineering platform, which enables plug-and-play functionality across the entire digital thread from product development to manufacturing and services. The apps discussed in this section may not be suitable for enterprise level applications since data is directly streamed to a 3rd party open platform. However, this would be perfect for academic and government labs to share data among the scientific community. The information flow shown here can be scaled to hundreds of manufacturing machines across the world, all streaming data to a cloud platform. Users, such as students and researchers can then download process related data files for analysis or process development. These models can be clubbed as 'Data-as-a-Service' Models which allow a repository of shareable manufacturing related datasets.

Application 1: Machine Status

Figure 3.6 demonstrates the "Machine Status" app. The user defines the inputs as per the format in the default html interface. At NC State University, three machines are connected to the local database which in turn weekly sends the updated data to an AZURE PostgreSQL DB on the DMC end. Once the inputs are defined and the user hits the Run button, the DMC does all the calculations at the backend in an Ubuntu Linux environment. Then the html page on the front end is refreshed and the user can see all the outputs as seen in the Figure 4. This app focusses on retrieving data related to machine performance and efficiency along with the status updates. Parameters like OEE and part count can be obtained which help the user realize the efficiency of the machines on the shop floor.

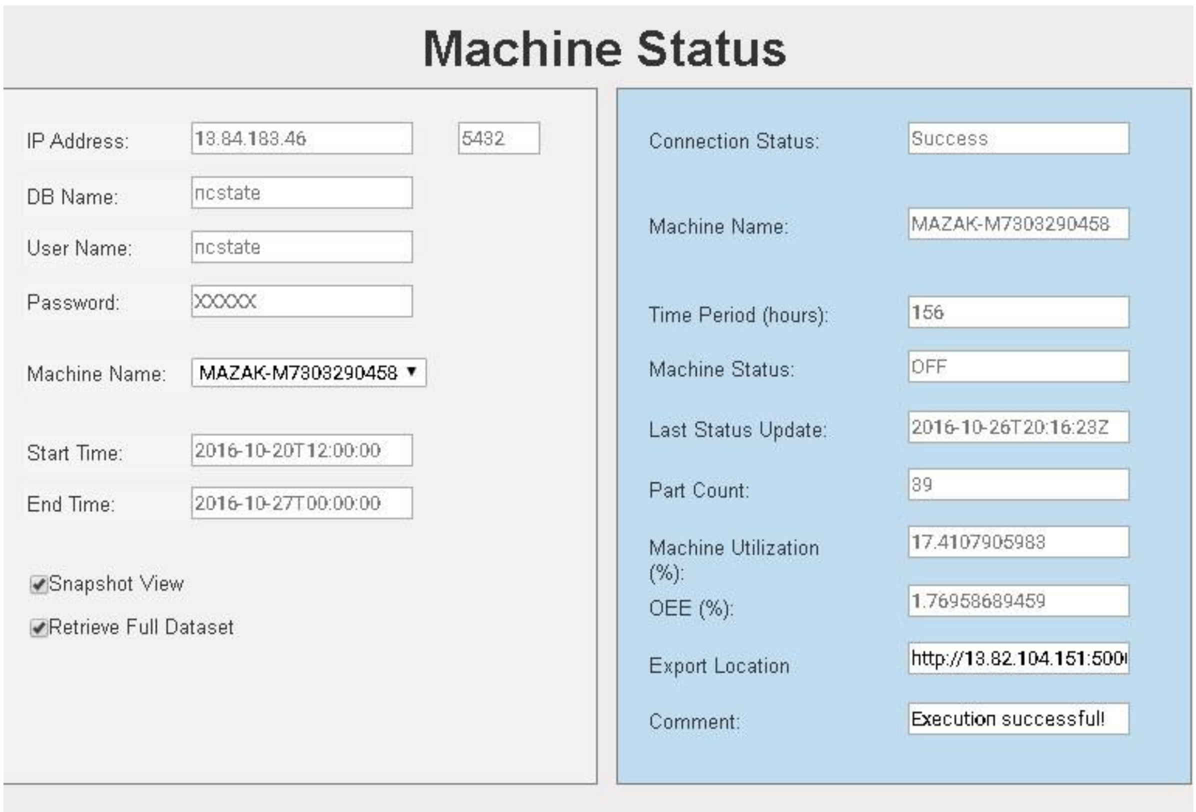

Figure 4: DMC App: Machine Status

Application 2: Machining Data Plots

Figure 5 shows the Machining Data app which retrieves sensor data from the database and calculates averages of the sensor values. The data is collected from two different sensors, Hall sensor and Vibration sensor, presently. This application has a similar input interface as that of the previous app. It also gives an option to the user to extract all the relevant data in a csv file. The user has the option to either simply collect the data or take a snap view at the parameters calculated using the data and the plots between Hall Sensor and Vibration Sensor data versus time. This helps in studying the how the behavior of the current and vibration fluctuations differs during a cutting cycle when compared to an idle state.

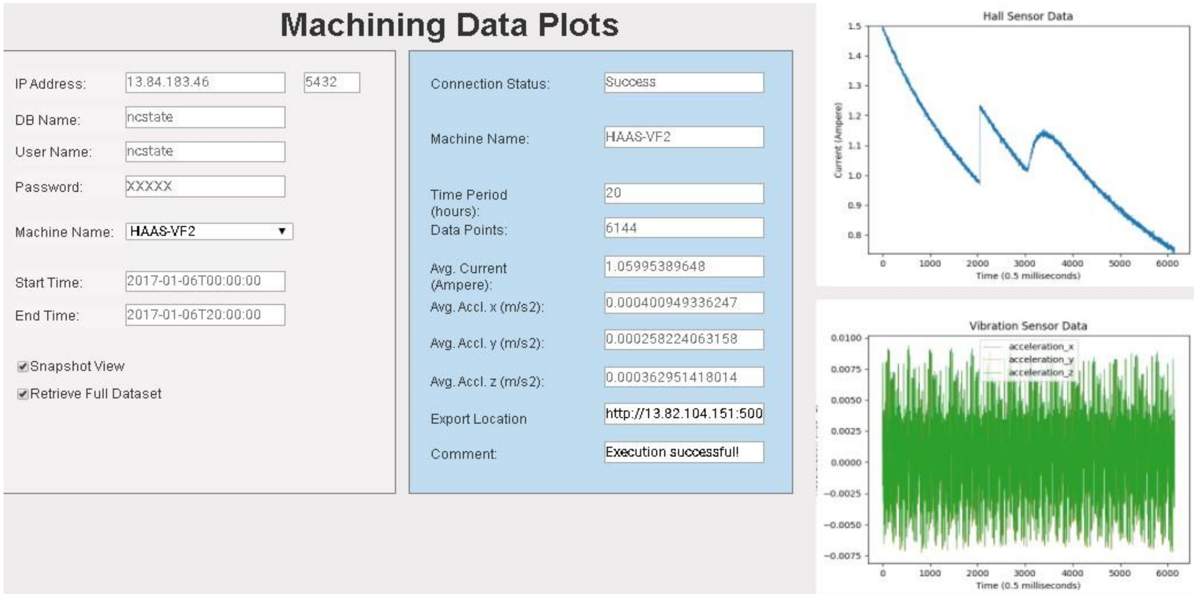

Figure 5: DMC App: Machining Data Plot

The code base (in Python and DMC specific code) has been attached with the submission documents for use by DMDII community members.

III. ACCESSING THE TECHNOLOGY

a. Background Intellectual Property
No background IP was used in this project. All code written and made available to the DMDII community has been built from scratch and provided under the MIT License with appropriate credit to North Carolina State University (Binil Starly and Shaurabh Singh). Open source hardware such as the Raspberry Pi 2, and open-source database PostGreSQL has been made use of in this project. Both of these platforms allow commercial development of solutions.

b. Technical and Systems Requirements
Connection of Machines: We have shown how to connect HASS machines or any other machine that has a RS232 serial port connectivity option. The low cost system-on-chip – Raspberry Pi2 along with the necessary cables can be easily obtained.

System Requirements: A server capable of hosting a PostGRESQL database on-premising or provisioning one on the Amazon AWS or Microsoft Azure will suffice. We have shown how the data can be streamed to either of these platforms.

VI. INDUSTRY IMPACT & POTENTIAL

a. Impact to the specific market the project was addressing and size of that market
The specific impact of this project is really to demonstrate a solution of connecting legacy machines on the physical shop-floor to the cloud, and have data streamed from the machines to a scalable database. It was not intended to address a specific market problem or size.

b. How could this technology be used in other industries

The technology could be used to expand the connection of physical machines on the shop-floor to a global manufacturing data store with the appropriate access rights and security made available to the users. The DMC can serve as a clearing house for information with regards to the machines to help manufacturers obtain new business opportunities through projection of capabilities and machine availabilities. This instant information retrieval can help designers or end users to instantly gain access to manufacturers' key capabilities in rural areas across the US.

In another scenario, this project demonstrates that we can link up manufacturing machines across US academic institutions to a global data store to allow any student to download/access the data for artificial intelligence research and building manufacturing intelligence apps.

c. Next step based on other use potential

The next step is to scale the connection of physical machines on the shop-floors of small manufacturing shops across the United States to help deliver value to their customers. Projection of their available capabilities and capacities can help to gain business value by not necessarily having to large marketing budgets to gain new business opportunities.

VII. TECH TRANSITION PLAN & COMMERCIALIZATION

a. Identify Future Plans

The main implementation architect of the solution presented here is now employed with AMT – Association of Manufacturing Technology, under Vice President Tim Shinbara. Mr. Shaurabh Singh plans to continue working on extending the MT-CONNECT protocol and improving the business case for implementing MTCONNECT in manufacturing shops across the country.

b. Identified Barriers to Adoption

The main barrier to adoption will be the extensive amount of legacy manufacturing machines out on the industry floor. While new CNC machines are constantly being upgraded with MTCONNECT adaptors/agents, there is still an enormous amount of work to be done to connect all machines to a data-store. Custom building MT CONNECT adaptors to the machines can be expensive. We have demonstrated a <100$ hardware solution to connect machines to a central server. But the complexity of machines and relative lack of network capability can severely hinder or make the project expensive for the connection of machines to a central cyberinfrastructure.

The second barrier is the resistance to data sharing by US small manufacturers. New manufacturers who are adapting to digital technology readily accept that this is the new norm to be competitive. It will be a challenge to convince all manufacturers to stream machine metrics over to a third-party platform. But if we can convince them that new business can be obtained, perhaps the tide will turn.

c. Additional Information to Consider

No commercial licensing or development is intended at this point. The main piece of code that will be most useful to US small manufacturers will be the solution to easily connect HAAS machines and any CNC machine to an on-site server. We have demonstrated how this can be done through this project. We hope DMDII members can utilize to build low cost commercial solutions for the benefit of the US small manufacturers, specifically in contract job-shop manufacturing.

VIII. WORKFORCE DEVELOPMENT

Drs. Starly and Y.S. Lee has offered a Digital Manufacturing course in the Spring semester for the last two years, an elective class offered to senior undergraduate students and graduate students. Topics covered will be Product Manufacturing Information, GD&T, PDM/PLM systems for design/manufacturing, Intelligent manufacturing particularly using MT_Connect adaptors/agents, cybermanufacturing in relation to internet of manufacturing things. We have found consistent enrollment of 30 or more students for each of the semester, which is fairly high for a graduate elective class at NC State University. This shows the interest among the students in learning the content. Dr. Starly will continue to offer this course. The syllabus for the course is attached in the Appendix for those academic institutions interested in learning how the course has been organized. Students have been introduced to concepts of the digital thread and digital manufacturing in general. We have utilized class time to introduce students to the DMC platform, writing simple apps on the platform and deploying them to the platform. We find there is a tremendous skills gap in current industrial and manufacturing students in that concepts of software engineering and programming are lacking. We hope to use this course as a stepping stone to gather interest from students and expand the availability of undergraduate and graduates with digital manufacturing expertise. A youtube link to DMC demo and how to start up apps on the DMC platform has been shown: https://www.youtube.com/watch?list=UUB9yv90uJXvKnCY-0vpjvtw&v=ajJdK30NM1g

In November 2017, we hope to also organize a workshop for local CNC job shop manufacturers to teach them the value of the Digital Manufacturing and current advancements made in connecting machines to an on-site server. We hope this is a stepping stone to showcasing value to network connecting the machines and investing in the upgrade of their factory infrastructure.

Dr. Starly has taught one-day workshops to DoD Contract managers and other non-technical executive managers on the benefits of digital manufacturing, Model Based Definition and the advancements in digital technology. This workshop has been offered through the Institute of Defense and Business (IDB), based in Chapel Hill, NC.

IX. CONCLUSIONS/RECOMMENDATIONS

In this project, a solution to interface machines on a shop floor towards a digital factory solution through a middleware architecture has been discussed. By being able to connect manufacturing machines on the shop-floor, a significant step is taken towards realizing the digital thread in product lifecycle management. The digital data can be collected to enable the digital thread throughout a product lifecycle starting from idea initiation to end of product life. The data extracted from the machines provide valuable in-process data that can serve to improve upon existing product designs. It can even help in improving future designs. It is also shown how streaming data from the machines can also be used to build third-party applications to enable the digital factory.

The first technical objective, throws light on how granular streaming data from the machines can be efficiently stored, archived and retrieved. The solution demonstrates how incoming streaming data can be stored into a next generation structured SQL database, such as PostgreSQL. This contrasts with using traditional SQL type databases such as Access, ORACLE or MySQL. PostgreSQL, an open source database is well suited for fast writing and reading of streaming time-series based data. This pilot solution can be replicated for all machines on the shop-floor. Machine monitoring apps discussed here are deployed to the DMC, opening the possibility of integrating a variety of machines on the shop-floor. DMC apps discussed here calculates various parameters like machine utilization and overall equipment effectiveness

(OEE), and shows various sensor data plots. A prototype application to verify a part's geometry by comparing original data with the coordinates obtained from the actual machine coordinates is also demonstrated. This will help to optimize part probing during machining and provide an initial verification pathway for part tested. An application to monitor the machine parameters using LabVIEW is also discussed. This is a primary approach which shows machine monitoring and axial data visualization. Even though most of these apps cannot be used on an industrial scale yet, they are good prototypes demonstrating the manner in which machine data can be utilized. The first half of this project essentially makes a successful attempt to bridge the machine and the digital platform at the back-end and explores manufacturing intelligence at the front.

The second half of the project primarily focusses on the middleware architecture involved in a digital-cloud manufacturing setup. It gives details on how the machine back-end and the user front-end interact through the middleware with the help of a DMC application. The middleware residing in the Amazon Web Services (AWS) consists of three important services: EC2 (the brain), RDS (PostgreSQL DB-the machine data library) and S3 (file storage). The application demonstrates how a customer can verify part specifications w.r.t the machine specifications. AWS EC2 contains the scripts which continuously runs in the cloud waiting for user inputs, performs necessary verifications through live data contains in the RDS machine data library. Currently, the machine data library consists of a few machines with a limited number of specifications which can be expanded upon. The input file used is a setup sheet generated through Autodesk Fusion. The specificity of which can be eliminated if there is a way to figure out secure extraction of part-data directly from the CAM software. There is also a time study analysis which gives us an idea as to which part of the data interaction cycle consumes the most time. Establishing the authentication between the middleware and the DMC front end takes the most time which can definitely be improved upon. The overall idea here is to define a middleware architecture which provides a safe and efficient platform for interaction between the customers and the manufacturers.

Technical Contributions: This project has made several technical contributions to the digital manufacturing community. The work perform primarily lays down the infrastructure for a digital factory. The code for each of the various software adaptors built for the machines are uploaded to the GitHub account. The link for the corresponding GitHub repository is listed below: https://github.com/ssingh23/shaurabh_project.

The specific technical contribution are as follows:

1) A low-cost hardware solution to gather machine data from the machine's hardware controllers. Both an Intel NUC and a Raspberry PI has been used as low-cost computing solution to gather data from the machines.

2) Data has been formatted to create MT-CONNECT agent platforms for both the benchman and the HAAS VF series of machines. Since HAAS machines are widely used in US manufacturing, the adaptor and agent can be adopted and extended by the community. Specific scripts were written in the Python program language were written and stored in the computing hardware which constantly streams its data to the database.

3) Demonstrated the use of the next generation of SQL databases that support multi-concurrency that can handle time series based data - PostgreSQL. This database is currently storing data collected from machines in the ISE MFG laboratories. A copy of the database also exists in the Azure Cloud and the data made available to the community through the Digital Manufacturing Commons.

4) A series of 5 manufacturing apps were demonstrated and made available in the Digital Manufacturing Commons marketplace. Each app demonstrated various examples of how to interface with machine generated data. The apps are made available to the DMDII community at - https://portal.opendmc.org/marketplace.php#/home?product=services.

5) A middleware architecture is demonstrated using AWS infrastructure. The middleware allows direct data collection from the machines while interacting with users at the front-end in a cloud manufacturing marketplace. The middleware acts as the bridge between two-way interaction between the front end and the back end while being safe and a secure neutral third party. Customers must find the right manufacturer to build their parts. To achieve this, the customers must find the manufacturer with right set of tools and machines with the right specifications, verifying and vetting them before prototype or production orders can be sent. Many customers though, are not willing to share detailed part specifications before the deal is finalized and at the same time the manufacturers are also hesitant to share their machine utilization and capacity information with their clients. The middleware architecture discussed here addresses this issue. The middleware stores all the machine specifications and machine updates from the manufacturer and the setup-sheet from the customer. It does it without having to share one party's information with the other. This AWS middleware is extremely safe and efficient and the security can be further strengthening by using Identity and Access Management (IAM) service of the AWS.

Recommendations: Cloud manufacturing is still an expanding field with significant advancements in hardware and software computing. Two direct future work that can be expanded on based on the current work are as follows:

Connecting Various Types of Machines to an Integrated Network: The biggest challenge remains to be the installation of a successful digital factory setup on a shop floor predominantly occupied by machines incapable of interacting with the outside world. Most of which still are old legacy machines. The immediate future work is digitally connecting as many machines as possible in the ISE lab to the NC State network. This would require building customized MT-CONNECT adapters for each type of machine. This work can also be extended to additive manufacturing machines in the future. Future version of the MTCONNECT standard will allow data transfer from 3D printing machines and metrology machines, thereby broadening the scope of this work.

Dynamic Production Scheduling and Instant Pricing Models: If we can achieve the above integration of machines, then the work described in the second technical objective can be extended to include more automated services. Machine schedules stored in a table in the machine data library are manually input at present. Perhaps, a forecasting algorithm could be developed or an existing one could be used which would assess the scheduling history and build models to predict capacity into the future. Unutilized capacity on job shop floors can be sold to allow product prototypes to be built at much lower prices than currently practiced. Such streaming data through middleware can even inspire new business models around prototype manufacturing.

X. LESSONS LEARNED

a. Problems Encountered
Most of the problems encountered in this project was the infrastructure provided by the DMC code base, which on our assessment is outdated technology. The DOME Software Development Kit is archaic and in no way should be the way on how manufacturing apps should be built. There is far better technology that exists on achieving the mission of the DMC. That being said, we were able to get the Apps built using DOME and have it deployed on the DMC. But we fear that many of the academic partners will be reluctant to utilize DOME to build apps because the original technology was built in the late 90s and 2000.

b. Plan/Scope of Work/Proposal Claim Deviations
Deviations from the Original Proposal

1) Manufacturing Apps to be built Centered Around SolidWorks, Excel and Matlab. We originally intended to build apps that integrated SolidWorks and Matlab code to the DOME and DMC code. However we were not able to do it since DMC – DMDII did not have appropriate licenses of either of these software available to be deployed on DMC servers. We then replaced these apps with other apps that might equally serve of use to others in the community.

XI. APPENDICES

a. List Document Deliverables
dd0882_UI LABS
2016-02-03 EAA - PROPERTY INVENTORY
Licensing of Software Contributions by DMDII Members
DMDII Digital Acceptance Check-List
Project Close-Out Summary
Project Final Report
Post Project BIP and IP Claims
2016-02-03 EAA - PROJECT TEAM LEAD RELEASE

b. Demos

c. Setup Instructions
Buy the entire raspberry pi set at
https://www.amazon.com/CanaKit-Raspberry-Complete-Starter-Kit/dp/B01C6Q2GSY/ref=sr_1_2/135-5132430-7726449?ie=UTF8&qid=1494618275&sr=8-2-spons&keywords=canakit+raspberry+pi+3+starter+kit&psc=1

Format the sd card using SDformatter
https://www.sdcard.org/downloads/formatter_4/

Write raspbian jessie using Win32DiskImager
https://sourceforge.net/projects/win32diskimager/

Connect it to a monitor (with the right resolution), keyboard and mouse, through the HDMI port and USB ports respectively.

Open a terminal and type 'ifconfig' and note down the mac address of the PI and get it registered to the network.
Execute

```
sudo apt-get update
sudo apt-get upgrade
sudo pip install --upgrade pip
sudo apt install libpq-dev python-dev
sudo pip install psycopg2
```

Install tightvncserver on the PI as well as your personal system from which you want to access the pi remotely.

execute for linux:

```
sudo apt-get install tightvncserver
vncserver #to setup the password
tightvncserver #to initialize the server; also note down the ipaddress
```

information which will be in the form of raspberrypi:1 or :2 or so on.

#raspberrypi:1 is supposed to be used as IPADDRESS:1 under remote host in tightvncviewer on the user system.

#tutorials for tighvncserver can be found on youtube easily.

if you restart and want to setup the server again you can do it as mentioned above or use putty to login through ssh and type "tightvncserver" to initialize.

Enable ssh and serial in the configuration window by following steps on
http://www.instructables.com/id/Read-and-write-from-serial-port-with-Raspberry-Pi/

simply open configuration window by typing the following command

```
sudo raspi-config
```

Create a directory and download and extract all the files from
https://github.com/ssingh23/shaurabh_thesis/tree/master/MTCAdapter-HAAS

Connect the raspberry pi to the HAAS machine using the cables that can be purchased through the following links:

Null modem cable:
http://www.amazon.com/StarTech-com-10-Feet-Cross-Wired-Serial/dp/B00066HL50/ref=sr_1_1?s=electronics&ie=UTF8&qid=1445375930&sr=1-1&keywords=db9+to+db25+null
RS 232
http://www.amazon.com/Plugable-Adapter-Prolific-PL2303HX-Chipset/dp/B00425S1H8

Once you connect the raspberry pi, start the tightvncserver.

Using the tightvncserver remote interface run final.py, server.py and data_collection.py simultaneously and endlessly. #can also create a batch file to do the same.

2. Bill of Materials

Raspberry Pi 3 – one for each machine
RS232 Serial DB9 Adapter Cable – one for each machine
Server class computer loaded with PostGRESQL OR Provisiong a POSTGRESQL database on Azure or Amazon AWS.

3. Exceptions

This solution will work only with CNC machines that at minimum has a serial port connection option. If the controllers on the CNC machines are supported with a MTCONNECT agent, then implementation is easier and only scripts to read the agent at the DB end need be provided.

d. Appendix 1: Presentation at the ASME MSEC Conference Symposium

e. Appendix 2: Digital Manufacturing Course Syllabus