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Abstract:	This document provides an overview on the current state of the real demonstrators. Demonstrators are specified and realized, suitable to demonstrate and evaluate the most relevant use cases from the smart manufacturing domain.
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Executive Summary

This smart manufacturing demonstration specification and realization report provides a description and evaluation of the current OPTIMUM project.

In this document, the demonstrators about smart manufacturing domain that are part of the OPTIMUM project will be explained. Each section is written by the corresponding partner.

Each demonstrator described will have the following format:

- Overview of the demonstrator.
- Design of the demonstrator.
- System architecture description.
- Process flow in the demonstrator line.
- Description of the most relevant use case.
- Testing and verification.

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1 Spanish Demonstrator

1.1 Overview

The Spanish demonstrator consists of the development of integrated industrial control systems, capable of executing modular distributed control and assistance functions in industrial environments. In that way, these concepts have been integrated into a pilot plant which is in charge of assembling batteries. The pilot plant consists mainly of a robotic arm that actively interacts with the operator in a semi-automatic and sequential process.

This Human Robot Cooperation (HRC) demonstrator allows an operator to assemble battery packs for mobility applications, in tandem with a collaborative robot. In addition to the collaborative robot, there is a projector which guides an operator through an assembly process, a camera which identifies objects and assesses the quality of the process, and a battery quality control system which determines the state of health of individual battery cells.

The aim of the project is to manufacture a lithium-ion battery whose characteristics are shown in Table 1:

Table 1: Battery characteristics

	Voltage	Current	Power	Capacity	Electric charge	Energy
Battery (30 cells)	36 V	10 A	360 W	7500 mAh	105 Ah	0,270 kWh

The manufactured batteries can be used both industrially and commercially, for example, in electric bicycles. Figure 1 shows the assembled and welded battery, in the absence of placing the Battery Management Systems (BMS), connectors and protective cover.

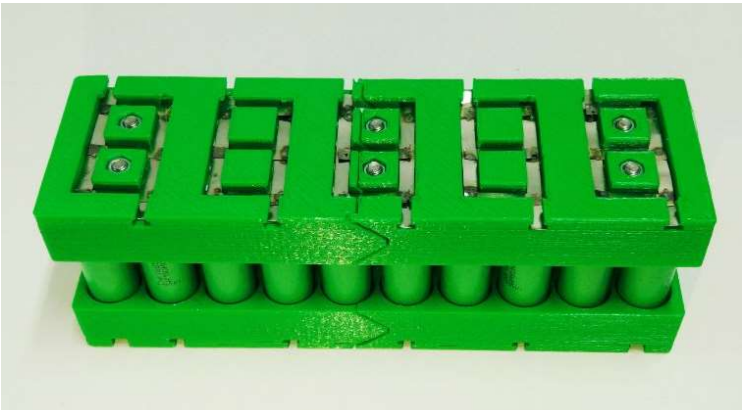


Figure 1. Battery prototype

Figure 2 shows the final battery with BMS, connectors and protective cover.

Figure 2. Battery prototype

1.2 Demonstrator design

1.2.1 Pilot plant design

The dimensions of the pilot plant are 2,00 m length, 0,64 m width and 2,60 m height. It consists of a steel structure designed so that all elements included in the battery manufacturing process are correctly positioned for their functionality. Specifically, there are two protruding supports, the first one for the computer vision (CV) camera and the second one for the projector. Figure 3 shows the design of the Magtel demonstrator.

The structure is complemented with a wooden table and four stable legs:

- The wooden table fits the measurements of the steel structure. In addition, it is white to facilitate the projection of instructions by the projector.
- The stable legs are composed of levelling feet, support 300 kg of weight and are robust.

Figure 3. Spanish demonstrator design.

1.2.2 Battery design

The dimensions of the battery are 0,22 m length, 0,07m width and 0.075 m height. It is made up of an upper matrix and a lower matrix. Both are designed to attach easily the nickel strips (for welding process). The main difference between the upper and lower matrix is the design for the placement of the nickel, as shown in Figure 4. The battery is designed and manufactured by Magtel.

The battery consists of 30 cells, forming a rectangle with 3 rows and 10 columns. A compact block is made by screwing 6 screws between the upper and lower matrix. The matrix is designed so that the heads of the screws and nuts do not protrude.

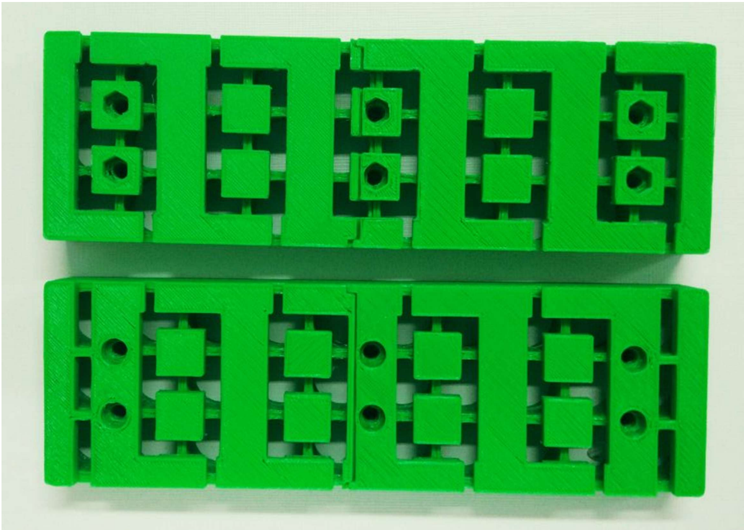


Figure 4. Bottom and upper matrix design.

1.3 System architecture description

The main hardware elements that are part of the demonstrator are the cells, the robotic arm, the welding device, the camera, the projector and the cell supplier.

1.3.1 Cells

The cells used are the famous Samsung INR 18650 25R, shown in Figure 5, which works at any rate voltage of 3.6V. It is likewise a lightweight cell which weighs only 45 grams. It is a profoundly productive cell with higher limit and low inner obstruction.

It is used 10 batteries in series, each of these batteries are a pack of 3 cells in parallel. So, the battery has 10 packs in series of 3 x 3.6V batteries in parallel and that it gives a total of 36V and a capacity of 7500mAh.

Figure 5. Samsung INR 18650 25R cells.

Technical data are in Table 2 (SAMSUNG, 2017):

Table 2: Samsung IRF 18650 characteristics.

Characteristic	Measure	Unit (SI)
Nominal discharge capacity	1100	[mAh]
Standard discharge capacity	≥ 950	[mAh]
Charging voltage	3,6 ± 0,1	[V]
Nominal voltage	3,6	[V]
Charging method	CC-CV with 50mA cut-off	
Charging current	550	[mA]
Charging time	100	[min]
Cell weight	40,0 ± 3,0	[g]
Cell dimension	Diameter: Φ18,15 ± 0,10 Height: 64,80 ± 0,15	[mm]
Operating temperature	Charge: 5 to 45 Discharge: -10 to 60	[ºC]
Cell temperature	Charge: 0 to 60 Discharge: -20 to 80	[ºC]

1.3.2 Cells supplier

The cell supplier device, shown in Figure 6, works as a quality control system which determines the state of health of individual output cells. States can be correct with polarity A, correct with polarity B, or incorrect.

Figure 6. Cells supplier device.

The analysis runs with an Arduino UNO. There are two metal contacts, shown in Figure 7, placed in the output cell to check the position of its poles and its voltage.

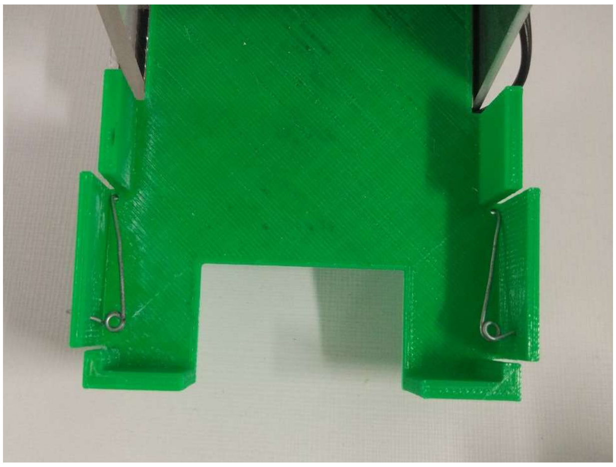


Figure 7. Contacts placed in the output cell

Also, it includes a small screen, shown in Figure 8, that shows the status of the output cell. The Arduino is connected to the Input/ Output (I/O) of the robotic arm and, depending on the state of the output cell, the robot executes one program or another.

Figure 8. Screen that shows the status of the output cell

The cell supplier is designed with three ramps of different height levels so that the cells fall under their own weight, shown in Figure 9. The total capacity of the supplier is 40 cells.

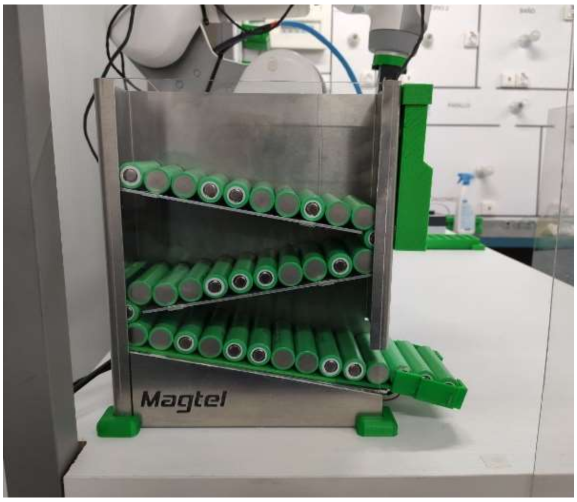


Figure 9. Ramps of cells supplier device.

1.3.3 Robotic arm

The robotic arm used is the new model of Eva company shown in Figure 10. It is a complete industrial robot, engineered to be lightweight, user friendly and accessible to all shop floor workers (EVA AUTOMATA, 2019).

Figure 10. EVA robotic arm.

The robot is programmed to:

- Assemble the cells in the lower battery matrix.
- Carry out the welding in nickel sheets connections.

The robotic arm achieves movement and maintains its position with six revolute joints, shown in Figure 11. Each axis has its own mechanical brakes. These are engaged by default, and disengaged when the robot is instructed to move.

Figure 11. EVA 6 axes movements.

The programming of the robotic arm, shown in Figure 12, is based on an internal program used from a web browser, which stands out for being very intuitive and visual.

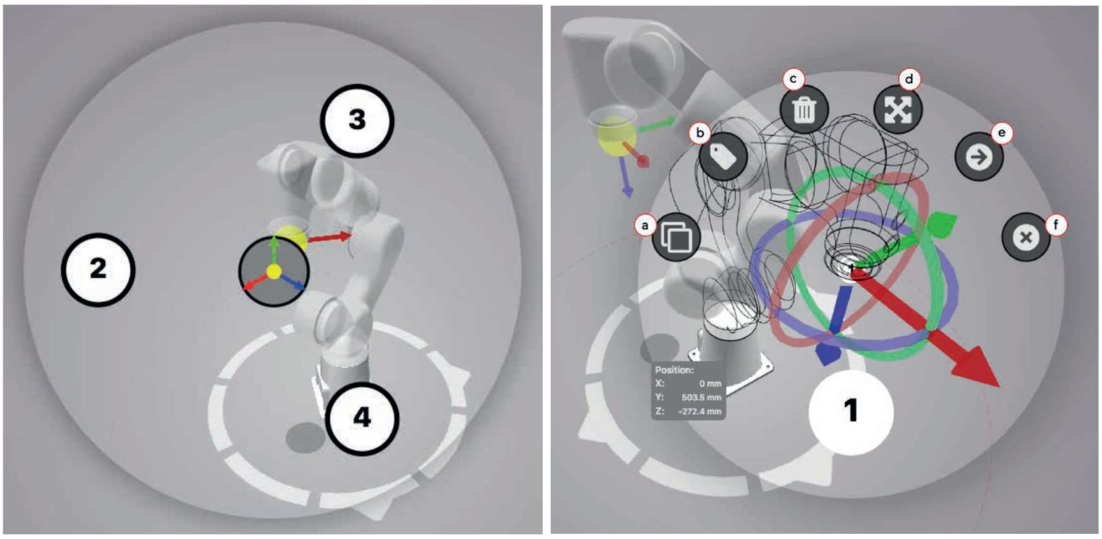


Figure 12. EVA programming interface.

The clamp consists of 3 parts:

1. **The link between robot and gripper:** This piece has been designed and manufactured by Magtel and it is perfectly suited to its needs. Figure 14 shows the link between robot and gripper.

2. **The gripper**: it has two operating states which opens or closes the fingers. It is a commercial gripper that offers very good performance. It is connected to the I/O of the robotic arm. Figure 13 shows the gripper.

Figure 13. EVA gripper

Technical data are in Table 3 (SCHUNK, 2020):

Table 3. Technical data of the SCHUNK EGP 40N

Technical data SCHUNK EGP 40N		
Characteristic	Measure	Unit (SI)
Stroke per jaw	6	[mm]
Min. Gripping force	35	[N]
Max. Gripping force	140	[N]
Recommended workpiece weight	0,7	[kg]
Max. Permissible finger length	50	[mm]
Max. Permissible mass per finger	0,08	[kg]
Repeat accuracy (gripping)	0,02	[mm]
Closing time	0,2	[s]
Opening time	0,2	[s]
Weight	0,32	[kg]
IP protection class	30	
Length	40	[mm]
Width	26	[mm]
Height	88,4	[mm]
Nominal voltage	24	[V]
Nominal Current	0,2	[A]
Communication interface	DI	

3. **The fingers**: the design and manufacture has been made by Magtel and it is adjusted to the needs of the project. Figure 14 shows the link between robot, gripper and fingers.

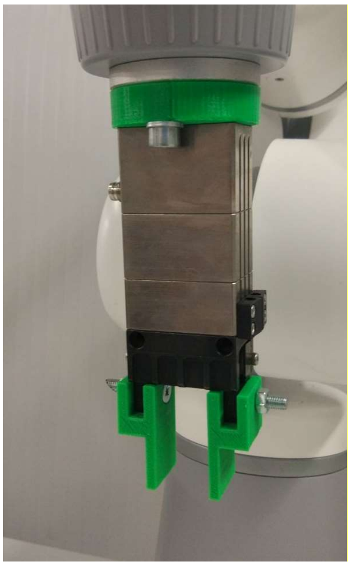


Figure 14. The link between robot, gripper and fingers.

1.3.4 Projector

The projector shows indications to coordinate the work between the robotic arm and the operator. It illuminates the work area helping to have stable lighting for the correct operation of the camera for CV analysis. Its function is centered on two points:

1. Shows instructions to the operator.
2. Shows process status.

The model of projector used is the digital BenQ TH671ST, shown in Figure 15.

Figure 15. BenQ TH671ST projector.

Technical data are in Table 4:

Table 4. Technical data of the BenQ TH671ST

BenQ Digital project TH671ST		
Dimensions	296 x 120 x 224	(W x H x D) [mm]
Net Weight	2,7	[Kg]
Power supply	AC 100 to 240V, 50/60 Hz	
Operating temperature	0-40	[ºC]
Resolution	1080p (1920X1080)	
Brightness	300	[lm]
Contract ratio	10000:1	
Speaker	5W x 1	
Projection system	DLP	
Zoom ratio	1,2x	
Colour wheel segment	RGBYCM	

Figure 16 shows an example of how the projector works.

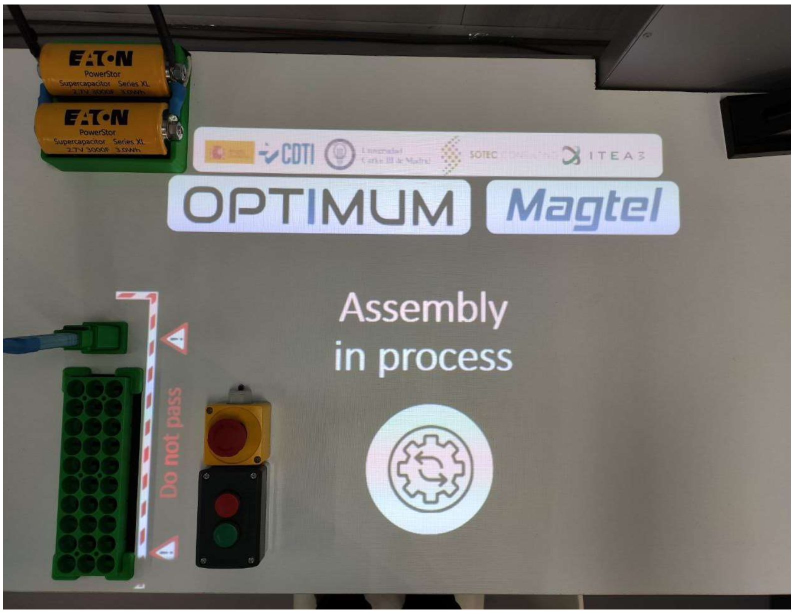


Figure 16. Example of projector operation.

1.3.5 Welder

Spot welds are performed by a supercapacitor, shown in Figure 17, whose characteristics are in Table 5 (EATON, 2020). The design of clamps is made by Magtel and they are displaced by the robotic arm. Nickel strips are used for soldering and joining cells.

Figure 17. EATON supercapacitor series XL

Table 5. Technical data of the Supercapacitor

SUPERCAPACITOR		
Model	Serie XL	EATON
Capacity	3000	[F]
Voltage	2,7	[V]
Power	3	[Wh]
Operating temperature	-40 / +65	[ºC]
Material	Acetonitrile	

Super-capacitor technology offers potential for high levels of energy storage (kilojoule levels) at low voltages (single volt levels). Supercapacitors are characterized by rapid charge and discharge cycles, as well as high secondary current delivery. Further, supercapacitor-based systems have proven to be tolerant to large numbers of charge/discharge cycles without degradation. This makes supercapacitors ideal for those energy management applications where charging and discharging is a priority. For this reason, the supercapacitor is continuously connected to a Power Supply, shown in Figure 18, which prevents its complete discharge.

Figure 18. Power Supply.

The application of supercapacitors for spot welding offer both technical and economic advantages. The benefits of using supercapacitors as welding power supplies are clear. These include reducing weights and reducing infrastructure requirements to the welding system. This analysis provides indications of the potential for supercapacitors for this application. To increase the efficiency of these elements, two supercapacitors have been installed in parallel.

The welding system is shown in Figure 19 and it is designed to be used by the robotic arm. The connection between the supercapacitor and the welding pencil is made with a 25 mm semi-rigid copper wire, which prevents the loss of current.

Figure 19. Welding system.

1.3.6 Camera

The camera is a Raspberry Pi Camera Module V2 installed on a Raspberry Pi 3 model B, shown in Figure 20, whose characteristics are in Table 6 and Table 7:

Table 6. Technical data of the Raspberry Pi 3 Model B.

Raspberry Pi 3 Model B		
CPU	Chipset Broadcom BCM2837 a 1,2	GHz
RAM	1	GB LPDDR2
Wi-Fi	802.11n	
Ethernet	100 Base-T	
Bluetooth	4.1	
GPIO	40	Pines
Dimensions	85,6 x 56 x 21	(W x H x D) [mm]
USB Ports	4	ports
Price	35	[€]

Figure 20. Raspberry pi 3 model B

Table 7. Technical data of the Raspberry Pi Camera Module v2.

Raspberry Pi Camera Module v2		
Sensor	Sony IMX219	
Still resolution	8	Megapixels
Video modes	1080p30, 720p60 and 640 × 480p60/90	p
Sensor resolution	3280 × 2464	pixels
Pixel size	1,12 x 1,12	[µm]
Sensor image area	3,68 x 2.76 (4,6 diagonal)	[mm]
Weight	3	[g]
Prize	25	[€]

The camera is located 90 cm above the table and its range of vision covers a large part of the robotic arm's working area.

On the one hand, the camera, shown in Figure 21, analyses the correct position of the cells assembled by the robot using CV. In addition, it is capable of analysing the weld points to check the correct state of the same.

On the other hand, the camera acts as a security barrier by analysing a video recording in real time.

Figure 21. Camera

- **Cell placement analysis:**

To detect the position of each of the cells that are part of the battery, a process is carried out using CV. This process consists of a simple comparison of images between a photo taken without cells [Image A] and another one after finishing the placement process [Image B], as shown in Figure 22.

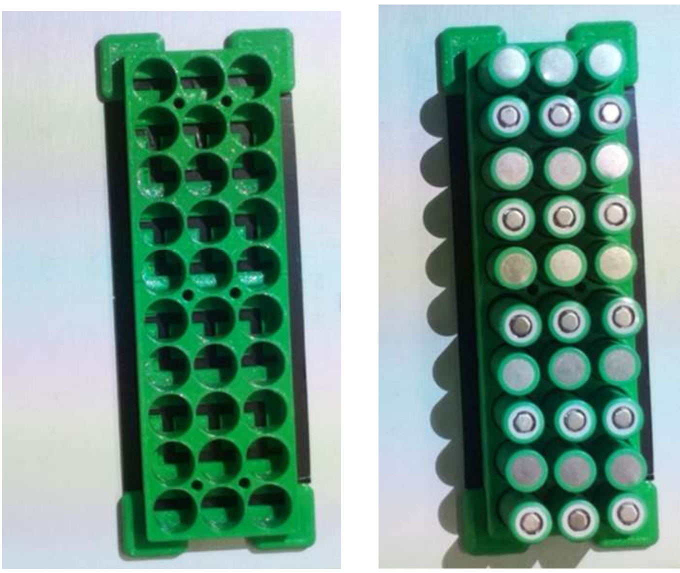


Figure 22. Matrix without cells [Image A] and matrix with cells [Image B]

This comparison is made after modifying the image to grayscale and, when applying this modification, the pixels of the image have a value between 0 and 1, where "0" corresponds to the full black colour and "1" corresponds to the full white colour. The values between them would be the different grey tones.

Then, a "black-white contrast" filter, shown in Figure 23, is applied to each part of the image which is going to be analysed. Using an intermediate grey tone as a reference, each pixel is scaled to full white (value 1) or full black (value 0). Consequently, the sum, corresponding to the set of pixels in the place where each cell should be, is made and analysed.

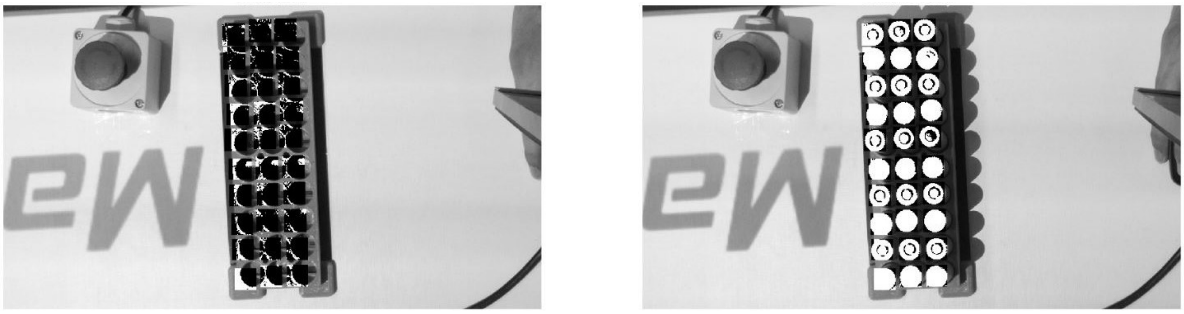


Figure 23. Analysis of cell placement.

Carrying out the procedure previously described for both “Image A” and “Image B”, a comparison will be made between both where two different cases can be obtained:

- If the cell placement has been correct, the sum of the pixels in image A will be less than the sum of image B, so the difference between the two images will be noticeable and the result obtained will be positive.
- If the cell placement has been incorrect, there will not be a great difference between both images and the result obtained will be negative.

- **Analysis of the welds.**

The study of the welds is performed with the same procedure used to detect the cells. It is actually a more complex process since the difference between the two images is much smaller.

The verification of the welds is only visual. Most of the time it is well executed, although there are some cases where the welding has not been done correctly. Therefore, the operator must check each one of them manually.

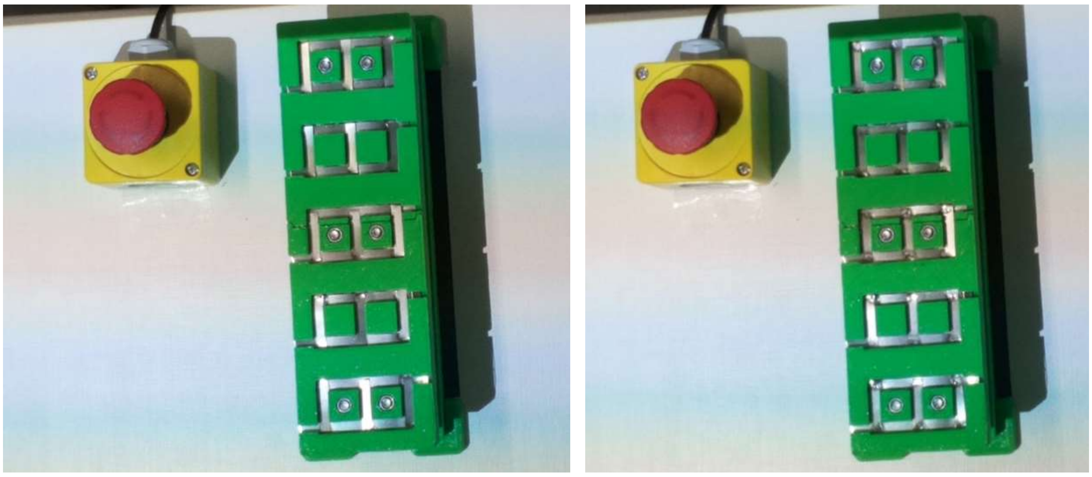


Figure 24. Weldless nickel (left) and welded nickel (right).

- **Safety barrier through CV.**

Through the real-time analysis of a video recording made by the camera, it is able to restrict the operator's access to certain work areas during the operation process of the robotic arm. The Raspberry Pi will send a signal to the robot when it detects warm colours in the programmed viewing range, in order to avoid accidents.

Methacrylate screens have been placed around the work table to complement the securities of the project.

Figure 25 shows how the CV camera is programmed to only detects the hand, regardless of the welder or battery.

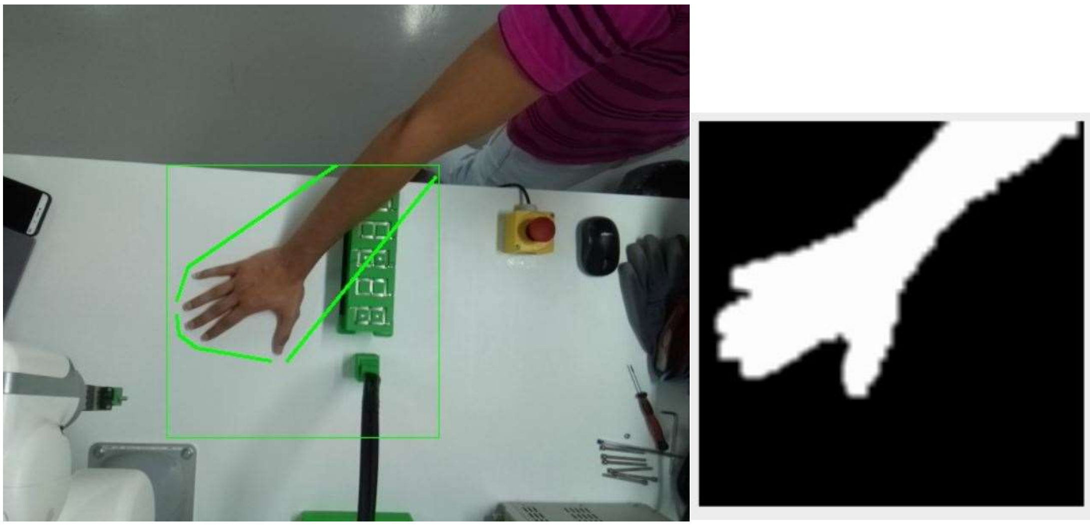


Figure 25. Safety barrier through CV 1.

Figure 26 shows how the CV camera is programmed to only detects the hand, regardless of the robotic arm or gripper during the work process.

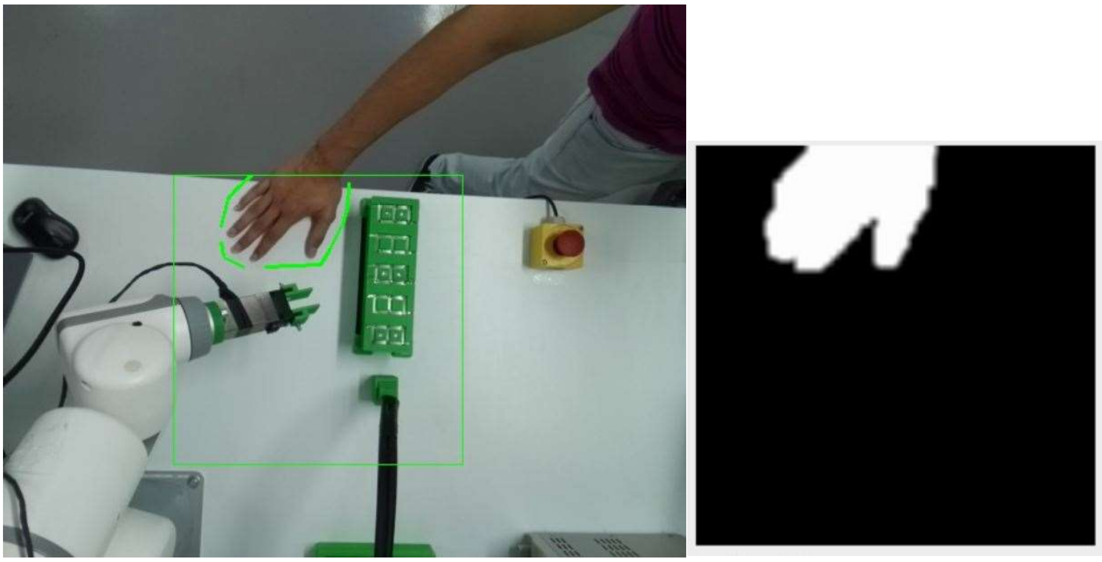


Figure 26. Safety barrier through CV 2.

1.4 Process flow in the demonstrator line

The basic process flow steps to follow are:

1. Cells supplier device analyses output cell.
2. The robotic arm places the cells in their bottom matrix, according to the information from the cells supplier device.
3. Raspberry Pi checks the correct placement of the cells using CV.
4. The operator, guided by instructions displayed by the projector, places the top matrix, screws the battery, and places nickel sheets to weld the cells.
5. The robotic arm grabs the welder and welds the battery cells.
6. Raspberry Pi checks the assembly and welding to inform the operator of the corrections to be made.

7. The operator completes the assembly of the battery with the BMS, the connectors and the protections.

Communications and their protocols are explained in work packages 2 and 3. In general, the main points about Industrial Internet of Things (IIoT) communications are the following:

- Communications are mainly wireless.
- Node red is the program that manages general communications.
- Message Queuing Telemetry Transport (MQTT) protocols are in charge of communication between the different devices and networks.
- Decentralized control platform (DCP) publishes a response with the status of the system. This can be used for debugging purposes or simply to check the current state of the DCP.
- Devices are connected with the server through Open Platform Communications United Architecture (OPC UA) to exchange information with the INDIGO software. Client reads device's state information from OPC UA server.

Access to the INDIGO platform is done through a web browser, such as Google Chrome, Mozilla Firefox or Microsoft Edge. It is designed and programmed through an interoperable interconnection interface based on OPC-UA communication protocols.

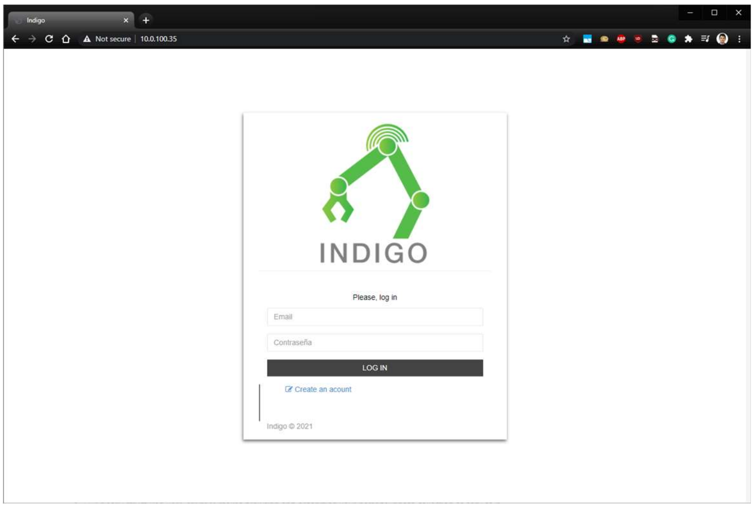


Figure 27. INDIGO - Login page.

The platform is a software programmed at a high level in which the different cyber-physical systems that make up the demonstrator are registered. It is possible to consult their status, modify certain values and access the data collected for each one of them.

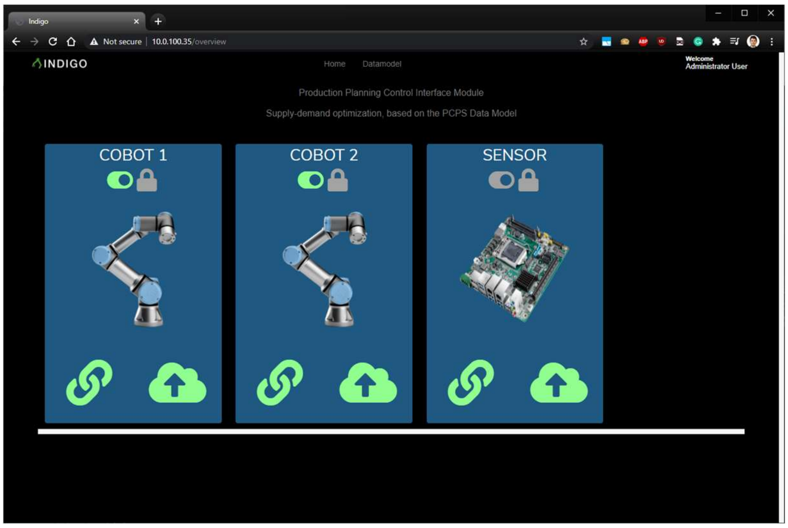


Figure 28. INDIGO - Home page after adding cyber-physical systems.

Depending on the type of data, the representation of the values may change, showing them as a numerical value, as a bar graph, as rotations, as a map (in the case of coordinates), etc.

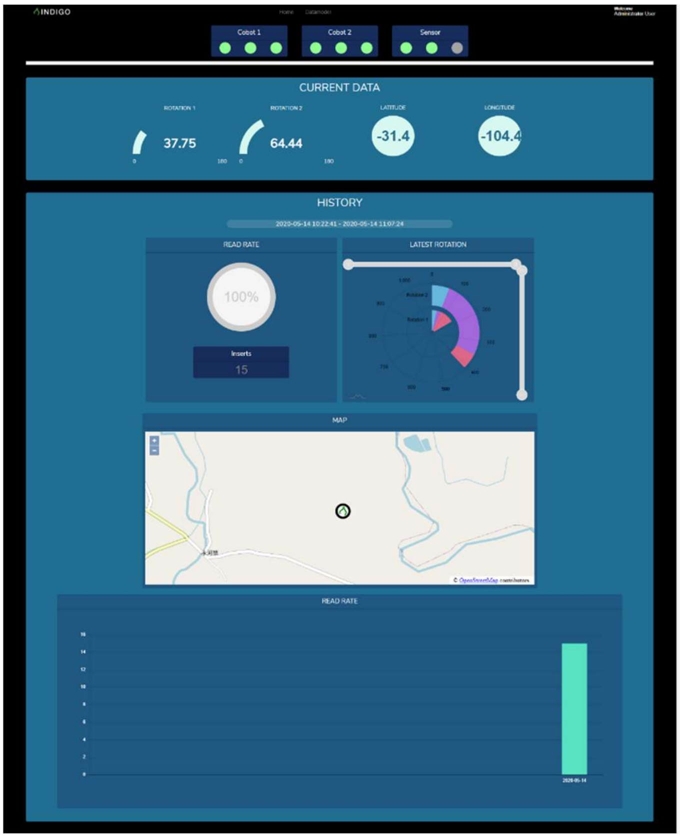


Figure 29. INDIGO - Example content for COBOT 1.

1.5 Description of the most relevant use case

The operation of the pilot battery assembly plant is a mainly sequential, logical and semi-automatic process, where there is great iteration between operator and machine. The communications between the main actuators described above are in charge of executing the entire process. Figures 30 and 31 show the process flow diagram, where its programming is explained.

The phases of the demonstrator operation are as follows:

Phase 1: Initialization:

The start of the pilot plant begins, after connecting to the demonstrator's electrical network, by pressing the confirmation button located near the operator's work area. In this way, all the actuators will be activated and waiting to receive information to execute their task.

Next, obeying the instructions of the projector, the operator will have to fill the supplier with cells, making sure that there are at least 30 cells to complete the battery.

Finally, the projector will instruct the operator to place the lower matrix in its corresponding position on the work area.

After all of this, the operator will press the confirmation button to go to phase 2.

Phase 2: Cell assembly:

This phase begins with the analysis of the output cell at the supplier. As appropriate, the cell will be correct with polarity A, correct with polarity B or incorrect if the voltage is less than 3.0 V.

According to the supplier's response, the robot will be in charge of placing the cell or discarding it, until completing the lower matrix.

At this moment, the artificial vision camera intervenes, which scans the lower matrix and checks that all the cells are well placed. The projector displays the generated result.

Subsequently, the projector orders the operator to place the upper matrix, to screw the battery and to place the nickel strips in order to carry out the welding of the next phase.

After verifying the entire process, the operator will press the confirmation button to proceed to phase 3.

Phase 3: Welds:

The welding points, in the first instance, will be carried out by the robot, grasping the welding clamp and going through all the cells. The nickel strips must be well placed to execute the correct welding.

Once the welding in the upper matrix is complete, the artificial vision camera will run its analysis of the welds, the projector will show the generated result and the operator will verify them.

After that, the projector will instruct the operator to rotate the battery to the lower matrix in the welding position and carry out the same process previously explained to weld the lower matrix.

Finally, when the operator verifies all the welds, he will press the confirmation button to proceed to phase 4.

Phase 4: Ending

In this final phase, the projector instructs the operator with several instructions to finish assembling the battery. There are instructions for soldering the BMS wiring, attaching connectors and insulators, and other items to complete the battery.

After all this, the confirmation button will be pressed and a new battery assembly process will begin.

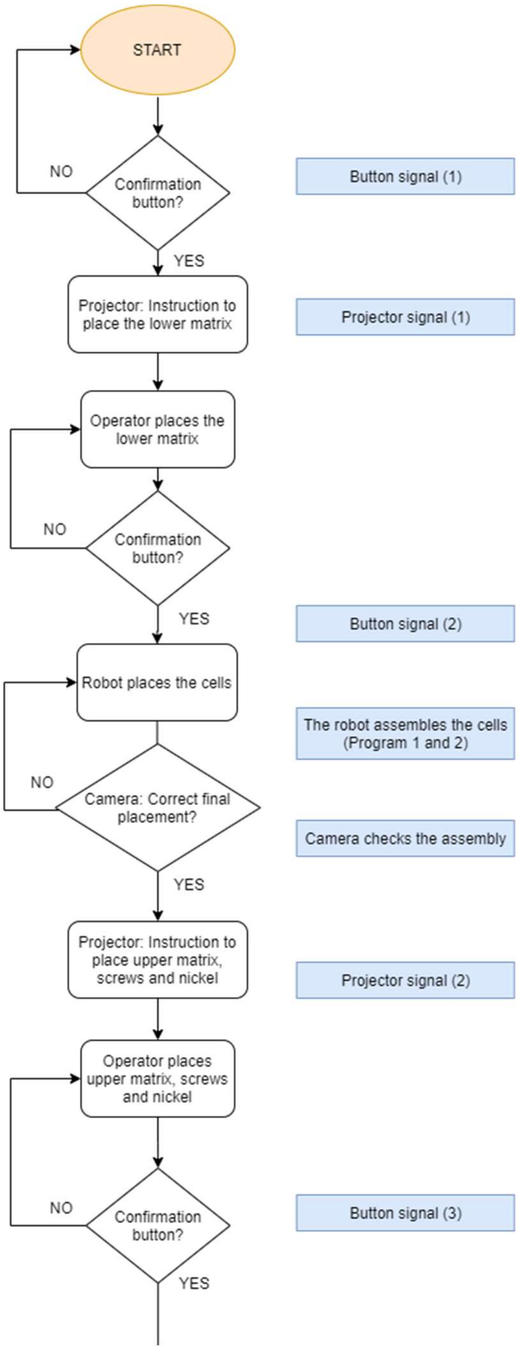


Figure 30. Flowchart (Part 1)

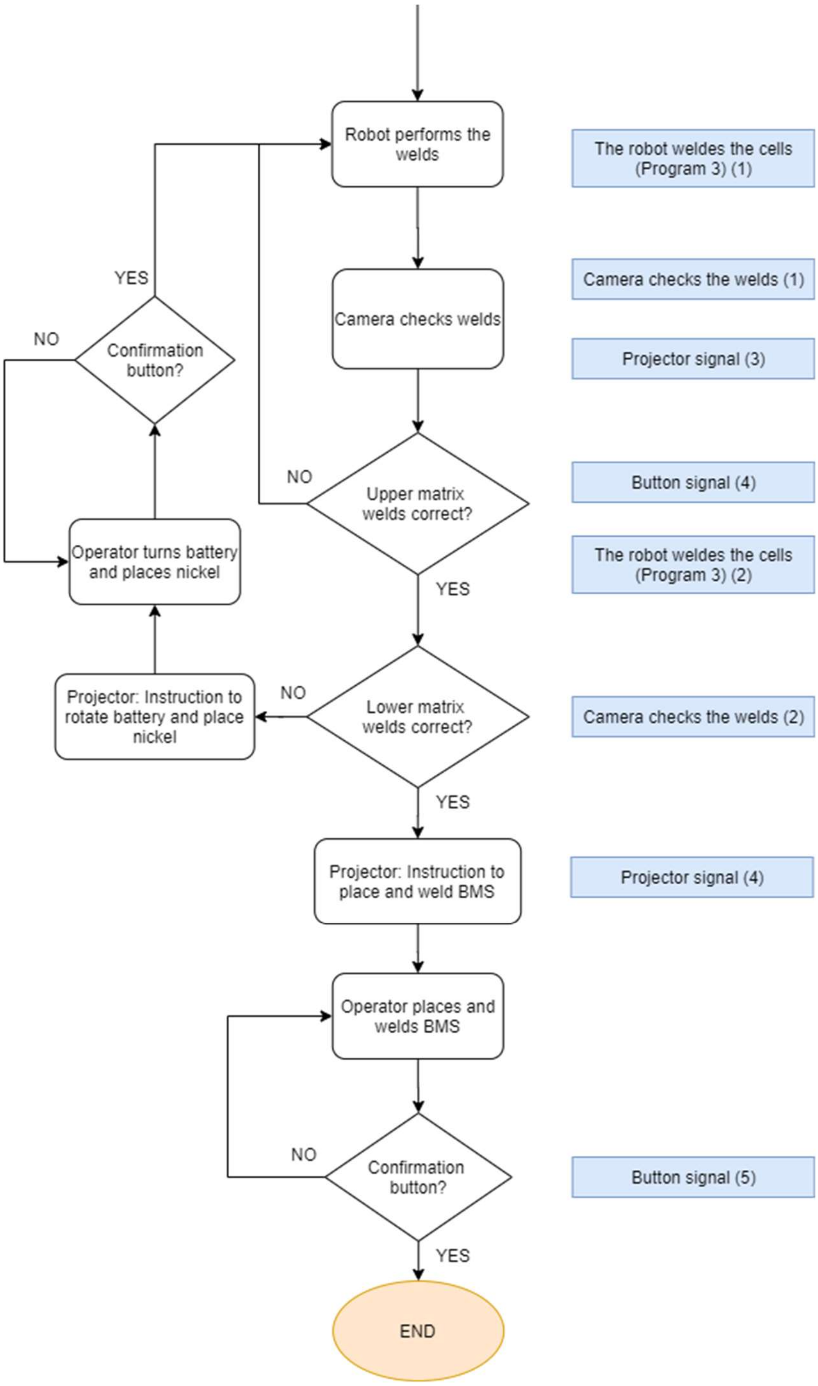


Figure 31. Flowchart (Part 2)

The security measures of the demonstrator are not shown in Figures 30 and 31. These security measures are:

- Emergency stop button.
- Artificial vision camera to ensure the robot's workspace. The plant would be disabled if an obstacle or element gets in the robot's workspace.
- Methacrylate screens.

1.6 Testing and verification

The tests have shown good results.

- The cells supplier device analyses output cell:
    - Duration: < 1 second
    - Effectiveness: 100%
- The robotic arm during assembly:
    - Duration for 1 cell: 15 second
    - Duration for 1 battery (30 cells): 460 second / 7,5 min
    - Effectiveness: 95%
- The robotic arm during welding:
    - Duration for 1 face of battery: 90 second / 1,5 min
    - Effectiveness: 75%
- The Raspberry Pi Camera checks the correct assembly:
    - Duration: 5 second
    - Effectiveness: 95%
- The Raspberry Pi Camera checks the correct welding:
    - Duration: 5 second
    - Effectiveness: 70%
- The Artificial vision camera secures the robot's workspace:
    - Duration: while the robot is working.
    - Effectiveness: 95%
- Projector operation.
    - Duration: when need to communicate something to the operator.
    - Effectiveness: 100%
- Wireless (WiFi) communications:
    - Effectiveness: 100%
- Wire communications:
    - Effectiveness: 100%
- Emergency stop and confirmations buttons.
    - Reaction time: < 1 second.
    - Effectiveness: 100%
- Communications with INDIGO.
    - Reaction time: < 1 second.
    - Effectiveness: 100%

2 Turkish Demonstrator

2.1 Overview

Demonstrator size is determined as 2.5x1.5x2 m (width x length x height), with approximately scale of 1:10 of the actual production environment; roll size determined as 20x20 cm (diameter x width).

Validation Requirements Matrix is taken as reference in determining functional properties. The position verification of the crane system will be provided by the rotary encoder. ERMETAL use case scenario does not require the operator to enter the crane work area. For this reason, it was not considered necessary to take special measures for position verification for the operator. The designated position of the crane moved by the industrial device will be verified by comparing it with the position data received from the rotary encoder, also by the industrial device. The locations of the actors present in the environment will be recorded by the industrial device. In the event that an operator or an object enters the crane work area unexpectedly, an object detection sensor will be placed on the tong to prevent collision, and when the crane detects an obstacle that is not registered in the system, it will be made aware of the obstacle by the industrial device. Weight sensors are placed on both legs of the tong for the balanced transportation of the roll of the crane located in the ERMETAL coil transport area. In addition, the receiver and the transmitter of the laser sensor placed on the two legs of the tong can close the tong legs in the correct position by seeing each other when the legs of the tong reach the gap in the middle of the roll. Taking these safety applications as an example, load sensor and infrared sensor will be used at the feet of the tong for the demonstrator.

2.2 Demonstrator design

Turkish demonstrator consists of four main components;

Scaffolding: It is the structure that constitutes the boundaries of the demonstrator, which consists of a crane, a sheet metal cutting machine and a stocking area, and will carry the equipment to be used in the demonstrator. For the profile selection of the scaffold; It is preferred to use aluminum sigma profile as shown in Figure 13 (1) instead of steel square profile pipe. Thus, no welding labor is required and scaffolding installation will be performed much more simply with bolt connections. Lightness is another advantage.

Crane horizontal movement system: These are the systems that enable the crane to move horizontally in the X and Y axes and serve as a bedding for this movement. In order to overcome the referencing difficulty that may arise due to the construction of the scaffold made of aluminum sigma profile, the timing belt modular system shown in Figure 32 has been used in the motion and bearing systems. Thus, the crane will be able to perform its horizontal movement correctly independent of errors such as vertical and parallelism in the scaffold.

Figure 32. Timing belt modular system that creates the horizontal movement of the crane

Crane vertical movement system: It is the system shown in Figure 33 (2) that enables the crane to move the load vertically. Hoist system was used, considering that linear motion mechanisms would not reflect the real environment. According to this system, at one end of the hoist, the rope is wound on a pulley while the load attached to the other end will move vertically.

Cutting line system: It is the system that represents the line where the sheet metal cutting is performed in the real environment. It consists of the coil car (3) and the cutting line (4) shown in Figure 33. Additionally, it consists of a coil car and a cutting line. In this system, there are two moving mechanisms in which the coil is transferred from the coil trolley to the cutting line and the coil is carried on a conveyor in the cutting line. In the real environment, the coil is transferred from the coil trolley to the cutting machine by an operator. Ermetal use case scenarios prepared within the scope of the OPTIMUM project were also designed in such a way that the transfer of the coil from the coil trolley to the cutting machine is carried out by the operator. However, during the demonstration, it was considered that transferring the coil from the coil trolley to the cutting machine by hand would interrupt the demonstration, and it was decided that the transfer would be performed mechanically.

Another moving mechanism in the cutting line is the conveyor belt system that allows the coil to be carried. In the real environment, after the coil is transferred to the cutting machine, the coil is opened and cut in determined sizes. The cut sheet metal pieces are stacked at the end of the line and counted by a counter. Thus, information about the completion amount of the work can be obtained. However, these mechanisms are too complex systems to be demonstrated in the demonstrator. On the other hand, the amount of completion of the coil cutting process is an important factor to be highlighted in the display. Therefore, cutting the sheet in real environment and counting the completion amount will be represented in the demonstrator as the progress of the roll on the conveyor belt. The marks on the conveyor belt line corresponding to the progress of the coil will also show the percentage of completion of the cutting process. The percentage of completion of the cutting process will also be shown on a screen.

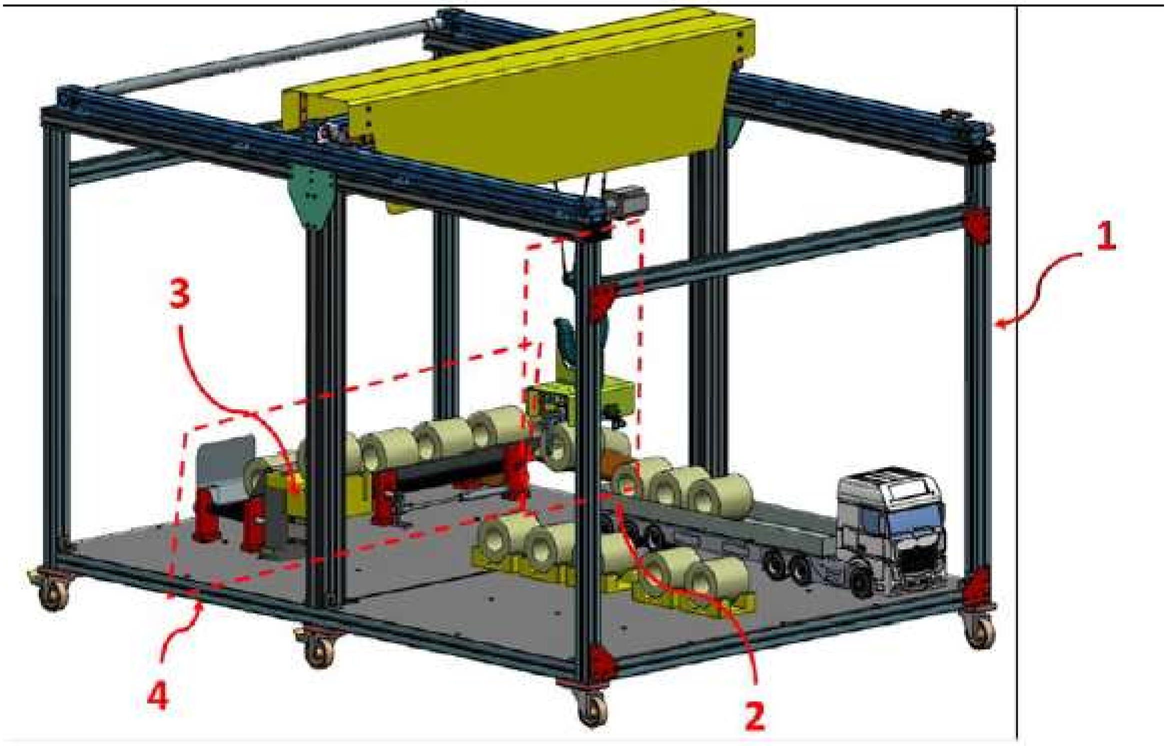


Figure 33. Overview of the demonstrator design

2.3 System architecture description

2.3.1 Hardware architecture description

For Turkish demonstrator, the following hardware is used which supports OPTIMUM functions.

Motors:

Axis Step Motors: It will be used to produce the mechanical movement required in the crane and cutting line system. In the real environment, the crane operates in a large volume of 50 x 20 x 13.5 m (length x width x height) m. Therefore, AC / DC motors are sufficient for the positioning accuracy of the crane in the real environment. In other words, positioning errors of AC / DC motors are not significant for large operating volumes. However, it was evaluated that the volume of the demonstrator, which is 3 x 1.8 x 1.8 m, which is much smaller than the real environment, may cause problems in positioning accuracy that may cause disruptions in the operation of the system in case of using an AC / DC motor. For this reason, step motors with high positioning accuracy will be used in the demonstrator to represent AC / DC motors that provide the movement of crane axes in the real environment.

Conveyor Step Motor: In the system of cutting line, a step motor will be used for the movement of the conveyor belt to ensure position accuracy.

Coil transfer servo motors: The transfer of the coil from the coil car to the cutting machine will be provided by an arm pushing the roll by performing an angular movement. Since there is no continuous movement for the coil transfer and the movement takes place at a partial angle, a servo motor will be used to move the arm.

Crane leg servo motors: In the real environment, the crane catches or releases a roll, it is provided by the crane's two legs mechanically opening or closing, entering or exiting the space in the middle of the roll. The legs of the crane will be represented in the demonstrator by providing the opening and closing movement of a servo motor.

Obstacle detection servo motors: In the real environment, there is no collision avoidance system for the movement of the crane. Turkish consortium fictionalized obstacle detection sensor for collision avoidance system with the scope of OPTIMUM project requirements. In order to provide multi-directional detection, the obstacle detection sensor needs to be rotated around its own axis. Servo motor will be used to make the collision avoidance sensor rotate around its own axis.

Sensors:

1- Position Sensor: Crane axis movements will be provided by step motors. Step motors are inherently controlled by step signals. This enables the step motor position to be determined by counting the signals sent to the step motors. However, the fact that the step motor provides location information digitally creates an obstacle to represent the real environment entirely. Position sensors for the three axes will be used to detect the actual amount of movement of each axis to enable the step motor to represent the AC / DC motor characteristic. Thus, it is aimed to meet the localization requirement of the OPTIMUM project. It is planned to use a rotary encoder as a position sensor.

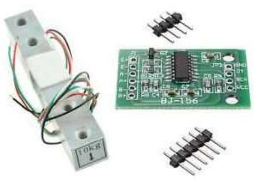
2- Weight sensor: Weight sensors located on both legs of the crane in real environment; It checks whether the load is evenly distributed on both legs, whether the load is caught and whether the captured roll causes overload. In order to ensure that this safety condition realized in the real environment is represented in the demonstrator, a weight sensor will be placed on each leg of the crane that enables the roll to be caught. Thus, it is aimed to provide the special security conditions of the OPTIMUM project.

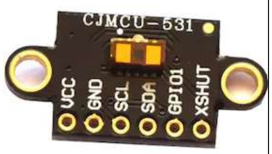
3- Collision avoidance sensor: Sensors will be placed on the crane to prevent the crane from colliding with any actor, an obstacle, operator or unexpected object. As the Collision avoidance sensor, ToF sensor will be used.

4- Obstacle sensor: In the real environment, the obstacle sensor located on both legs of the crane, one of which is a receiver and a transmitter, checks whether the legs of the tong are positioned in the exact middle space of the coil. In order to ensure that this safety condition realized in the real environment is also represented in the demonstrator, an obstacle sensor will be placed on each leg of the crane that enables the roll to be caught. Thus, it is aimed to provide the special security conditions of the OPTIMUM project.

The technical characteristics of the motors and sensors used in the demonstrator are shared in Table 8.

Table 8. Motors and Sensors

Material	Piece	Image	Features
Digital Servo Motor FT5313M	4		Turning angle: 120° In 6V voltage Speed: 0.10 sn / 60 ° Torque: 13,8 kg · cm In 4.8V voltage Speed: 0.13 sn / 60 ° Torque: 12,5 kg · cm
Servo Motor Parallax 360°	2		Min. Voltage: 5.8 V Max Voltage: 8.4 V In 6V Voltage Speed: 140 RPM Torque: @ 6V: 2,52 kg · cm
Rotary Encoder	1		Operating Voltage: 5-24V Resolution: 400 puls/rev Max. mechanical speed: 1000 rev / min
Loadcell and communication card Hx711	2		Load Cell Capacity: 5 kg Seperator Entrance Voltage: ± 40mV Data sensitivity: 24 bit (24 bit A / D Converter Integrated) Renovation Frequency: 80 Hz Operating Voltage: 4.8 - 5.5V Exit Voltage Range: 2.6V ~ 5.5V Operating Current: <10 mA
Infrared Sensor	1		Operating Voltage: 5 V Current Value: 5 mA Distance: 0 ~ 300mm Feedback time: 1 ms

ToF Sensor VL53L1X	2		Operating Voltage: 2.6 V - 5.5 V Current Value: ~15 mA Distance Modes Short: Up to 130 cm Medium: Up to 300 cm Long: Up to 400 cm Emitter: 940 nm invisible Detector: 16×16 SPAD Angle of field of view: 27°

2.3.2 Software architecture description

This section describes the software components that are developed to realize the Turkish Demonstrator. In Figure 34 all the components are depicted along with their relations with other components. As shown in the figure, there are 4 main methods of inter-process communication

1. OPC-UA,
2. MQTT,
3. Serial interface,
4. HTTP.

OPC-UA and MQTT communications are part of the OPTIMUM architecture and they are utilized as the architecture suggests. That is, OPC-UA is used to communicate with the upper layers in the architecture (such as HMI) and MQTT is used for communication within the industrial device. Serial interface and HTTP communication are due to the specifics of the Turkish Demonstrator and are used to communicate with either lower-level devices (e.g., sensors and actuators) or with the legacy/existing components (e.g., ERP system).

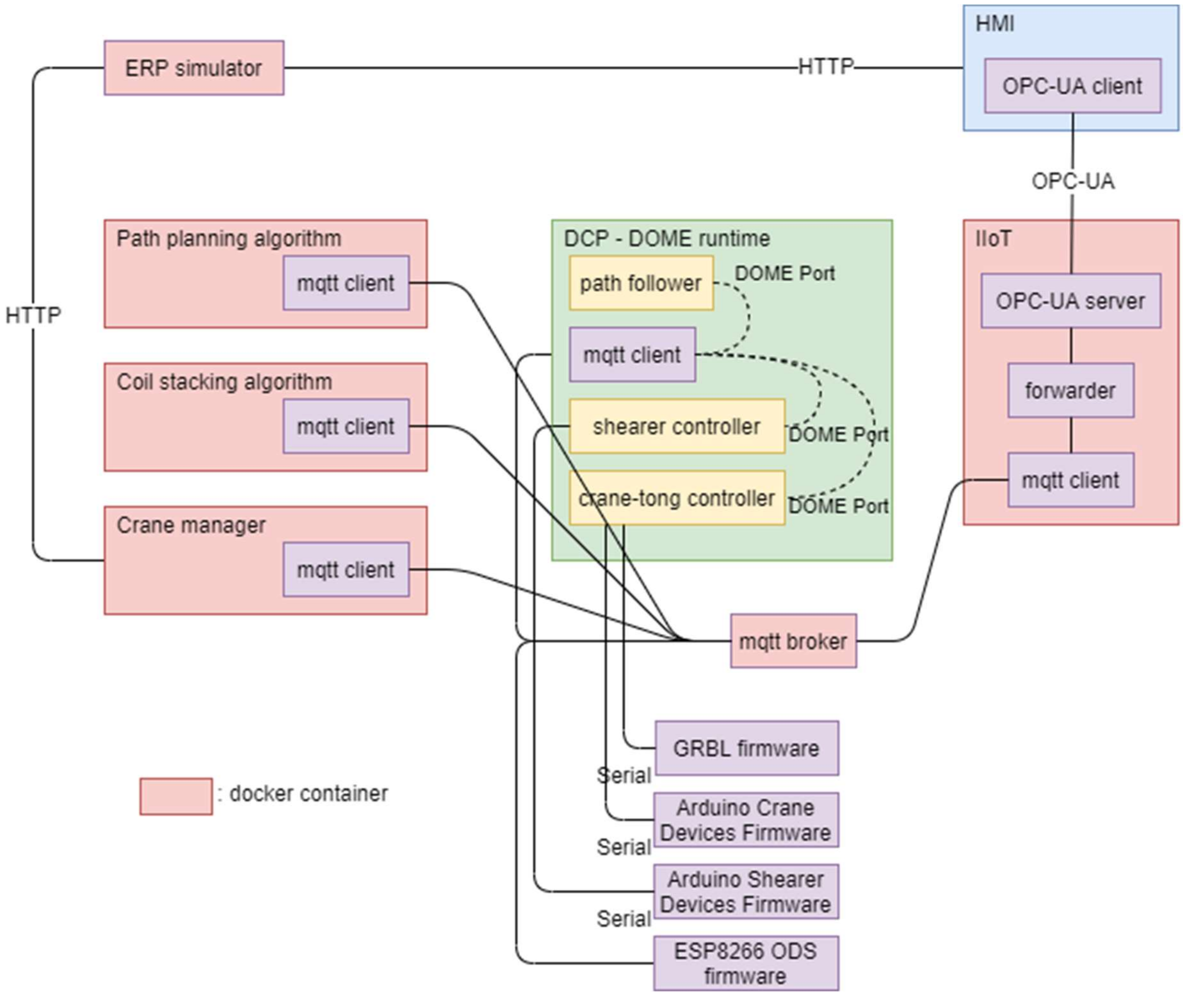


Figure 34. Turkish Demonstrator - Software Components

2.3.2.1 Crane Manager

This software component coordinates the actions of the system. Following are the main functionalities of this component

- Processes the commands sent from HMI.
- Interacts with the ERP to get and store the current configuration of coils (i.e., which coil is located where on the stacks).
- Interacts with the coil stacking algorithm and provides the necessary input (e.g., coil configuration, coil to be stored/extracted) to get the necessary steps to store or extract a certain coil.
- Converts logical steps for coil storage/extraction to real world coordinates.
- Interacts with the path planning algorithm and provides necessary input (e.g., start and end coordinates, known obstacles) to get the path that the crane should follow at each step.
- Interacts with DCP to control the crane (to follow a path) and the tong (to grab/release)
- Sends feedback to the HMI about the activities.
- Gets information from object detection system (ODS) about the surrounding objects and stops the current movement if necessary.

This component is implemented in Java and mainly follows the state chart given in Figure 35.

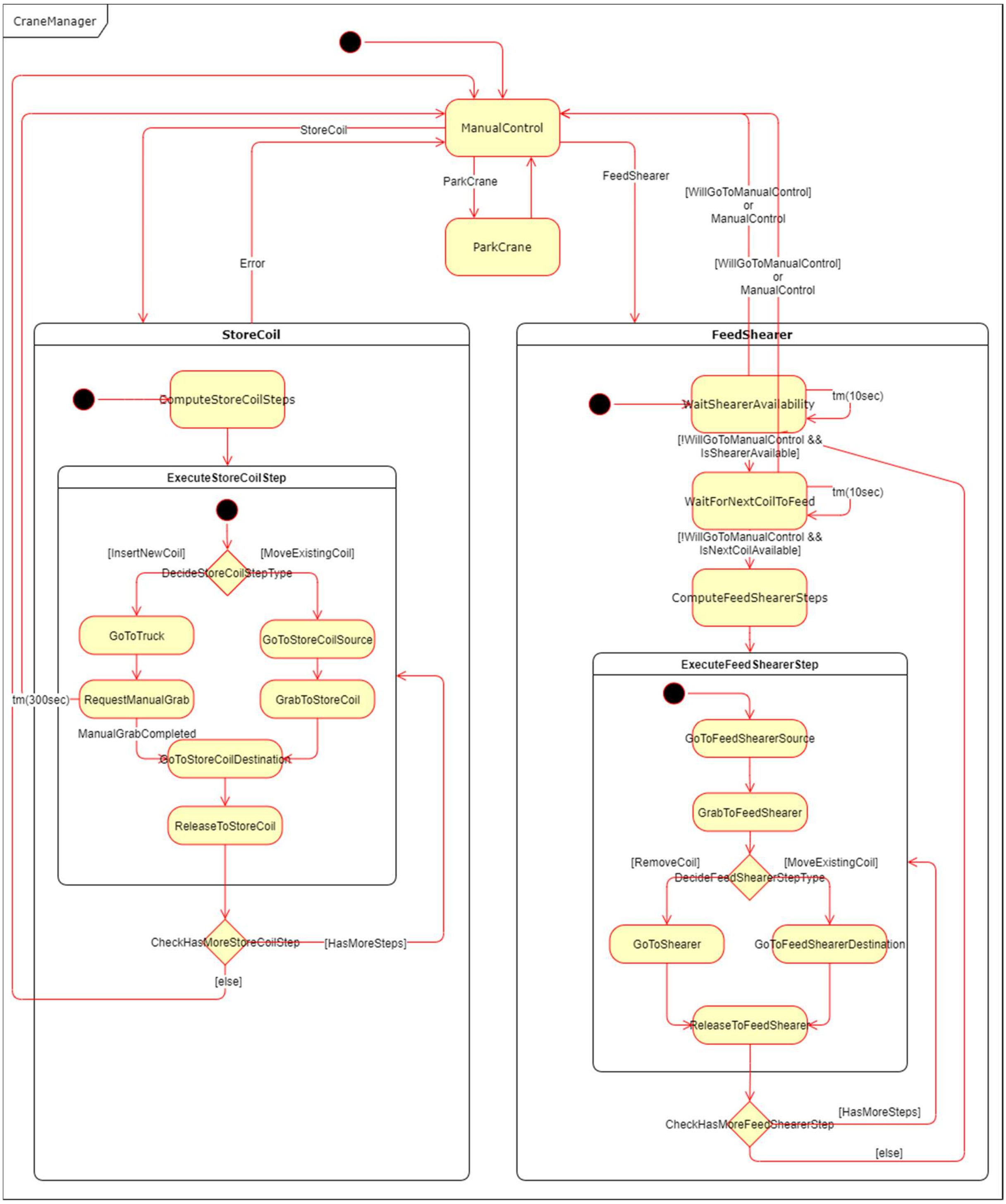


Figure 35. Crane Manager States

2.3.2.2 DCP (Distributed Control Platform)

DCP is used to control the crane and tong model through an Arduino device. Also, it publishes the current position of the crane and the current state of the tong. It is implemented in C++ using the DOME environment provided by IFAK. It has four control application objects: Path Follower to control the crane to follow a given path, Crane Tong Controller to control the crane and tong, Shearer Controller to control the shearer, and MQTT Client to provide the MQTT interface with the other components.

In the Turkish Desktop Demonstrator, that was developed earlier as an intermediate result, two separate DCP instances, one for crane control and other for shearer control, which run on two separate industrial devices, were used. That approached better represented the real-world situation, but in this demonstrator for the sake of hardware topology simplicity, they are combined to run in a single DCP. But the DOME runtime environment allows easy modification of deployment alternatives by abstracting the inter Control Application Object interfaces. Hence, if required, it is a trivial modification to have two separate DCPs from software point of view.

2.3.2.3 IIoT

IIoT component serves as a gateway between the upper layers (e.g., HMI) and components running on the Industrial Device (e.g., Crane Manager and DCP). It is implemented in Python and runs as an OPC-UA server for vertical communication and runs as a MQTT client for in Industrial Device communication.

2.3.2.4 Path Planning Algorithm

Given start and end locations and obstacles in the environment, Path Planning Algorithm computes the path (i.e., way points) from the start to end positions avoiding the obstacles. It provides an interface via MQTT and is implemented in Python.

2.3.2.5 Coil Stacking Algorithm

Given the current state of the main and swap coil stacks and the coil to be inserted/removed, Coil Stacking Algorithm returns the steps to be followed (e.g., move a certain coil from a certain position of a stack to a certain position of the same or other stack, insert a new coil to a certain position of the main stack, etc.). It provides an interface via MQTT and is implemented in Java.

2.3.2.6 HMI

HMI provides the user interface of the system. Interacts with IIoT and Inventory. It provides necessary controls to

- Manual crane control,
- Add new coils,
- Store a certain coil,
- Switch to “feed shearer” state
- Park the crane

HMI is implemented in Java and runs on Android operating system.

2.3.2.7 ERP Simulator

ERP Simulator simulates the required interfaces of a hypothetical ERP system. Those interfaces are

- Add, delete coils and manage data about each coil, such as id, weight and material
- Get and set the current coil configuration, that is the location of each coil in the stacks
- Get the next coil that needs to be fed to the shearer

It is implemented in JavaScript.

2.3.2.8 GRBL Firmware

GRBL[1] is used to control the crane in 3 axes. It accepts the necessary G codes and GRBL commands to move the crane and controls the 3 stepper motors accordingly. In the earlier Turkish Desktop Demonstrator, the stepper motors were directly controlled, but this time GRBL is preferred due to a smoother (i.e., with a controlled acceleration) movement on all the axes both for manual control and path following scenarios.

2.3.2.9 Crane Devices Firmware

Crane Devices Firmware is designed and implemented to run on an Arduino Mega device and provide communication with the following devices that are part of the crane

- 3 rotary encoders for x, y and z axes to obtain the current tong location
- 2 weight sensors to get the weight on the arms of tong, this information is later used to detect any imbalance while carrying the coil
- 1 infrared sensor to detect whether there is an obstruction between two arms of the tong
- 2 servos to control the arms of the tong

2.3.2.10 Shearer Devices Firmware

Shearer Devices Firmware is designed and implemented to run on an Arduino Mega device and provide communication with the following devices that are part of the shearer

- Shearer servo
- Shearer stepper motor

2.3.2.11 Object Detection Subsystem (ODS) Firmware

ODS Firmware is designed and implemented to run on a ESP8266 processing unit. It controls 2 servo motors to scan certain angle range and it reads the distance values from the 2 sensors attached to each servo. It combines the distance values with the current direction of the servos and broadcasts this information through MQTT.

2.3.3 Deployment description

Section 2.3.2 presents the software components developed and used to realize Turkish Demonstrator as well as the relations among them. This section gives information about how they are deployed to different processing units. In Figure 36 the software – hardware mapping is depicted. Furthermore, the communication interfaces and neighbouring devices such as sensors and actuators are also shown.

[1] https://github.com/gnea/grbl/wiki

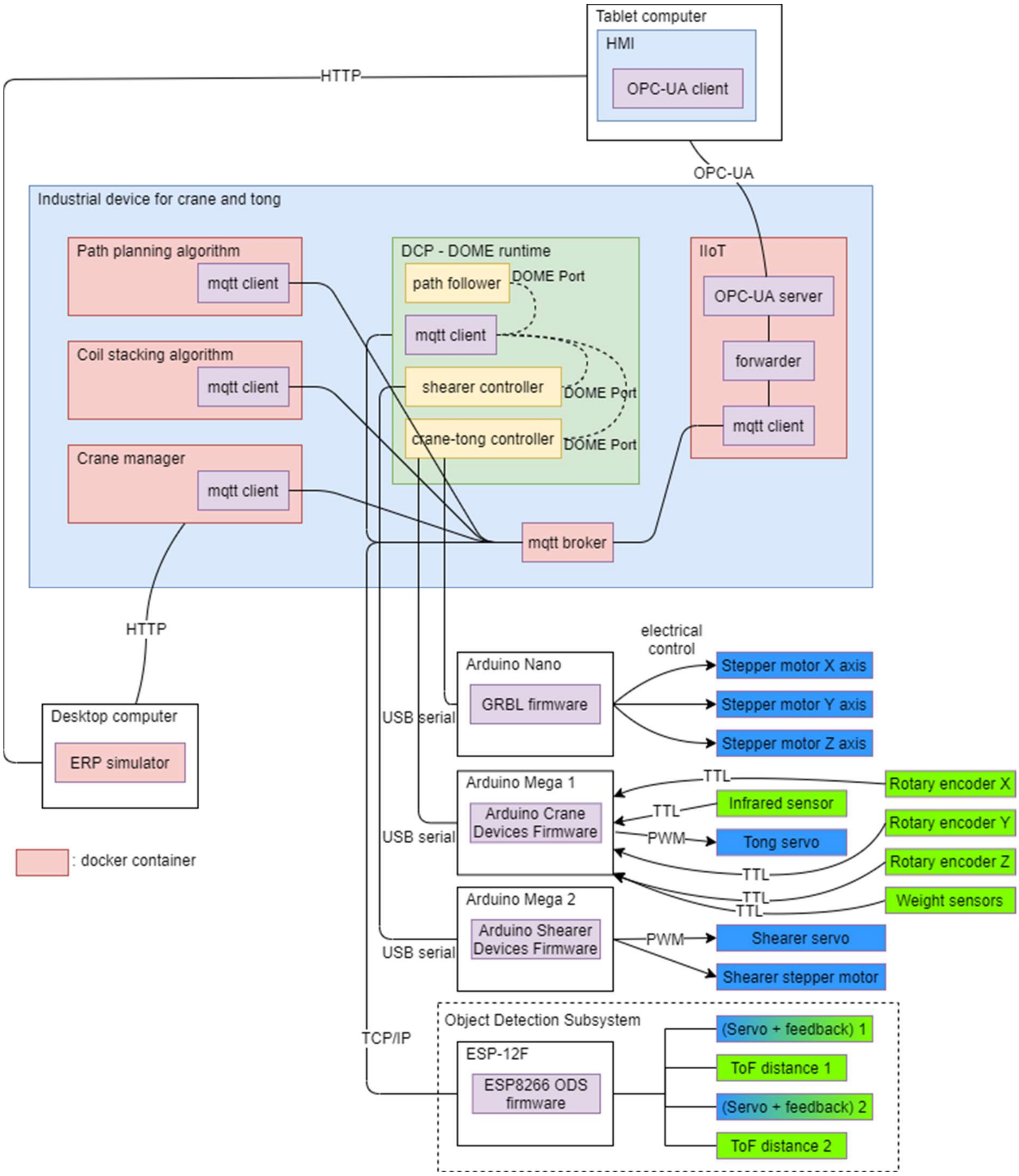


Figure 36. Turkish Demonstrator - Software Deployment

There are 7 relevant processing units that runs the developed software and Table 9 presents how the software components are deployed on these processing units.

Table 9. Turkish Demonstrator - Software Deployment

Processing Unit	Software Component
Raspberry Pi 3 – used as Industrial device - Main Processing Unit	Crane Manager
	DCP
	IIoT
	Path Planning Algorithm
	Coil Stacking Algorithm

Processing Unit	Software Component
	MQTT Broker
Android Tablet	HMI
Desktop Computer	ERP Simulator
Arduino Nano	GRBL Firmware
Arduino Mega 1	Crane Devices Firmware
Arduino Mega 2	Shearer Devices Firmware
ESP-12F	ODS Firmware

2.4 Process flow in the demonstrator line

The process flow consists of the following steps;

Acceptance of New Coil

In the initial state, there are no rolls in the environment. The demonstration starts with the acceptance of the roll on the truck. The operator identifies the coil on the truck from the HMI device and approves the coil. Crane approaches the truck and lands on the coil. The operator allows the crane to catch the coil manually with the HMI device. The operator switches the crane in automatic mode. Crane places the roll in the most convenient position in the stock area.

Arrangement of Coils

The operator accepts new coils. Heavy and large diameter coils must always be under the light and small diameter rolls. If there is no room for this rule during coil acceptance, the crane moves the appropriate roll from the stock area to the temporary stock area before receiving the new coil. After leaving the new coil in the most convenient location, it moves the roll that has been moved to the temporary stock area back to the stock area.

Cutting of Coils

The operator chooses one of the coils in the stocking area to be cut with the HMI device. Crane automatically takes the selected coil and places it on the coil trolley. If there is no processing coil in the cutting machine, the coil in the coil trolley is automatically transferred to the cutting machine. The coil moves along the band on the cutting machine. The advance amount of the coil on the belt shows the state of completion of the cutting process. At the same time, the percentage of completion of the cutting is shown on a screen.

Automatic Coil Cutting

If there is an ongoing process in the cutting machine at the moment of a coil is selected for cutting, the selected coil is queued. When 80% of the ongoing process in the cutting machine is completed, the crane automatically takes the first coil in the queued coils and carries it to the coil car. As soon as the ongoing process is completed, the coil in the coil trolley is transferred to the cutting machine.

2.5 Testing and verification

Test and verification results will be provided as part of deliverable D6.4 - Evaluation report and lessons learned.

3 Abbreviations

BMS	Battery Management System
OPC UA	Open Platform Communications United Architecture
MQTT	Message Queuing Telemetry Transport
DCP	Decentralized control platform
I/O	Input / Output
IIoT	Industrial Internet of Things
CV	Computer Vision
ODS	Object Detection System
GRBL	GRBL is a free, open source, high performance software for controlling the motion of machines that move, that make things, or that make things move, and will run on a straight Arduino. If the maker movement was an industry, GRBL would be the industry standard. https://github.com/grbl/grbl/wiki

4 References

[1] EATON. (2020). XL60 Supercapacitors. *Technical Data* .

[2] EVA AUTOMATA. (2019). Technical reference user manual. *Technical Data*.

[3] SAMSUNG. (2017). Lithium-ion rechargeable cell for power tools INR 18650-25R. *Technical Data*.

[4] SCHUNK. (2020). Gripper for small components EGP 40. *Technical Data*.