A warm welcome to Cyber Physical Lab developed by FSM. This Cyber Physical Lab consists of three assembly stations and a robotic cell to showcase a discrete manufacturing setup. A combination of assembly workstations and robotic cell has been developed to demonstrate Smart manufacturing solutions in both. A wide range of features have been incorporated in these workstations and robotic cell to solve the needs of manufacturing plants. These solutions have become possible by use of a bouquet of Industry 4.0 technologies.

These work stations and robotic cell have been designed and produced from scratch by our FSM team. For FSM guests who are more familiar with discrete work stations or for those who are more familiar with robotic cell, we are demonstrating that Smart Manufacturing solutions exist for both. At present, assembly of Directional Control Valve or DCV is done at these 3 workstations and robotic cell. However, these workstations can easily be adapted to assemble another product from another manufacturing sector for example automotive sector.

We will demonstrate the communication and collaboration between workstations and with robotic cell. To showcase real-life situation, we have deliberately used different brands of PLC and communication protocols across workstations and robotic cell to show that collaboration is possible even if the hardware used is from different companies. We will demonstrate two-way flow of data between these workstations and also with robotic cell.

To achieve this data flow, we will also demonstrate two-way flow of data to server located at our premises and also to cloud which demonstrates remote monitoring and control of these work-stations and robotic cell. The data from machines will be analyzed to create dashboard to enable effective decision making on real-time basis. These dashboard are possible to be viewed and monitored remotely. Similarly, these workstations will be shown to be commanded remotely to start production of a product which was remotely selected in terms of variant and quantity.

Let us start by explaining the communication and control between these machines. As mentioned earlier, our FSM team deliberately installed Rockwell PLC in first workstation, B&R make PLC in second workstation, Mitsubishi PLC in third work station and Siemens PLC in robotic cell. All the 3 workstations and robotic cell communicate in their own language which is their own communication Protocol. So we first established a common language which is understood by each PLC in all workstations and robotic cell. We used the open-source communication protocol OPC-UA to communicate between these PLC from different companies and with the server. OPC UA is an industry accepted communication protocols. OPC UA is an acronym for Open Platform Communications United Architecture. It is a data exchange standard for industrial communication that is machine-to-machine or PC-to-machine communication. To give an easy-to-understand analogy about its usage – let us imagine a situation when four persons meet from different part of country say Delhi, Mumbai, Chennai and Kolkata, we placed an English knowing person who can understand each of those four persons and tell us in English and when we speak in English then communicates to them in their language. In our Cyber Physical lab, OPC UA enables our server to communicate with Rockwell PLC which operates on Ethernet; B&R PLC operates on Powerlink; Mitsubishi operates on Profinet and Siemens PLC on Profinet. All data received at server is in OPC UA and all commands given by server are communicated in

OPC UA. So it becomes so much more convenient to the user. OPC UA Server is set up in each PLC in each machine because each PLC is OPC UA enabled.

Next let us take an overview of remote monitoring and command of these machines. To achieve this, we established an edge device which communicates between machines and cloud. We have used an Intel NUC as an edge device in our Cyber Physical lab. The acronym NUC is for Next Unit of computing. It is an ultra-small self-contained tiny little personal computer. Intel believes that in future the home computers will be this size and therefore calls it Next Unit of computing – NUC. The programming language that is used here is the Python which runs on the Intel NUC. This edge device has two-way communication with workstations using OPC UA and this edge device uses Python programming language to do its own computing and also to two-way communicate with Cloud. So this edge device is like a brain of our Cyber Physical lab.

The Google FIREBASE is used as a cloud service provider. Since we have used Google Firebase so the cyber security of cloud is provided by Google.

As a result, we have achieved a two way communication with the machines using our open source cloud that is Google Firebase and algorithms written in Python and running on our on premise edge gateway device Intel NUC. With this connectivity, workstation machines can communicate via Python with the cloud and thereby with other devices and machines. This communication results in select data from each machine being collected at cloud and ability to send specific data commands from cloud to each machine. This easily accessible data at the cloud can be used for real-time remote monitoring of each machine asset. The data sent to each machine from cloud is used for remote control of each machine asset. We save majority of data in our on premise storage system and a selected data is securely sent to cloud and securely stored on cloud. This select data is useful for dashboard and the app. As a result, the cloud database can be used on any network and the applications on that network become connected to our Cyber Physical lab. This enables remote control and monitoring of machines.

This edge device is on the same network as the machines, runs on Windows OS and connected to a speaker. The edge device continuously runs a Python program. This program acts as an OPC UA client and reads/writes on nodes. Reading nodes gives us machine data and writing nodes helps us control the machines.

The PLC in each workstation and robotic cell has a device which is OPC UA enable and acts like a OPC UA server. For this OPC UA server, the Python software program on Edge Device becomes the OPC UA Client which accesses the data being provided by PLC for further processing or monitoring or using it for dashboard or the app. This resultant connectivity between each machine and cloud is utilized to send command to our Cyber Physical lab.

The edge device also acts as the Process Control Unit for the Robotic Cell. The Python program can log data on Google Firebase (a cloud database). Data read from the OPC UA nodes is pushed to the cloud using Firebase. We have built a dashboard to help visualize machine data using React.JS which is a JavaScript web app framework. This dashboard is also connected to Firebase and displays the machine data from the database.

Once the production order reaches the Edge Device, the python script recognizes the order and writes on an OPC UA node to start the work sequence. The edge device simultaneously gives voice updates of the operation being conducted using the speakers.

As mentioned earlier, each operation step on the work station is getting communicated to the edge device. This information is converted from text to voice form by using NLP – Natural Language Processing programs. This voice information is announced through speakers. This is to demonstrate the convenience of freedom from looking at the screens and getting voice updates of the operation being performed at the machine while we continue to work at another task. It is also remote monitoring.

Text to speech feature may be done in different languages and voice changeovers. On the edge device, Text to speech is done through AWS. The python script runs in the background for this and uses python packages. As a result, we get choice of different languages like English & Hindi etc and voiceovers like male & female voice. These are predefined recordings available in the package. So when we use it in the code for example if I put in the program like "All station has been connected" then this is being converted to speech and announced through the speaker.

For remote monitoring of our work stations and robotic cell we utilize various manufacturing metrics. The manufacturing metric most popularly used is Overall Equipment Effectiveness or OEE which has three critical sub components of the manufacturing process – Availability, Performance and Quality. Formula for OEE is programmed in each PLC so it provides the data accordingly for our remote monitoring and control.

The first step is to instruct machine on what to produce and how much to produce. This can be informed to machine locally at the Cyber Physical lab by on- premise server or manually operating the control panel of machine. Same instruction can also be sent remotely. Depending on who the customer is and its size & complexity of requirements, the customer may inform their requirements across the Supply chain network in several ways for example by email, EDI – Electronic Data Interchange, API – Application Program Interface, TMS – Transportation Management System on Logistics Network, RPA – Robotic Process Automation and many more.

Here, we demonstrate a method suited to a very small lot size and from an individual customer and that too with customized requirements. We have developed a mobile-phone operated App which informs our Cloud. It is an Amazon or e commerce like user experience app through which we can place, from a list of options of Valve body assemblies, a customized order for valve body assembly to the machines which will start automatically without any human intervention. This app is built using REACT Java script. Once an order is placed on the mobile app, this data reaches the cloud. The python script on the edge device recognizes the order and writes on an OPC UA node to start the work sequence on the machine.

Now let us demonstrate the work-stations to you. Each work station is an integration of OT & IT. Operational Technology or OT is the manufacturing operation being performed at that workstation. Instead of manually operated operations, these are automated operations. Information Technology or IT is demonstrated by PLC operating the machine and the data being communicated through edge device to cloud and other machines. You will see the OT including automation in the upper half of each workstation. The lower half will showcase the IT.

Each workstation has an HMI – Human Machine Interface. This is needed when we wish to manually control or instruct the machine to do some specific task or when we want to manually operate the machine under emergency situation. This HMI designed and set up by FSM team incorporates Security enabled Network Switch. This HMI demonstrates feature called User defined access on HMI. It means access is given on HMI as per advance information provided by the decision maker or owner. All the access has been given to the administrator, whereas operator can only start and stop the machine, the operator can only make those changes which are required for maintenance. Guest user is given only access to read however guest user cannot write or control the machine. These access control lists help us in ensuring that only authorized devices, users, and traffic can access the network. It works on MAC address level and can provide access to a MAC address. MAC is an acronym for media access control address which is a unique identifier assigned to a network interface controller for use as a network address in communications within a network segment. These are required to make a local Ethernet network function. It is a more secured way to give access to MAC address rather than an IP address. We can map a particular MAC address to a specific port. We can also restrict the number of IP addresses or MAC addresses that can be connected to the network. These are the features which provides us a secured network.

Another feature on our HMI is State diagram implementation on HMI and machine PLC. With this feature different states of the machine have been pre-defined for example Executing, Idle, Reset, etc. These have been programmed in the machine PLC and we can see the state of machine on HMI. This feature comes under PackML industry standard.

Each workstation has photo sensors at the entry, exit and various points along the conveyor belt to track the pallet.

Along with an emergency switch, each station has a light curtain to detect station breach as a safety measure for human beings. When there is a breach in light curtain, machine will stop and it will move to safe position after resetting the light curtain. Cycle will resume from the previous step. When there is any emergency and emergency is pressed, machine will stop. Cycle will start from the start.

Each work station has an ANDON light or Tower light indication for the machine with Red, yellow and green lamps. The lighting of lamp of particular color indicates whether the machine is stopped or operational. These lights can be either manually or automatically activated. These color lamps alert operators and managers of problems in real time so that corrective measures can be taken immediately.

Let us now show you the OT and IT integration at workstation 1. We start with describing the functionality at this workstation 1 that is the OT – Operational technology at this workstation 1. After order is received either from the app or from ERP program running in remote server or manually from HMI, the order execution begins by engaging the pallet at the operational area. Objective at this workstation 1 is to – Retrieve correct workpiece from the inventory storage area to place it on the pallet and thereafter to verify its four faces to re-confirm that correct workpiece is loaded on the pallet and lastly the loaded pallet is transferred to workstation 2 by conveyor.

The workpiece currently being assembled on this workstation 1 is valve body for assembling a DCV Directional Control Valve. These valve bodies have been manually filled in inventory storage area in random order. These valve bodies are of four types as required for assembling several types of DCV. These four types of valve bodies are 5/2 single solenoid, 5/2 double solenoid, 5/3 double solenoid, 3/2 valve bodies. Each of the valve bodies are already laser printed with a 2D QR code.

The bar code scanner checks QR code pre-printed on each workpieces kept in the inventory storage area and sends data to PLC about the type of valve body and its location in the inventory storage area. The gripper picks the correct workpiece from its QR code and loads it on the pallet. After placing the body on the pallet, rotary axis rotates the valve body 360 degrees and vision sensor inspects all the four sides of the body.

A profile matcher laser vision sensor is used for quality inspection of the critical areas of DCV that is all the four faces of the particular valve body which is now loaded on the pallet. The 2D laser vision sensor one by one scans the profile of 4 faces of the valve body. It is mainly checking the profile that is shape of object and geometric features like holes, rectangles, etc that are present on that face. When the profiles match with the pre-defined master profile which is already fed to the PLC, the pallet is transferred to the next station by conveyor. When any one of the face profile does not match the image of master profile as stored in PLC then the gripper picks that rejected valve body and unloads in the rejection rack. Thereafter, the gripper picks the next workpiece from the inventory storage area and loads the same on the pallet. This cycle is repeated till the correct workpiece is found where all four faces match the images of master profile as stored in PLC.

We will now further explain the pneumatic system for loading of pallet and picking & placing operations of the valve body. A gripper has been used to pick the valve body. Three linear slides are used to provide motion in three axes – x, y & Z directions. These axes are required for pick and place operation. Rotary axis rotates the pallet shaft 360 degrees for vision inspection. Four servo drives controls the motion of these axes. A pneumatic stopper stops the pallet and a locking cylinder locks it in position. A motor cylinder engages the shaft of pallet and a pallet release cylinder subsequently locks and releases this shaft. A pallet pulling cylinder opens the pallet so that valve body can be placed by gripper on the pallet. For all of these pneumatic cylinders, their extended or retracted positions are detected by reed switches which are connected to DO – digital outputs. Four Photoelectric sensors sense the position of pallet. These sensors are physically connected to IO link master, instead of directly connecting to PLC. IO link master collects the data from these sensors and sends to PLC on Ethernet IP. The advantage of using IO link master is that IO link master also communicates data regarding health and state of the sensor, along with the digital data. This avoids the situation where breakdown in photoelectric sensor gets mis-interpreted by PLC as a negative data by this sensor.

All workstations have been designed to communicate with each other on two modes: Automatic and manual. The machine parameters like order details, type of valve body, inventory, conveyor and photo-sensors status - these are published by PLC using OPC-UA protocol. These parameters are made available on NUC and thereafter programmed for receiving orders at next work station and synchronizing the work stations with each other (like machine is ready, conveyor is running/not running).

For the manual communication, a RFID tag is already mounted on each pallet and a RFID reader/writer is made available on each work station to track the work-piece loaded onto pallet. The RFID reader/writer writes the data on RFID tag after all the operations at that work station have been performed. This RFID tag is read when the pallet enters the next workstation and thereby the next workstation receives all data pertaining to work piece and the operations performed at previous work stations.

So, we have achieved two layers of machine to machine communication first by using the edge gateway and second by using pallet as the data carrier.

At the end of work station cycle, the pallet is moved to the next work station by conveyor. This conveyor motion is controlled by VFD that is Variable Frequency Drive. VFD communicates with the PLC installed at work station 1 on Ethernet IP.

On workstation 1 we have installed a Rockwell PLC which were earlier known as Allen Bradley PLC. Rockwell PLC communicate by using communication protocol Ethernet IP and serial communication. Whereas the communication protocol for communicating with edge device NUC and with other machines having different brands of PLC happens by using OPC UA protocol.

Ladder Logic is the programming language which has been created by Rockwell for PLC programming and therefore it can only be implemented on those machine which are with Rockwell PLC. It makes the motion programming much easier.

Rockwell PLC as a hardware has one compact logix PLC and two units of Micrologix PLCs. Compact logix PLC is the master PLC in this work station 1 and it is responsible for all the operations at this work station except QR code scanning and laser vision inspection. These QR code scanner and laser vision sensor serially communicate. It means that these exchange data one bit at a time. Compact Logix PLC do not communicate serially. Micrologix PLC enable serial exchange of data between a microprocessor and peripherals. The peripherals on work station 1 are QR code scanner and laser vision sensor.

So, we have used two micrologix PLCs. One micrologix PLC can communicate to only one serial device or sensor. Therefore, QR code scanner and laser vision sensor communicate serially with one micrologix PLC each on RS485 serial communication. As a result, QR code scanner sends data to and receives inputs from one micrologix PLC. The laser vision sensor send data to and receives inputs from second micrologix PLC. Both micrologix PLC communicate with compact logix PLC on Ethernet IP.

Communication on Ethernet IP from remote or distributed Inputs or outputs with the machine PLC is by AENTR which is an Ethernet IP adapter. These inputs and Outputs are digital inputs and outputs. In this machine, we do not have any analogue inputs and analogue outputs. In this machine digital inputs are from Reed switches of cylinders, Light curtain, Emergency button and Start button on HMI, Light curtain reset button where as digital outputs are outputs given to ANDON Tower lights having Red, Yellow, Green color indications, Buzzer, etc.

As mentioned earlier, the communication protocol for communicating with edge device NUC and with other machines having different brands of PLC happens by using OPC UA protocol. Rockwell PLC used in workstation 1 is an OPC UA enabled hardware. OPC UA is implemented in server/client pairs.
Rockwell PLC software runs the OPC UA server which is a software program. This software program converts the hardware communication protocol used by a machine PLC into the OPC UA protocol. Factory talk linx gateway is the OPC UA software which communicates with the machine PLC and collects the data. Thereby, this software creates OPC UA server.

OPC UA server sends the data to OPC UA client. This client may be edge device NUC or another machine having a different brand of PLC which operates on a different communication protocol.

We have also created an open source modular dashboard which is built using the EACT which is JAVA script library created by Facebook. It is a User Interface or UI library and a tool for building UI components. It provides real time state dashboard for machines. Modular means that this dashboard is designed in such a way that others can use it to create it further once they have the access to it. The dashboard helps us visualizing the data from machines.

Now let us focus on workstation 2. The main activity being performed here is pick up of appropriate spool after inventory checking and thereafter insertion of the spool in to the hole in the DCV body as received from work Station 1.

The pallet on the conveyor with correct DC Valve body enters the workstation 2. After receiving the pallet from station1, conveyer moves the pallet to operation area and then the RFID controller, on work station 2, reads the RFID chip or tag which is mounted on the pallet. As a result, RFID controller gets information on the type of DCV Assembly which is to be produced as per the order received. RFID controller send this information to PLC. At the same time, this PLC also receives the same information from NUC through OPC UA software.

Based on this data, PLC instructs the gripper to pick up appropriate type of spool from the inventory area. In our use case, 4 types of spools are differentiated by size and these are kept on different slots in station 2.

A pneumatic stopper stops the pallet and a locking cylinder locks it in position. A motor cylinder engages the shaft of pallet and a pallet release cylinder subsequently locks and releases this shaft. For all of these pneumatic cylinders, their extended or retracted positions are detected by reed switches which are connected to DO – digital outputs. Four Photoelectric sensors sense the position of pallet. These sensors are physically connected to IO link master, instead of directly connecting to PLC. IO link master collects the data from these sensors and sends to PLC on Ethernet IP. The advantage of using IO link master is that IO link master also communicates data regarding health and state of the sensor, along with the digital data.

For doing the spool pick up after inventory check of the inventory area, a proximity sensor and parallel finger gripper are mounted on a semi-rotary pneumatic device. The function of gripper is to grasp the spool and function of semi-rotary device is to pick and insert the spool in the DC valve body. Pneumatic system allows to switch the use between the proximity sensor and gripper. This semi-rotary pneumatic device is itself mounted on linear slides. These three linear slides ensure required motion of proximity sensor plus gripper in x, y & Z directions over spools placed on a tray in the work station 2. Three servo drives drive these three linear slides to ensure this detection & thereafter pick & place operation of spool. These proximity sensor are capacitive sensors, these sensors detect the presence of spools kept in the tray when these proximity sensors reach near the spools with about 4 millimeter gap between proximity sensor and the spool. The PLC at work station 2 keeps the count of detected spools, and inventory status is thus updated.

The semi-rotary device then shifts to operate the parallel finger gripper by rotating it to appropriate position. The gripper on semi-rotary device picks up the spool in horizontal mode and rotes it to vertical mode while inserting. The pneumatic manifold used on this workstation 2 is of SMC make as compared to FESTO make used on workstation 1. This is to demonstrate integration of diverse product makes.

The spool insertion operation is highly sensitive and prone to error. The spool and hole in the DC valve body have a tolerance of 0.02mm. Any misalignment between spool and the hole will result in a clash and the spool insertion operation will get aborted.

To overcome this, a camera is attached to this work station. Before the insertion of spool starts, this camera captures the top view of the valve body. This image is sent to the nVIDIA Jetson device mounted with camera. Image of top view of valve body is processed MATLAB software which also finds the precise coordinates of the center of the hole. These coordinates are sent to the PLC and the PLC updates the coordinates for the gripper. So nVIDIA Jetson is the data processing device between camera and PLC. As a result the center points of spool and hole get aligned. With this accurate placement of the spool above the hole, the gripper smoothly inserts spool in the DC Valve body.

The RFID reader/writer writes the data on RFID tag after all the operations at this work station 2 have been performed.

At the end of work station cycle, the pallet is moved to the next work station by conveyor. This conveyor motion is controlled by VFD that is Variable Frequency Drive. VFD communicates with the PLC installed at work station 2 on Ethernet IP.

Similar to work station 1, features like User defined access on HMI, State diagram implementation (PLC) and Light curtain and manual emergency operation are also available at this work station 2 and next work station 3.

The PLC mounted on workstation 2 is a B&R make PLC. This B&R PLC is the master controller on this work station and it communicates on Powerlink protocol. Similar to workstation 1, Ethernet IP module is the hardware used with PLC for Ethernet IP protocol. Communication protocol used to communicate with other workstations and for machine to machine communication is OPC UA.

As our objective is to demonstrate a usage of a spectrum of programming languages, devices and technologies, so we have used Structured Text language for programming the PLC at workstation 2. You would recall that programming language Ladder Logic was used for Rockwell PLC at work station 1.

This RFID tag is read when the pallet enters the next workstation and thereby the next workstation receives all data pertaining to work piece and the operations performed at previous work stations.

Next is the workstation 3. The function at work station 3 is to fasten the two end plates on the DCV body in which spool has been inserted at previous work station. These two end plates are the child parts or sub-parts of the final assembly of DCV. these are similar parts on the either side of the body of the DCV and therefore also called prismatic parts.

Inventory is filled manually in this station too. After receiving the pallet from station2, conveyer moves the pallet to operation area and RFID reads the RFID tag. After reading the tag, gripper picks the required part and places on the valve body. After placing the part, screwdriver screws the part on the body. After assembling and screwing all the parts, RFID writes the information on the RFID tag and station sends the pallet to next station. , after input from the RFID controller the gripper picks up the respective prismatic parts one by one and the parts are screwed by the screw-driver. After successfully screwing, pallet passes to the Multi-Purpose Robotic Cell (MPRC) for further assembly, Electrical Testing and packaging.

To prevent the end plates from falling down due to loosening of the screws, our FSM engineers have designed & built an in-house torque sensing screwdriver. Torque gets auto adjusted according to the reverse torque experienced while tightening the screws.

The pneumatic system is similar to workstation 1 and 2 except for one difference. At this work station 3, seven servo drives control six linear slides and one rotary axis device whereas work station 1 and 2 had only four servo drives. At this station, 3 linear slides are used for motion in x,y,z directions of gripper and other 3 linear slides are for motion in x,y,z directions of screw driver. Gripper axes are required for pick and place the two end plates which are the child parts. Screwdriver motions are required for the screwing operation. Rotary axis device rotates the valve body 360 degrees to allow assembly of end plate before the tightening of screws. The pneumatic manifold used on this workstation 3 is of SMC make.

At work station 3, the master controller is Mitsubishi PLC. We have installed a base rack on which PLC, 32 point DI/DO modules and Communication modules are mounted. PLC and these remaining modules get the power from SMPS through the base rack. Ladder Logic is the language used for programming the Mitsubishi PLC. The communication protocol for Mitsubishi PLC is Profinet and CC Link. In this work station also, Communication protocol used to communicate with other workstations and for machine to machine communication is OPC UA.

At the start of work station 3, conveyer moves the pallet from work station 2 and after completing all operations at work station 3, the same conveyor moves the pallet to Multi Purpose Robot Cell. VFD or Variable frequency drive controls the motion of conveyor and communicates with the Mitsubishi PLC on CC Link to control conveyer motion.

Our Multi-purpose Robotic Cell is capable of performing the operations performed by workstation 1, 2 & 3. In addition, the cell also assembles solenoid & DIN connector to the semi- finished DCV sub-assembly produced by workstation 1, 2 & 3. Thus, Robotic Cell itself can act an independent unit for complete assembly of a DCV and also process half-assembled DCV coming after Station 3. Quality Inspection & packaging of completed assembly is done by our Multi-Purpose Robotic Cell.