

# Industrie 4.0-compliant Digitalization of a Pick and Place Module with Real-time Asset Integration within a Digital Factory

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## **Abstract**

The Industrie 4.0 is a trend aimed at the digital transformation of different aspects of the economy. This digital transformation seeks to interconect equipment, processes, humans, and other assets of value to an organization by creating digital representations of them.

The digital representation is called a digital twin and the assets can be anything from the real world be it tangible such as machinery, tools, and raw materials; and intangible such as software, processes, and even intellectual property. Digital twins enable the cooperation, collaboration and interoperability of assets in an enterprise.

The Industrie 4.0 proposal for a digital twin is the Asset Administration Shell (AAS). The AAS contains all the information of that is necessary to represent an asset in the digital world.

This report presents a project to create a functional prototype of an AAS-compliant digital twin for a pick and place module of the Digital Factory if the University of Applied Sciences in Emden, using the RAMI4.0 model as a theoretical background and the FA<sup>3</sup>ST service tool as the implementation technology. The project focuses on the real-time syncrhonization of the asset's data to and from the digital twin.

# 1 Introduction

The Plattform Industrie 4.0[4] is a German government initiative aimed at advancing the the fourth industrial revolution. The Plattform Industrie 4.0 name for this concept is **Industrie 4.0**.

Industrie 4.0 refers to the intelligent networking of machines and processes for industry with the help of information and communication technology. Its fundamental purpose is to facilitate cooperation and collaboration between technical objects (assets), which means they have to be virtually represented and connected [12].

## 1.1 RAMI4.0

The Plattform Industrie 4.0, in partnership with many other stakeholders, has created the **DIN SPEC 91345**. This DIN SPEC describes the RAMI4.0 which is a reference architecture model and provides an architecture for technical objects (assets) in the form of layers, and allows them to be described, tracked over their entire lifetime and assigned to technical and/or organizational hierarchies. It also describes the structure and function of Industrie 4.0 components as essential parts of the virtual representation of assets. [12]. Figure 1 shows a visual representation of the RAMI4.0.

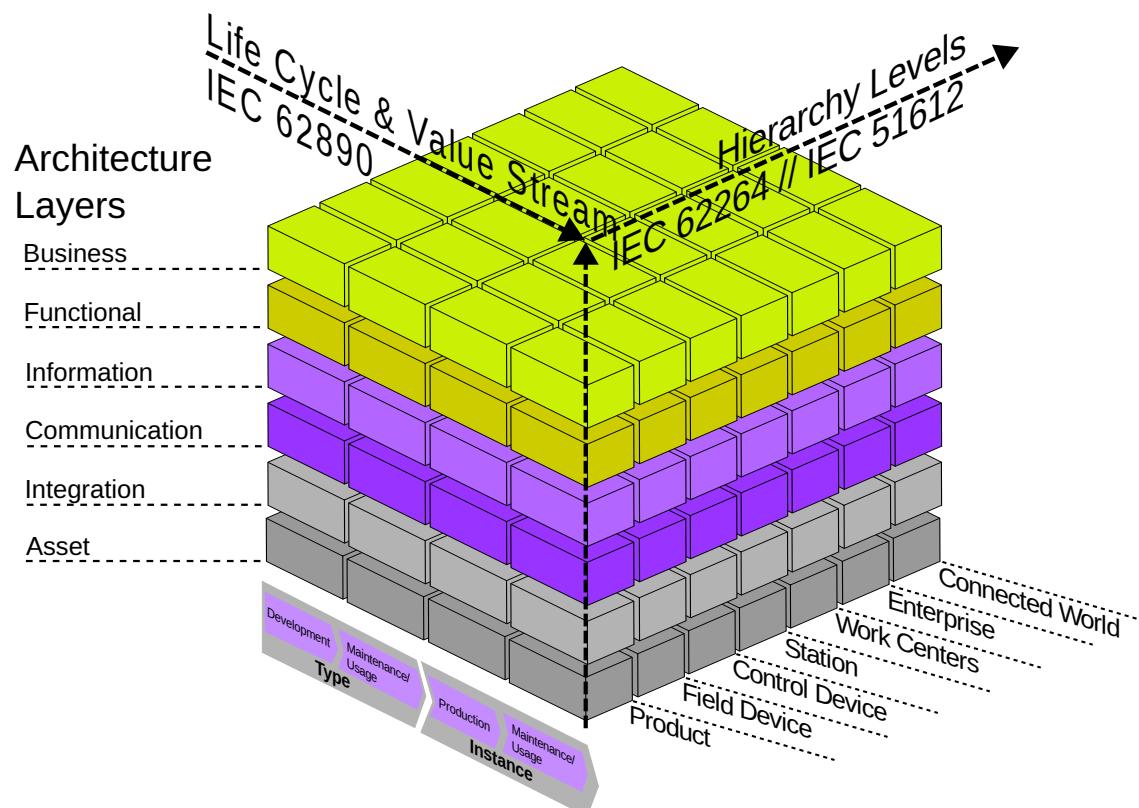


Figure 1: RAMI4.0 model

## 1.2 Digital Factory

The Digital Factory at the University of Applied Sciences in Emden is a flexible manufacturing system, which is used to demonstrate key concepts and features in the field of industrial digitalization and Industry 4.0.[11].

One of the key features of the design of the Digital Factory includes a modular approach, where individual functional parts of a production process are isolated in a modular frame. Each of these modules are designed to be self-contained, meaning they implement a specific production capability and include all necessary devices (e.g. power management, control devices, safety devices, etc.) and supplies inside the module. This way, each module is theoretically capable of being used by itself without the need of any other part of the system, but the full potential will be developed through collaboration with additional modules to allow a more complex production including different production steps. The modules are movable, allowing them to be placed flexibly on the Digital Factory's shop floor and enabling a job shop production[11].

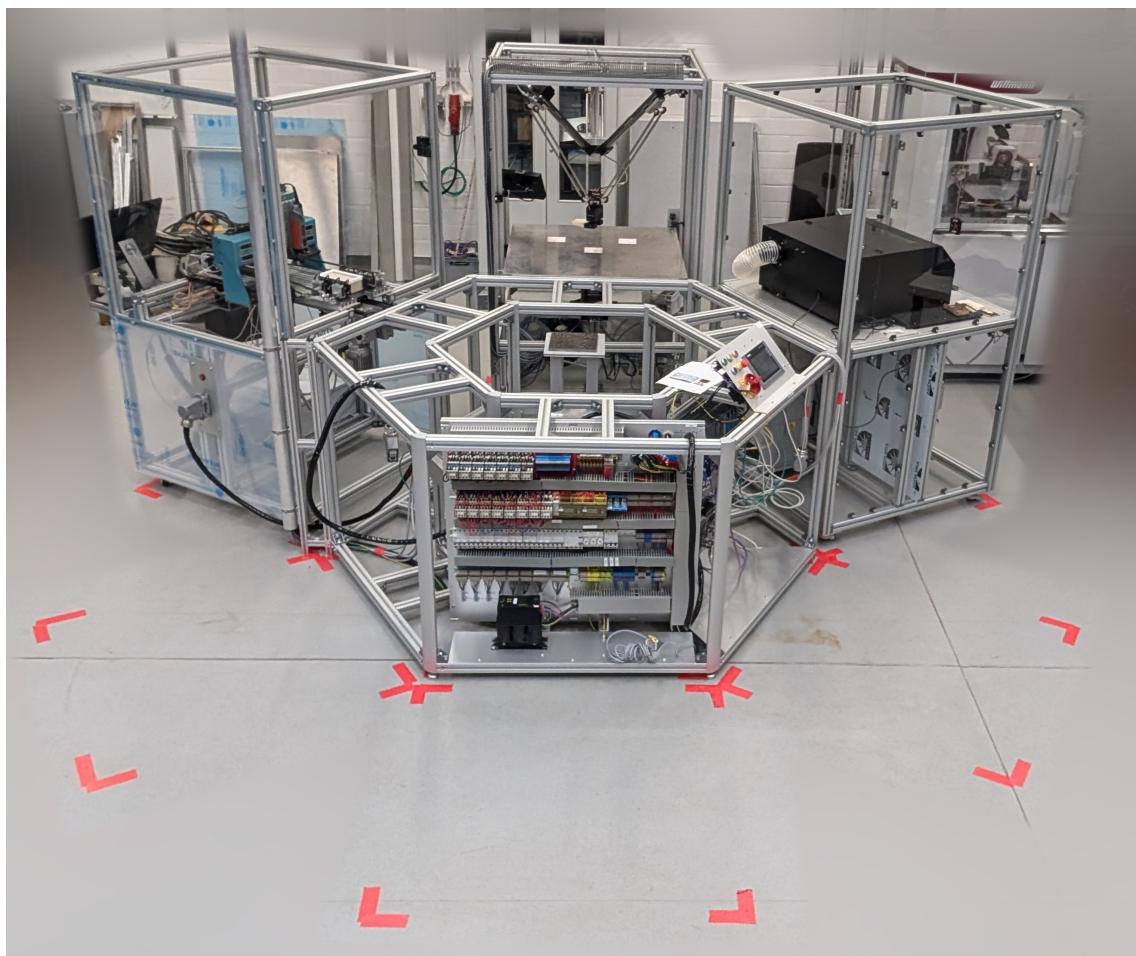


Figure 2: Digital Factory with 3 modules

### 1.2.1 Pick and place module

One of the modules in the Digital Factory is the pick and place module. Worked previously under the name of “Delta robot”<sup>[7]</sup>. The module is composed of the following hardware and software:

- An Igus 3-axis Delta Robot with its iRC robot control hosting a modbusTCP/IP service
- An in-house made gripper controlled with an ESP32 development board
- A Raspberry Pi with Raspbian OS
- A touch screen connected to the Raspberry Pi for desktop display and control
- An adjustable-height table base

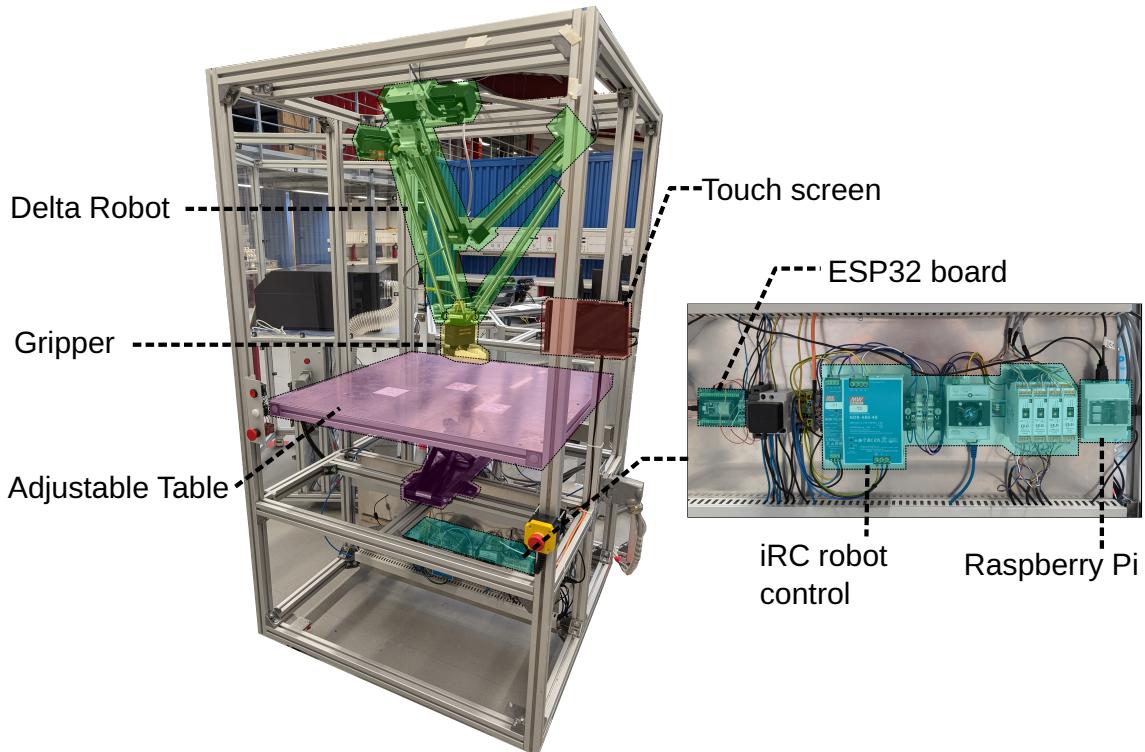


Figure 3: Pick and place module components

### 1.3 Structure of this report

This report is structured as follows: Section 2 describes the use of the RAMI4.0 to create a conceptual model of the digital twin. Section 3 describes the technologies, tools, design, and implementation of the digital twin following the model devised in the previous section. Section 4 presents the results of the implementation by demonstrating its use. Finally, Section 5 discusses the most significant technical issues encountered and provides ideas for improvements and future works.

## 2 Methodology

This section describes how to use the RAMI4.0 as the theoretical basis to digitalize the pick and place module in the context of Industrie 4.0. The output of this section will provide the definitions, technologies, and requirements for the actual implementation.

### 2.1 Asset position in the RAMI 4.0

The RAMI4.0 is a reference model that when applied yields a more concrete, implementation-independent model of the digitalization of an asset. In a broad sense applying the RAMI4.0 involves three steps:

1. Determine the position of the asset in the Hierarchy Levels axis.
2. Determine the position of the asset in the Life cycle & Value stream axis.
3. Determine definitions, technologies and general requirements of each architecture layer.

Steps 1 and 2 help to determine **what** data and information is relevant to digitalize. Step 3 helps to determine **how** to digitalize the relevant data. This is, how the data and information is going to be made available to the business as shown in Figure 4.

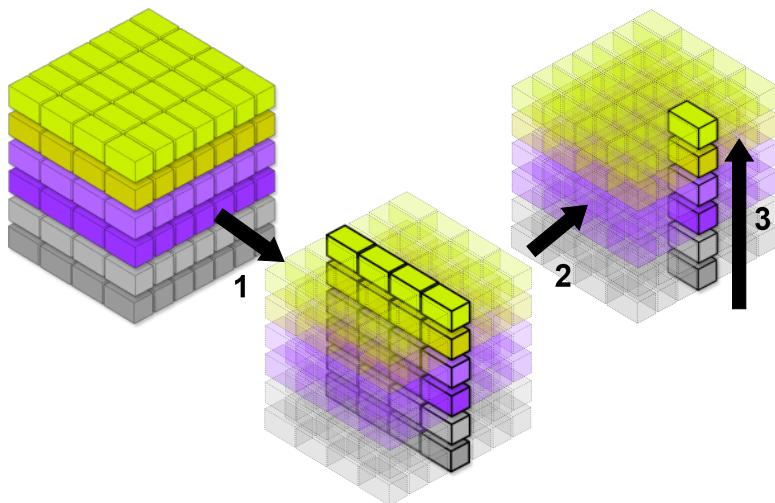


Figure 4: Three-step application of the RAMI4.0

The following three sections explain these steps in more detail.

#### 2.1.1 Position in the Hierarchy Levels Axis

The Hierarchy levels axis of the RAMI4.0 is based on the role-based hierarchy model of the IEC 62264[9]. This axis describes the assets of an organization that are involved in

the manufacturing and business processes. Figure 5 provides a broad picture of where the pick and place module is located in the hierarchy levels axis and how it relates to other components in the organization.

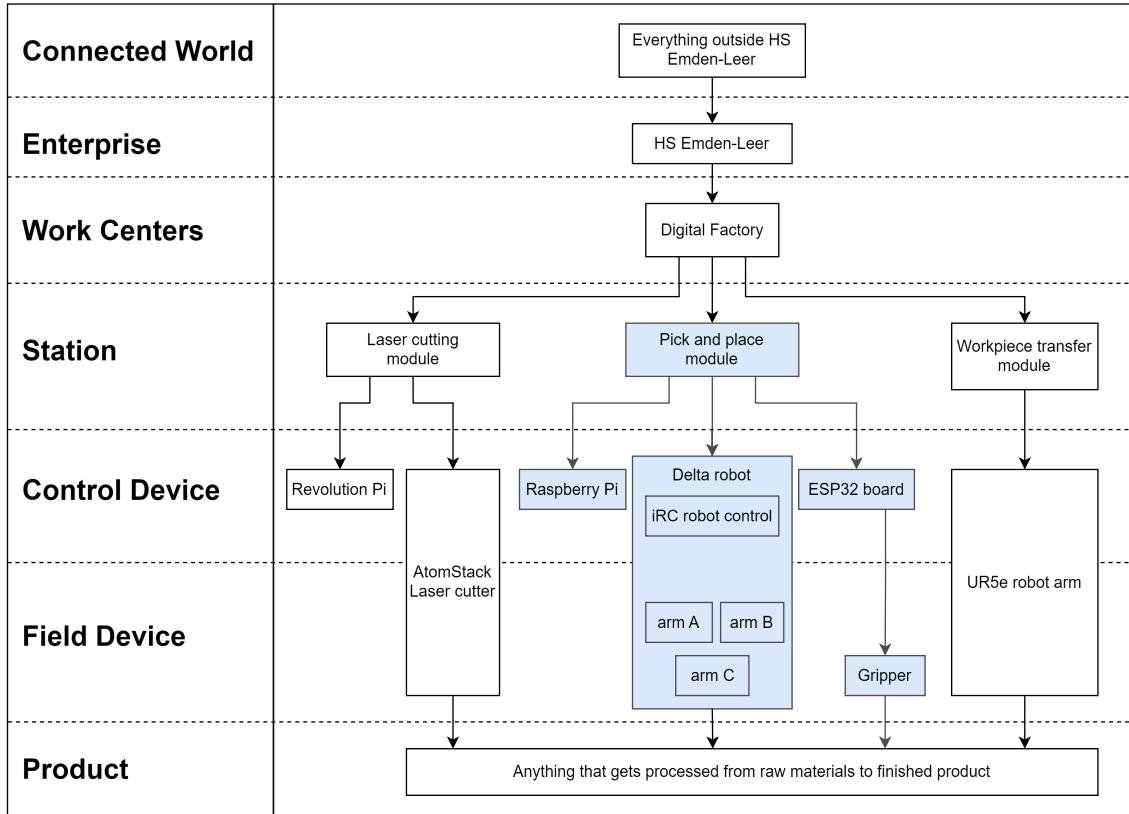


Figure 5: Hierarchy levels overview

A common, yet incomplete, definition of a station is an asset that is composed of sensors and actuators. A better definition of a station is an asset that has the equipment to manipulate a product (has sensors and actuators), has well-defined manufacturing capabilities and throughput capacities, it performs a segment of the manufacturing process, and is used for Level 3 functions (functions of manufacturing operations management). For more details on this refer to [9, chap. 5, “Hierarchy Models”]

The pick and place module is then classified as a **Station**.

*From now on “pick and place module” and “pick and place station” refer to the same asset.*

### 2.1.2 Position in the Life Cycle & Value Stream Axis

The Life cycle & value stream axis is used to describe an asset at a particular point in time during its lifetime, from its conception and design, to its production and value-added use right up to its disposal[12].

Because the main goal is to digitalize real-time operational data then the pick and place station can be classified as an **instance** in **Usage** phase.

### 2.1.3 Architecture Layers

The Architecture Layers axis describes the digitalization architecture in terms of properties and system structures with their functions and function-specific data in the form of layers [12].

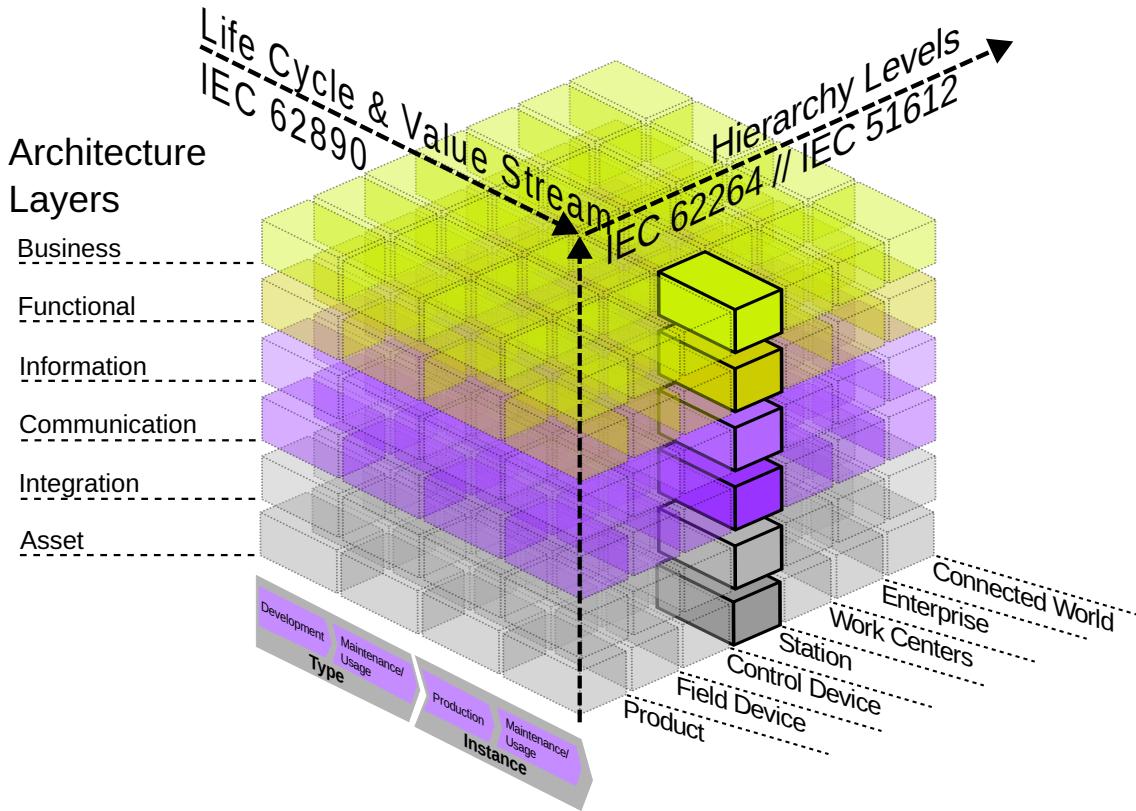


Figure 6: Architecture layers for station instance in maintenance/usage phase

By applying the RAMI4.0, the scope of the generic model is reduced and focused on the digitalization of the maintenance/usage data of a station instance. A visual representation of the result of applying the RAMI4.0 is shown in Figure 6.

A more concrete description of a solution can now be provided. The following subsections provide a description of each layer in relation to the pick and place station as well as the definitions, technology, and other general requirements for implementation. The actual description of the implementation will be described in Section 3.

### **2.1.3.1 Business Layer**

The business layer describes the commercial view. This can be understood not only as profit but also as what gives value to the organization.

The context in which the pick and place station provides value will be defined as: **Academic research and implementation of I4.0-compliant technologies**.

### **2.1.3.2 Functional Layer**

This layer describes the logical functions that enable the business. In the context of Industrie 4.0 these functions are defined as Capabilities. Capabilities are implementation-independent descriptions of the function of a resource to achieve a certain effect in the physical or virtual world[1].

Capabilities can be described at various levels of abstraction allowing them to be more or less specific as well as composed of other capabilities. For example: “Transport” is a capability. “Pick and place” is a more specific way to transport so it can also be a capability. Further more, “Pick and place” can be composed of the “Grip” and “Move” capabilities.

Capability descriptions are outside the scope of this project, still they provide a way to represent the logical functions defined in this layer.

For the pick and place station a logical function would be the **“Pick and place”** capability.

### **2.1.3.3 Information Layer**

This layer describes the data and information that is used by the functions in the functional layer.

Industrie 4.0 introduces the concept of the Asset Administration Shell (AAS) submodels. AAS Submodels are representations of different aspects of an asset and are used to organize the data and information and provide a separation of concerns[2, Annex A, section V, “The Concept of Submodels”].

Using the AAS is a requirement for this project.

Because this project is focused on digitalizing real-time operational data then the information layer will include an **“Operational Data” submodel**. This submodel will contain properties and operations providing data such as the position of the delta robot as coordinate properties, a move operation, status of the robot movement, and so on.

#### 2.1.3.4 Communication Layer

This layer describes the access to the information in an Industrie 4.0-compliant way. In other words, how to locate, read, and write the information.

Part of the AAS definition is the description of services, interfaces, and interface operations to access the information within. At the technology-specific level the information in the AAS can be accessed through HTTP, OPC UA, and MQTT interfaces[3].

As a requirement for this project the **communication must be done through OPC UA**.

#### 2.1.3.5 Integration Layer

This layer describes how to read and write data from the asset (the physical world) into the information world. In other words, this layer represents a bridge that allows the communication layer to interact with the asset.

An **HTTP API** will be used to integrate the asset's data with the upper layers.

#### 2.1.3.6 Asset Layer

This layer describes the real world. In this case the asset is the **pick and place station**.

Figure 7 shows an overview of the technologies and other definitions to be used for the architecture layers.

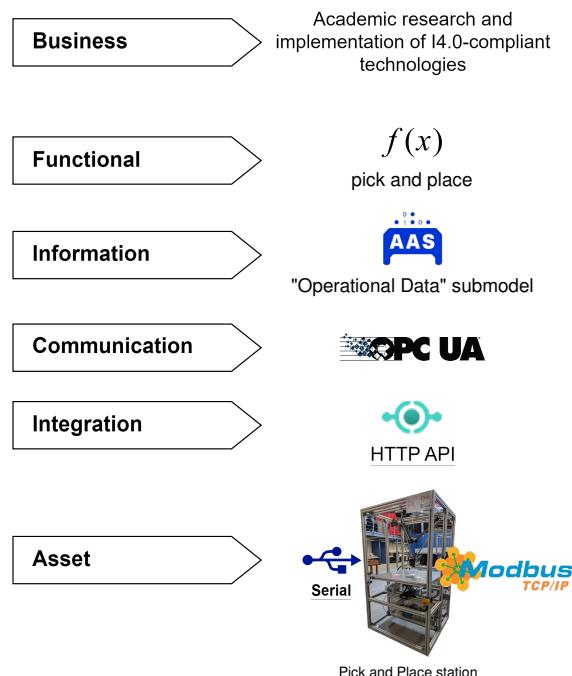


Figure 7: Architecture Layers technologies

## 3 Implementation

This section describes the implementation-specific details for the digitalization of the pick and place station following from the architecture layers definitions, technologies, and requirements described in Section 2.1.3. The output of this section will provide a description of the actual implementation in terms of software and hardware components in a way that the reader can replicate it and get the same results.

### 3.1 AAS and the AASX Package Explorer

The AASX Package Explorer is a tool to view, create, and edit AAS[8]. Version 3 of the AASX Package Explorer was used to create the information model of the AAS of the pick and place station. The general structure is as follows:

- **AAS: PickAndPlaceAAS**
  - **Submodel: OperationalData**
    - \* **Property: boolean** isModuleInitialized
    - \* **Property: boolean** isModuleBusy
    - \* **Property: integer** robotSpeed
    - \* **Property: integer** tableDistance
    - \* **SMC: robotPosition**
      - **Property: float** x
      - **Property: float** y
      - **Property: float** z
    - \* **SMC: gripperPosition**
      - **Property: float** opening
      - **Property: float** rotation
    - \* **Operation: initializeModule()**
      - **out string** result
    - \* **Operation: moveRobot()**
      - **in string** x
      - **in string** y
      - **in string** z
      - **in string** speed
      - **out string** result
    - \* **Operation: moveGripper()**
      - **in string** opening
      - **in string** rotation
      - **out string** result

\* **Operation:** pickAndPlace()

- **in float** xInitial
- **in float** yInitial
- **in float** xFinal
- **in float** yFinal
- **in float** objectWidth
- **in float** objectHeight
- **out string** result

Notice that the moveRobot() and moveGripper() operation's input properties are strings although they should take numeric values. By design the client must be able to move the robot or the gripper in a subset of directions but when exposed as an OPCUA method the server requires all values to be passed in. By defining them as strings the client can pass an empty string as the value of x, for example, and this means that the robot will not move in the x direction.

Figure 8 shows the GUI of the AASX Package Explorer with the OperationalData submodel expanded out.

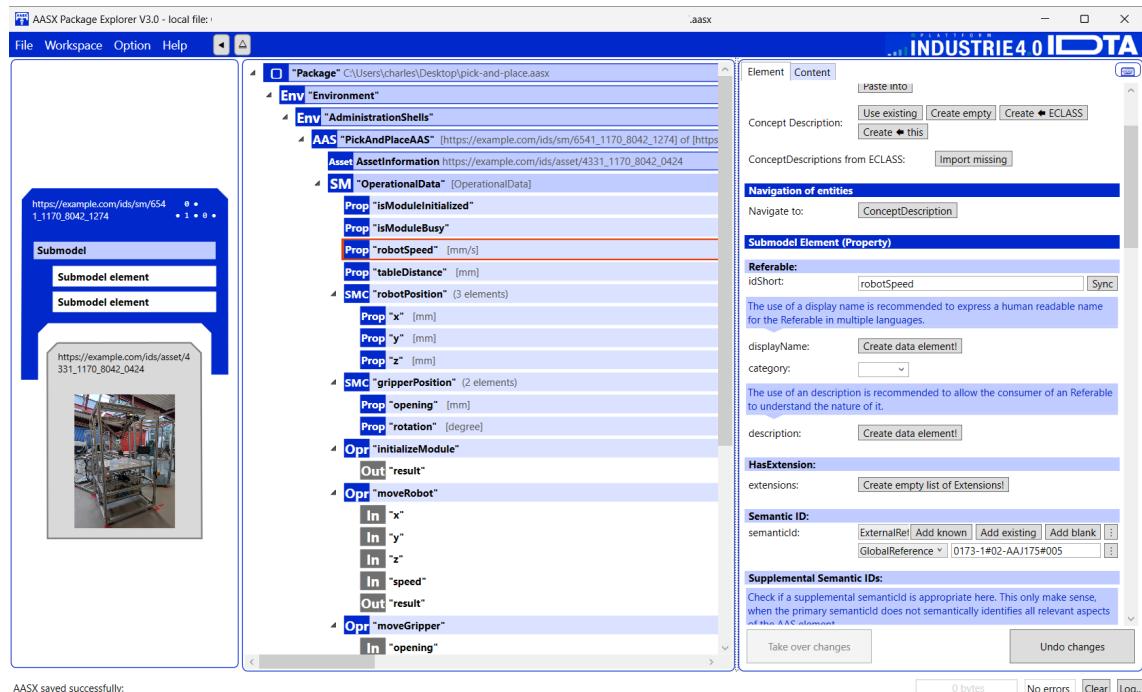


Figure 8: AAS Package Explorer GUI

## 3.2 FA<sup>3</sup>ST Service

A common way to expose an AAS as an OPCUA service is to create a custom server based on the OPCUA NodeSet exported from the AAS Package explorer.

This project presents a new way to implement an AAS using the FA<sup>3</sup>ST service[10] tool which takes the AASX file and directly exposes the information model as an OPC UA service. The FA<sup>3</sup>ST service also provides an interface to sync AAS properties and operations with an underlying asset, thus enabling real-time input/output of data from the asset. Figure 9 shows an overview of the FA<sup>3</sup>ST service setup.

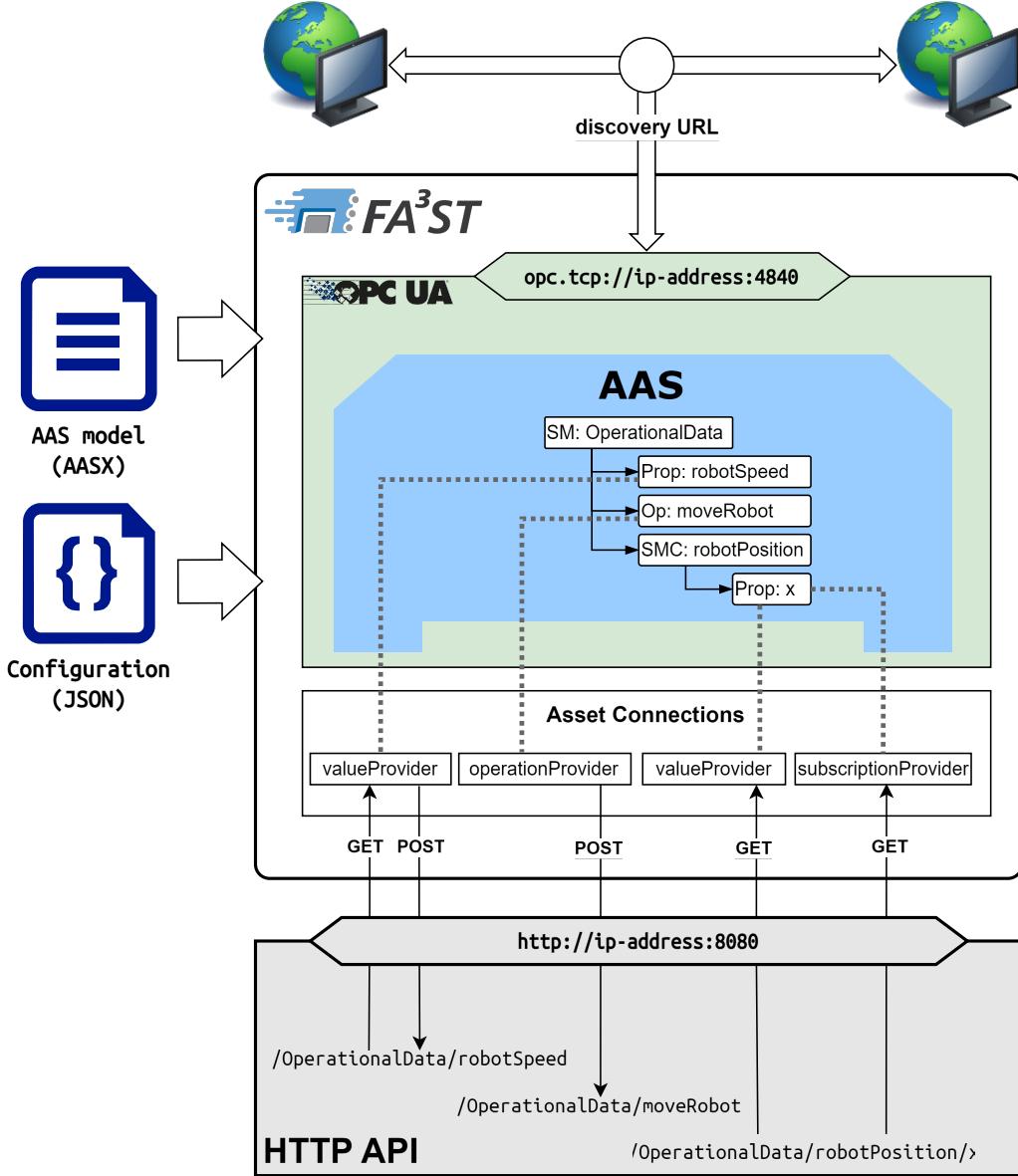


Figure 9: FA<sup>3</sup>ST service setup

### 3.2.1 Endpoint and Asset Connections

To expose the AAS through an OPC UA service as well as to synchronize the AAS with the pick and place station data the FA<sup>3</sup>ST service is configured with an OPC UA endpoint and an HTTP asset connection. This section describes the strategies considered for this custom implementation based on the interfaces offered by the tool. For documentation on the FA<sup>3</sup>ST service configuration refer to [13].

Two design considerations were used to structure the mappings between the AAS submodel elements and the HTTP API endpoints. This allows to decouple their implementation, allow for horizontal scalability, and make it easier to keep track of all the mappings.

1. The HTTP API endpoints will use the same path hierarchy as the AAS information model, starting from the submodel name and respecting the case.
2. All payload data (in requests and responses) must be in JSON format and must be structured as an object with the actual data in the `data` key. Examples are:

```
// scalars
{"data": 33.9}

// objects
{"data": {"success": false, "msg": "compilation error"}}
```

### 3.2.1.1 Read and write properties

Figure 10 shows an example of how read and write work on a property. This is valid for value and subscription providers. Notice that to read a value from the HTTP API the asset connection uses a GET request (GET requests don't have payload) and to write a value to the HTTP API it uses a POST request. The response payload of the POST request does not matter because the AAS property is updated independently.

If a POST request fails (response returns anything other than a 2XX status code) then the AAS property is not updated.

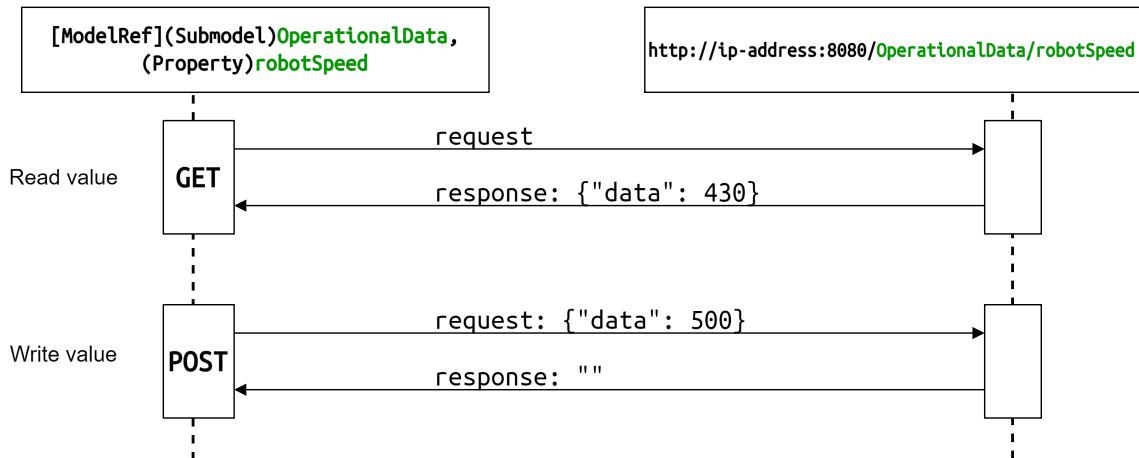


Figure 10: FA<sup>3</sup>ST asset connection for property read/write

### 3.2.1.2 Calling operations

Figure 11 shows an example of how an operation call works. This is valid for operation providers. Notice that the asset connection uses a POST request with a payload

structured so that the input values of the operation are mapped to a key with the same name.

If an operation returns a value then it must be returned in the `data` key of the response payload.

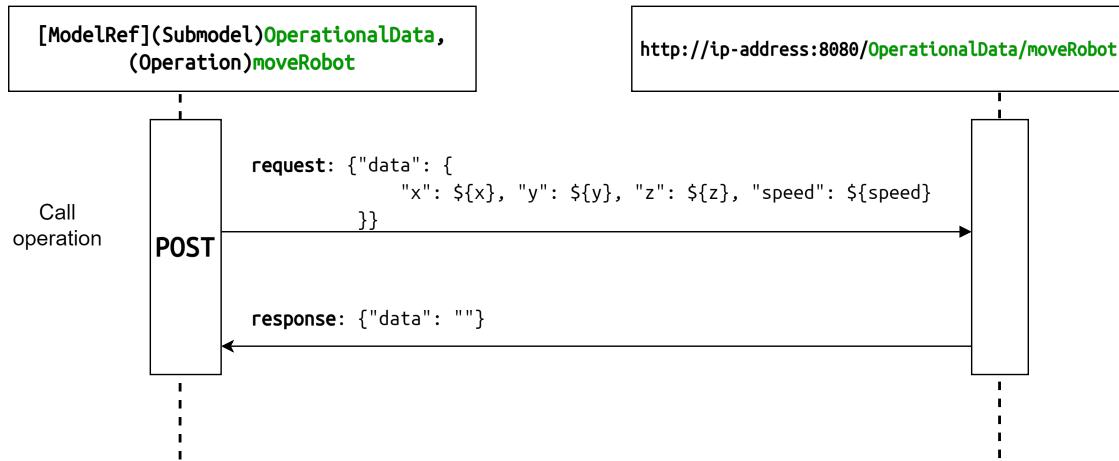


Figure 11: FA<sup>3</sup>ST asset connection for operation call

### 3.3 Asset Integration

A python application was created to integrate the delta robot and the gripper and expose their functions over an HTTP API. This application was specifically designed to integrate with the AAS OperationalData submodel properties and operations and its exposure through OPC UA. The following considerations were taken:

- The HTTP API is not a REST API nor a general API for that matter. The API request and response payloads contain just the necessary data to work with the FA<sup>3</sup>ST Service asset connection interface.
- The application implements just the necessary functions and API endpoints to sync the AAS property read-write and operation calls with the pick and place station.
- Asset actions that take long to complete are executed asynchronously by the HTTP API so that the underlying OPC UA method call is not blocked.
  - For example, the `moveRobot()` OPC UA method will start the action and will not block the client while the action is taking place. The property `isModule-Busy` tells the completion of the action.
- The choice to implement an HTTP API was made because the FA<sup>3</sup>ST service asset connection only supports OPC UA, HTTP, and MQTT interfaces and an HTTP API is the easiest option to implement.

For more information on this app refer to the [app's entrypoint script](#)

### 3.3.1 Delta robot

The delta robot is controlled by its own robot control system, iRC Robot Control[14]. This system exposes a modbusTCP service which can be used to interact with the robot over a TCP network.

The previous project provided a python library[6] that abstracted the input and output to the robot's modbus coils and registers as functions making it easier to execute commands and read and write data to the robot.

This python library was imported into this project, refactored, and improved. The most important improvement is on the homing sequence that initializes the robot. This homing sequence has to be run everytime the robot is started.

For details on the new delta robot python library refer to the [delta\\_robot.py script](#)

### 3.3.2 Gripper

The gripper is controlled by an ESP32 board. The communication with the ESP32 board is over a serial interface physically connected through a USB cable.

The previous project implemented a daemon process that would continually read two variables from the delta robot's modbus registers. One would define the rotation and the other the opening of the gripper. These two values would then be sent to the ESP32, over the serial interface, as two numbers separated by a space[5]. This implementation essentially couples the gripper to the delta robot.

This project makes two improvements over the gripper control:

1. The gripper control firmware now accepts data as JSON formatted strings which allow to issue commands to open and close the gripper independently as well as request status data. For example, the following command rotates the gripper to the 120 degree position:

```
{"action": "rotate", "value": 120, "relative": false}
```

2. The communication with the gripper is now completely decoupled from the delta robot. A python library was created to directly interface with the ESP32 serial interface.

For details on the new gripper firmware refer to its [README doc](#).

### **3.4 Running Application Environment**

A Raspberry Pi is used as the central platform for computation and communication for the pick and place station. When speaking about the Raspberry Pi as a platform it must be understood that this includes the hardware as well as the operating system.

Further more, to keep the overall implementation portable and free from software and system compatibility issues (or at least that is the goal!), it was decided to use Docker containers as execution environment.

The overall system must start upon system startup. For this it was added as a `systemd` service and orchestrated by Docker compose.

`Systemd` will start the pick-and-place service after the Docker service starts.

Docker compose will start the FA<sup>3</sup>ST Service container after the Integration app container starts.

Additionally a shell script was created to install the pick and place service and all its dependencies.

Figure 12 shows a component diagram of the architecture of the implementation.

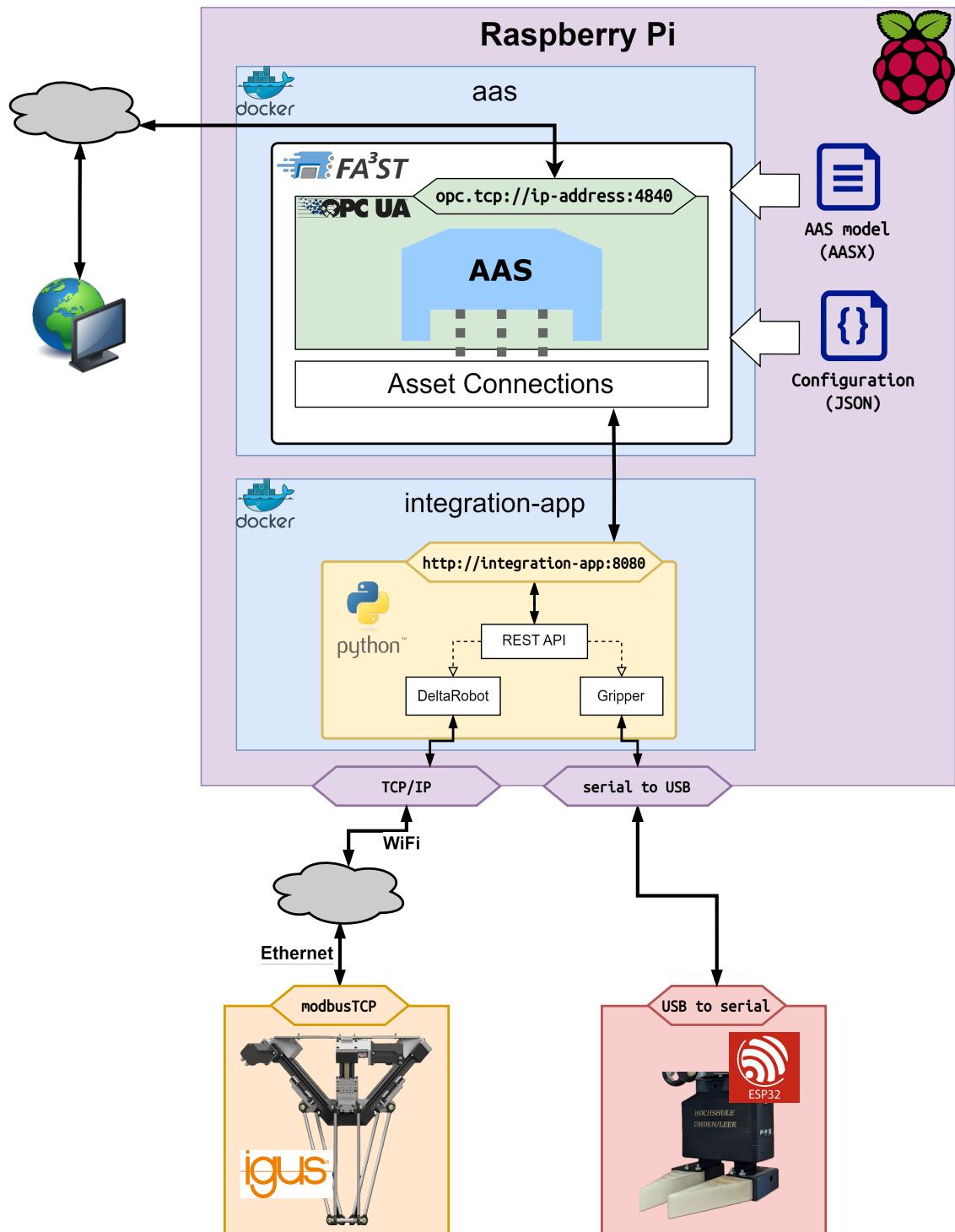


Figure 12: Pick and place station implementation

## 4 Results

This section presents the results of the implementation by showing an example of the interaction with the pick and place station through the exposed OPC UA service.

### 4.1 Installation

The installation performs these actions:

- Checks and/or installs dependencies
- Builds the Docker images
- Provisions the required input files for the FA<sup>3</sup>ST Service
- Creates, configures, enables and starts the systemd service
- Waits for the OPC UA service to respond

After the installation is complete the pick and place station's OPC UA server should be available at `opc.tcp://192.168.158.89:4840`. Where 192.168.158.89 is the IP address of the Raspberry Pi at the moment of this writing.

The installation is completely idempotent. This means that every time it's run the result is always the same.

### 4.2 System Initialization

The Delta robot needs to be initialized everytime it is powered up. To do this, the `initializeModule()` method must be called. The initialization process will perform the robot's homing sequence. This might take a few seconds. When the initialization is done the property `isModuleInitialized` changes from `false` to `true`.

### 4.3 Real-time synchronization example

This example will move the Delta robot by calling the `moveRobot()` method from an OPC UA client. The property values for the robot's coordinates will be updated in real-time while the robot moves.

This example is using UAExpert as OPC UA client. Figure 13 shows the UAExpert GUI with six properties being read to show the coordinates and speed of the robot. In the same order as the figure these are:

1. `isModuleInitialized = True`
2. `tableDistance = 600`
3. `robotSpeed = 100`
4. `robotPosition.x = 0`
5. `robotPosition.y = 0`
6. `robotPosition.z = 300`

The `tableDistance` and `robotSpeed` are read-write properties, so to adjust them they just need to be edited.

The `moveRobot` method call dialog shows the robot will be moved to the coordinates  $x=100, y=98.89, z=200$ .

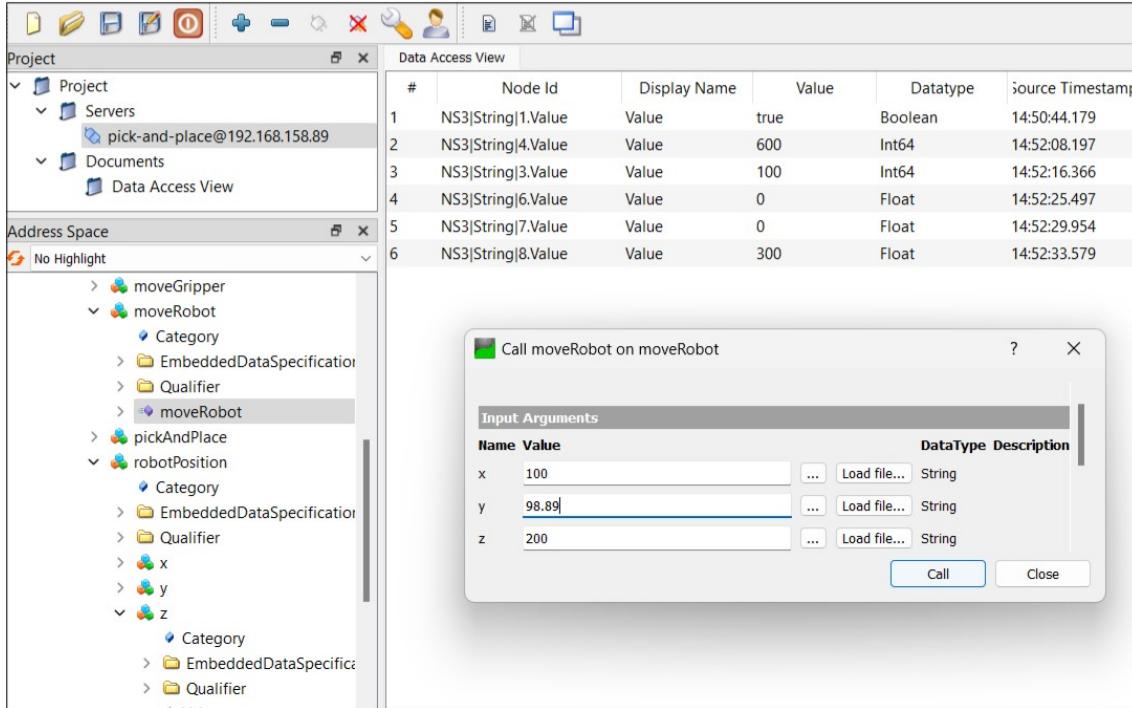


Figure 13: Status of the module before action

After calling the `moveRobot()` method the position of the Delta robot was updated in real-time in UAExpert. This is, while the robot is moving its coordinates can be seen changing in the UAExpert GUI. Figure 14 shows the result of the call and the new coordinates of the robot.

The Delta robot has a precision of 0.01 mm, thus the coordinate mismatch observed.

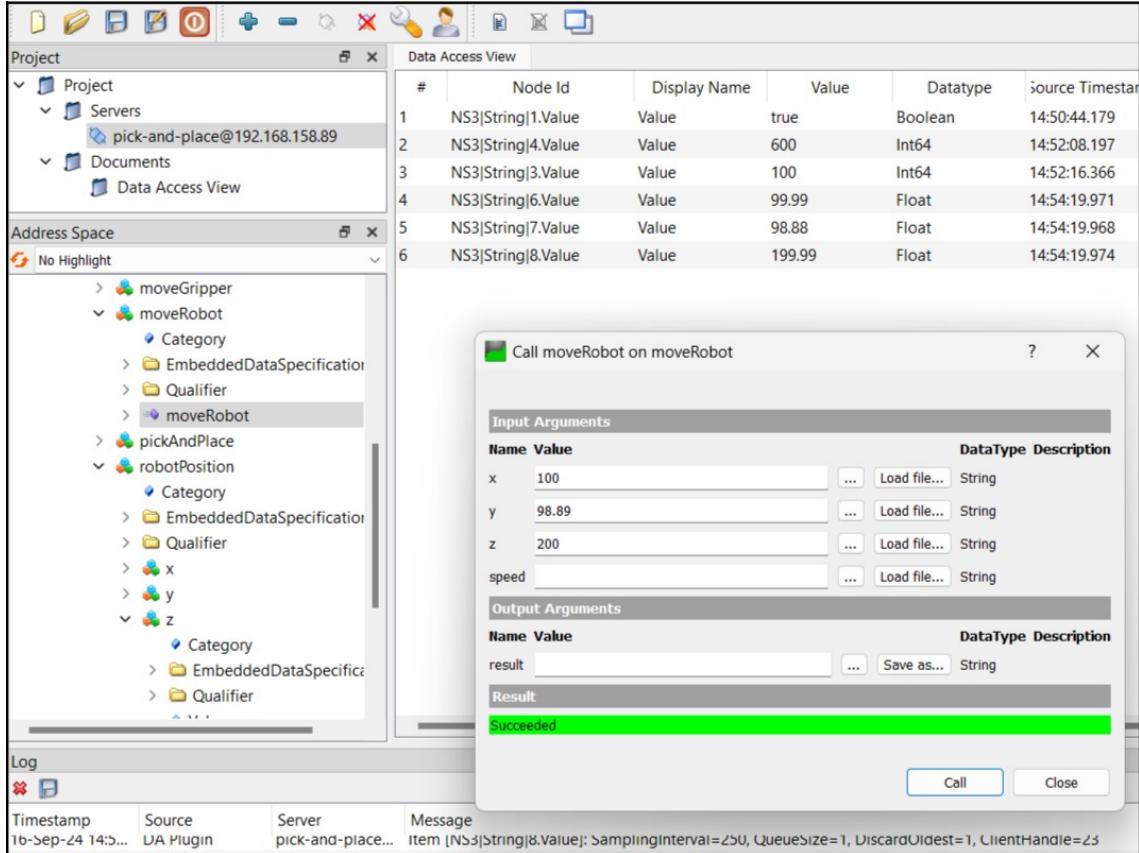


Figure 14: Status of the module after action

The Delta robot's arms have now moved to the specified coordinates at the specified speed. Figure 15 shows the robot's position before and after the action.



(a) Position before at  $x=0, y=0, z=300$

(b) Position after at  $x=100, y=98.89, z=200$

Figure 15: Delta robot position before and after calling `moveRobot()`

## 5 Discussion and Future Works

The OPC UA service implemented by the FA<sup>3</sup>ST service does not recognize the AAS value type “non negative integer”, so values such as `robotSpeed` had to be set as full integers.

A common way to implement an OPC UA service based on an AAS is to export the AAS information model to an OPC UA NodeSet schema XML file, then use a programming platform with a suitable framework which can take the XML file as input and create an OPC UA server following the schema. This option was not considered as it has been already presented in other projects and in this project the author wanted to present a new tool.

A second option to consider for AAS implementation is the [AASX Server](#) tool. While it does allow the implementation of the OPC UA server directly from the AASX file it does not have a native way to interact with the underlying asset. This means that the service implemented cannot provide real-time input/output of data with the asset.

The FA<sup>3</sup>ST service has no Docker image support for ARM based architectures such as the Raspberry Pi's. For this reason a custom Docker image was created based on the actual Dockerfile provided in the FA<sup>3</sup>ST project source. This came with the obstacle that the FA<sup>3</sup>ST service requires JDK version 17 or greater and the JDK distribution for ARM is incompatible with the compiler included in x86\_64 platforms. This incompatibility meant that the ARM-based Docker image for the FA<sup>3</sup>ST service cannot be built in x86\_64 systems (even with the `--platform linux/arm/v8` option!). It had to be built in the Raspberry Pi.

Despite the pick and place module being somewhat operational it still lacks a lot of the features to actually be an asset valuable to the Digital Factory.

So far the initial and final positions of the object to pick and place must be provided to the module, which is not useful except for prototyping as in this project.

A proposal for a future project is to include an object visual recognition system in which the the module can recognize objects to process on the table base, determine their position on the table, pick the object in the determined position and place it in the specified final position. This would be useful for packaging, sorting, aligning, etc. objects based on color or shape.

During the creation of this project the gripper was damaged to the point where it no longer opens or closes. The rotation still works but it is not precise nor firm. Despite these problems, the gripper was never really able to grip something in a useful way as it had not much gripping strength. The integration of a new gripper with proper controls and feedback, better grip strength, and a smaller size is considered imperative.

## 6 References

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