NOVA SCHOOL OF SCIENCE & TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

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Bachelor in Electrical and Computer Engineering

MARKETPLACE-DRIVEN FRAMEWORK

FOR THE DYNAMIC DEPLOYMENT AND INTEGRATION OF DISTRIBUTED, MODULAR INDUSTRIAL CYBER-PHYSICAL SYSTEMS

MASTER IN ELECTRICAL AND COMPUTER ENGINEERING

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Marketplace-Driven Framework
for the Dynamic Deployment and Integration of Distributed, Modular Industrial Cyber-Physical Systems

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To my friends and family.

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”

“The most important step a man can take.
It’s not the first one, is it?
It’s the next one.
Always the next step (...).
”

— Brandon Sanderson, Oathbringer

Abstract

The concept of Industry 4.0 revolutionized the manufacturing sector. It called for the use of Cyber-Physical Production Systems and the digitalization of many manufacturing processes. Even though the implementation of Industrial Multi-agent Systems as Cyber-Physical Production Systems comes with a lot of advantages, it has not seen much use by the industry.

As a consequence of this, Multi-agent Systems have not grown out of their infancy and have not evolved like other technologies through their practical use. This may be because there is still some scepticism surrounding the concept of Multi-agent Systems, and whether or not they can perform to the same efficacy when compared to already existing systems. Because they have not seen much use outside of research scenarios, there are still complications regarding the flexible integration of new and traditional hardware with agents part of a Multi-agent System.

In this work, an architecture which helps solve this problem is proposed. More precisely, this platform would allow for the flexible integration of agents with their respective hardware by proposing a method that selects one or more generic libraries based on the kind of hardware that is being integrated into the industrial Multi-agent System. Through this method, more devices are able to be integrated in less time and with less work, contributing for the flexibility and scalability that is characteristic of Multi-agent Systems.

This platform would facilitate the adoption of Industrial Multi-agent Systems, because not only would it make integrating them easier, it would also mean that any agent could use and reuse any library, which would reduce time and costs in the development and adoption of Multi-agent Systems for industrial applications.

Keywords: Industry 4.0, Cyber-Physical Production System, Multi-agent System, Manufacturing Systems, Hardware Integration

Resumo

O conceito de Indústria 4.0 revolucionou o setor de manufatura. Uma das características deste conceito é o uso de Sistemas de Produção Ciberfísicos e a digitalização de processos de manufatura. Apesar da implementação de Sistemas Industriais Multi-agente como Sistemas de Produção Ciberfísicos trazer várias vantagens, não tem sido muito adotada por parte da indústria.

Como consequência, Sistemas Multi-agente não passaram da sua fase inicial e não evoluíram através do seu uso prático como outras tecnologias. Isto pode ser atribuído ao ceticismo do qual o conceito de Sistemas Multi-agente ainda sofre, e à incerteza sobre se estes conseguem operar com a mesma eficácia quando comparado com sistemas já existentes. Como estes sistemas não têm visto muitas utilizações fora do campo da investigação, ainda existem complicações na integração flexível de hardware novo e tradicional com agentes parte de um Sistema Multi-agent.

Neste trabalho, é proposta uma arquitetura que poderá ajudar a atenuar este problema. Mais precisamente, esta plataforma permite a integração flexível de agentes com o seu respetivo hardware, propondo um método que seleciona uma ou mais bibliotecas genéricas baseadas no tipo de hardware que está a ser integrado no Sistema Multi-agente industrial. Com isto, mais dispositivos são capazes de ser integrados em menos tempo e com menos trabalho, contribuindo para a flexibilidade e escalabilidade que é característica dos Sistemas Multi-agente.

Esta plataforma facilitaria a adoção de Sistemas Multi-agente industriais, porque não só faria a sua integração mais simples, mas também permitiria que qualquer agente pudesse utilizar e reutilizar qualquer biblioteca, reduzindo tempo e custos no devenvolvimento e adoção de Sistemas Multi-agente para aplicações industriais.

Palavras-chave: Indústria 4.0, Sistemas de Produção Ciberfísicos, Sistemas Multi-agente, Sistemas de Manufatura, Integração de Hardware

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Acronyms

AGV Automated Guided Vehicle *(pp. 4, 27)*
API Application Programming Interface *(p. 8)*

CA Component Agent *(p. 17)*
COM/DCOM Microsoft Windows Distributed Component Object Model *(p. 11)*
CPPS Cyber-Physical Production System *(pp. 1–7, 12, 13, 15–17, 26, 59)*
CPS Cyber-Physical System *(pp. 1, 4, 5, 59)*

DA Deployment Agent *(pp. ix, x, 16, 17, 22, 27, 32, 34–38, 41, 45, 48, 49, 51, 57)*
DF Directory Facilitator *(pp. ix, 34, 35, 40, 49–51, 55, 56)*
DWPS Device Profile Web Services *(pp. 16, 18)*

FIPA Foundation for Intelligent Physical Agents *(pp. ix, 2, 10, 13, 17, 28–32, 35, 36, 38, 46, 50, 51)*

GUI Graphical User Interface *(pp. x, 27, 28, 34, 36, 41, 45, 46, 48, 57)*

HTTP Hypertext Transfer Protocol *(pp. 21, 43, 47, 56–58)*

IntA InterfaceAgent *(p. 14)*
IoT Internet of Things *(p. 12)*

JADE Java Agent DEvelopment Framework *(pp. 10, 13, 17, 18, 35, 36, 38, 40, 41)*

LL Link Library *(pp. x, 19–28, 32, 34–38, 42–45, 47–49, 51, 53, 54, 57–59)*

MAS Multi-Agent System *(pp. ix, x, 1–4, 6–8, 10–17, 19–22, 26, 27, 31, 32, 35–37, 39–42, 45, 46, 48–52, 55, 57, 59)*

ME Module Engine *(pp. ix, x, 19–28, 31, 32, 34, 35, 37, 38, 42–44, 47–51, 53, 54, 58, 59)*

MQTT Message Queuing Telemetry Transport *(pp. xi, 12, 43, 47, 56–58)*

OEE Overall Equipment Effectiveness *(p. 5)*

OPC Classic Open Platform Communications Classic *(p. 11)*

OPC UA Open Platform Communications Unified Architecture *(pp. xi, 8, 10, 11, 14, 15, 43, 44, 48, 56–58)*

PA Product Agent *(pp. ix, 13, 16, 17, 27–32, 34, 35, 40–42, 48, 50, 51, 56)*

PLC Programmable Logic Controller *(pp. ix, 7, 11, 15, 16, 18)*

PM Product Manager *(pp. ix, x, 27, 28, 32, 34, 35, 41, 45, 46, 48, 50, 51, 57)*

PMA Production Management Agent *(p. 17)*

PSA Prime System Agent *(p. 17)*

QoS Quality of Service *(p. 47)*

RA Resource Agent *(pp. ix, 13, 14, 16, 17, 27–32, 34–40, 45, 48–51, 55, 57)*

SMA Skill Management Agent *(p. 17)*

TA Transport Agent *(pp. ix, 16, 17, 27–32, 34–36, 38–40, 45, 48–51, 55, 57)*

TCP-IP Transfer Control Protocol - Internet Protocol *(p. 11)*

UDP User Datagram Protocol *(p. 11)*

WS4D-JMEDS Web Services 4 Devices - Java Multi Edition DPWS Stack *(p. 16)*

XML eXtensible Markup Language *(pp. 13, 36, 42–44)*

1 Introduction

In the Introduction, the motivations for this work are explained. The concept of Cyber-Physical Production Systems is analysed, what they are and how they are useful for the manufacturing industry. The concept of Multi-Agent Systems is also explored and why they represent Cyber-Physical Production Systems. Then some issues that have arisen since the conceptualization of Industrial Multi-Agent Systems are identified and a solution to help tackle them is proposed.

1.1 Motivation

In 2011 the term Industrie 4.0 was introduced for the first time during a German conference. This term was later translated into Industry 4.0 and it quickly became synonymous with the fourth industrial revolution [2]. With it, came the appearance of Cyber-Physical Production Systems (CPPSs). A CPPS is essentially, as the name implies, a Cyber-Physical System (CPS) capable of operating in an industrial setting. A CPS is a physical system that has a digital representation. Both the physical and digital counterparts exchange data to maintain coherence and work in tandem to achieve a goal. These CPPSs brought about the digitalization of the manufacturing sector, and despite there being different models, most of them follow these design principles [2]:

- Services offered through an online platform;
- Decentralized, enabling autonomous decision-making;
- Virtualized, to allow interoperability;
- Modular, making them flexible to changes in the system;
- Real-time capabilities;
- Ability to optimize processes;
- Communication is done through secure channels;
- Cloud service for data storage and management.

This new way of operating a production chain revolutionized the industry, because it brought about the changes needed to make manufacturing processes more flexible, adaptable and re-configurable, bringing with it a solution for the ever increasing complexity needed to address the rapidly changing costumer demands. In recent years, multiple companies have made the transition to this model. They have made diversified changes, from the way they analyse and process data to the way they manufacture and distribute products, with very positive results identified in [3].

In light of this, Cyber-Physical Production Systems became a popular research subject. These CPPSs would allow for more efficient, robust and flexible systems, equipped with Big Data analyzing algorithms, Cloud Storage to easily access data, service oriented manufacturing and interoperability.

This research was mainly done on the topic of Multi-Agent Systems (MASs) [4] [5]. These MASs are a coalition of agents, all part of one single system but completely independent of each other. They are intelligent, social and capable of performing tasks on their own, however due to their social capabilities, they can also perform tasks cooperatively, making them powerful tools in goal-oriented networks. Because this system is, by nature, decentralized, these agents can leave and join a coalition of agents as needed, to complete selfish or collective objectives. Evidently, the system is also highly flexible and robust, since agents can be taken out of commission and new agents can be introduced as needed, either because the overall system specifications need to change or simply because an agent has become faulty [6].

Multi-Agent Systems have actually been around for decades and as such, a lot of research and standardization already exists, like the Foundation for Intelligent Physical Agents (FIPA) specifications. FIPA as an organization have ceased operations, however their standard are still put to use in MASs nowadays [7]. An industrial MAS follows similar requirements as a non-industrial one, although it needs to take into consideration other factors, such as hardware integration, reliability, fault-tolerance and maintenance and management costs.

1.2 Problem and Solution

Despite all the advantages an MAS has for the manufacturing sector, it has not seen much success outside research fields. This could be due to the fact that there is still some scepticism surrounding agent-based systems for industrial production [8]. Because MASs never left the prototyping stages, real-world applications never evolved past their infancy. Therefore, they never gained much momentum in the industry at large [9]. Another consequence of this is the difficulty in designing a robust and scalable hardware interface, that allows, for example, the addition and removal of agents without system reconfiguration.

In this work, a new approach to developing interfaces for an Industrial MAS is proposed. It consists of a framework that allows the creation of industrial agents through the selection of generic libraries for the interface between agent and device. These libraries are picked based on the type of communication protocols the hardware implements and because they are generic, they can be re-used and replaced with minimal reconfigurations. The aim of this solution is to simplify the process of creating new agents for the system, enabling them to interface with any kind of hardware. This would minimize development time and costs when creating an Industrial MAS, making them a more viable option when implementing a CPPS.

2

State of the Art

In this chapter, a way of dealing with the challenges encountered by researchers while creating a Multi-Agent System based Cyber-Physical Production System is explored. The concepts of CPPS and MAS are examined in more detail and the most commonly used designs and tools, as well as the recommended practices for an industrial MAS, are identified. Finally, a brief analysis is made on some prototypes that were created to showcase the usefulness of an MAS in an industrial setting.

2.1 Cyber-Physical Production Systems

As stated before, a Cyber-Physical System is a system composed of two main types of subsystems, the physical subsystem that contains all the hardware and resources and the cyber subsystem that represents the physical system in the digital world. These two systems work together, the physical sends data taken from sensors from the environment to the digital system and the digital processes and stores this data and instructs the physical system on what actions to perform through the use of actuators. As such, this system works in a loop, constantly exchanging data and instructions between the physical entities and the digital ones, to achieve a set goal.

A coupling between a physical entity and a digital one can be called a cyber-physical entity.

A Cyber-Physical Production System is, as the name implies, a Cyber-Physical System that operates in a manufacturing setting. The physical system is composed of a myriad of devices like robot arms, AGVs, conveyor belts and other specialized machinery for manufacturing. The cyber system might be as simple as a computer program or as complex as a full-on three dimensional model of the physical system. Vogel-Heuser and Hess [2] proposed that a CPPS should:

- Be service oriented, meaning that it should offer its services through the internet;
- Be intelligent, with the ability to make decisions on its own;
- Be interoperable, by having the capacity to aggregate and represent human-readable information and by providing a virtualization of the physical system;
- Be able to flexibly adapt to changes in requirements and scale;
- Have Big Data algorithms capable of processing data in real time;
- Be capable of optimizing processes to increase Overall Equipment Effectiveness (OEE);
- Be able to integrate data across multiple disciplines and stages of the products life cycle;
- Support secure communications to allow partnerships across companies;
- Be capable of storing and accessing data in the Cloud.

In summary, these CPPSs abstract the hardware resources in the physical environment into their digital counterparts, giving them a measure of autonomy and intelligence, which in turn allows for the fulfillment of most requirements. The remaining requirements are fulfilled by integrating the CPPS with other existing tools such as Big Data processing platforms, Cloud storage services and data-sharing services.

These systems have a virtual representation of the physical system, that updates in real-time according to the information received from the physical world. This virtualization allows for a more efficient and realistic analysis of the real world, enabling more complex behaviors, better error correction and the optimization of industrial processes.

Although advantageous in comparison to existing industrial systems, CPPSs are still fairly recent and therefore creating one of these systems from the ground up still has its challenges. Leitão, Colombo, and Karnouskos [10] have compiled key challenges, as well as their difficulty and priority.

For these reasons, companies have not made a huge push to create CPPSs from the ground up, instead opting to adapt their already existing systems to integrate CPPS elements and characteristics. This is essentially an integration of a CPS in an already existing production line. many of these adaptations depend on creating interfaces capable of interacting with many types of hardware, to allow an easier and more streamlined integration of new entities into the system.

Some examples of CPPS retrofitting can be seen in Cardin [11] and Arjoni et al. [12]. Cardin [11] have done an analysis on the whole process of retrofitting a robotic arm. Before the retrofit, this arm was controlled through a remote controller or a serial interface.

After the retrofit, the arm was able to receive commands through a new interface, which was able to communicate through standard Wi-Fi and Ethernet protocols, sending sensor data and receiving commands to and from the network. This network also integrated a cloud service to allow for the storage and access of information. Performance-wise, the arm showed better energy efficiency and less operation latency after the retrofit and all values were below the thresholds for the standards in an Industry 4.0 CPPS.

Arjoni et al. [12] created a small manufacturing plant using old devices. They consisted of two robotic arm, a CNC machine and a welder arm. All three devices communicate through different protocols, but by using off-the-shelves hardware like an Arduino UNO and a Raspberry Pi 3, Arjoni et al. were able to give these devices the ability to be integrated into a more complex system. Although they recognize the system could still be optimized, they considered the result promising in the retrofit of old devices into a CPPS.

2.2 Multi-Agent Systems

To understand what should be the best practices in an MAS based CPPS, an understanding of its base characteristics is needed. An MAS is, in essence a system composed by many entities called agents that have their own capabilities. These agents communicate and collaborate together by exchanging data among themselves and acting on that data to achieve a common goal. They are capable of adapting their behaviour and of autonomous decision-making to determine the best course of action. This system is by nature decentralized and has no hierarchy, making it highly flexible and modular. At any point an agent can leave or join the system, without significant changes in architecture [6].

Industrial agents inherit all the qualities of software agents, like the intelligence, autonomy and cooperation abilities, but in addition are also designed to operate in industrial settings, and need to satisfy certain industrial requirements such as reliability, scalability, resilience, manageability, maintainability and most important of all, hardware integration [13]. An example of a base architecture for an MAS can be seen in Figure 2.1.

These requirements are generally tough to fulfill, especially so because despite the theoretical potential MAS have shown in supporting them, there aren't a lot of agent-based production systems outside the prototyping phase. This has stopped the growth of Industrial MAS due to the lack of practical knowledge in this field [14]. Another problem seen in Industrial MAS is the lack of models that can represent these systems. One of the key elements of an MAS are the changes made in structure and logic as the system operates. Thanks to the decentralized nature of the system, it is possible to add, remove or reconfigure modules freely to better adjust it to the systems needs [14].

Now, with a better formed idea of the characteristics and requirements for Industrial MAS, the most commonly used architectures, followed by what is recommended by the IEEE Standard, is explained in the following section.

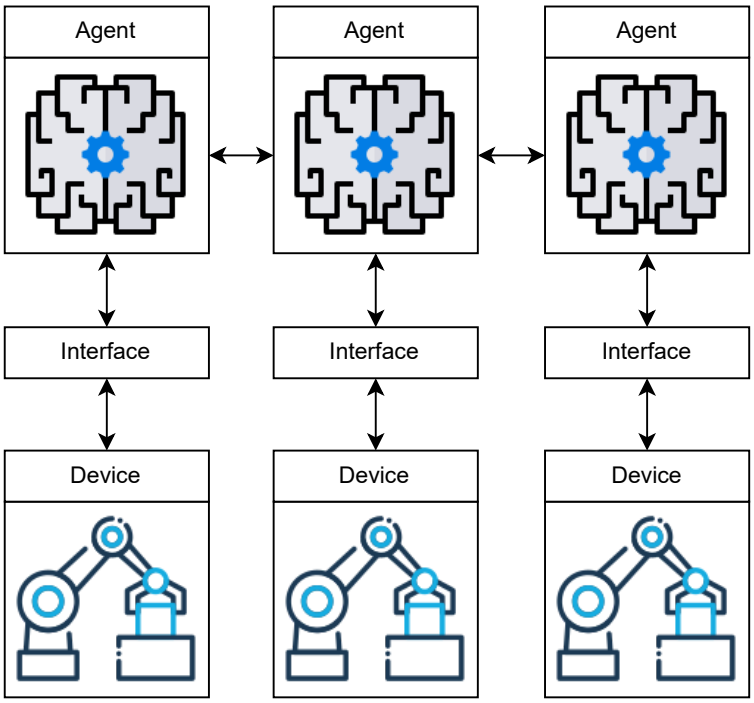


Figure 2.1: Industrial Multi-Agent System.

2.2.1 Best Practices and Common Architectures

Leitão et al. [13] analyzed the IEEE 2660.1 Standard for the recommended practices in integrating software agents and low-level automation functions. They described the use of an MAS as a CPPS, where control is decentralized, emerging from the interactions of agents that are part of the system. And as discussed before, one of the biggest problems is creating an interface between the agent and the device associated with it. Because of this, the IEEE 2660.1 Standard was created, defining the best practices in designing an appropriate interface.

As an example, the authors mention three main types of interfaces. An interface for a smart sensor, to acquire measurements. An interface for a PLC, to control simple devices like conveyor systems. And finally, an interface for a robot controller to control more complex functions in the CPPS. These three interfaces present different challenges on a development level, because each requires consideration on which architecture to follow, with different consequences to the evolution of the manufacturing plant over time.

The authors then created multiple scenarios, one of them being factory automation. They then proposed that the most valuable criterion was the response time of the system.

As a secondary criterion scalability was chosen, but with a lesser importance. From this scenario the authors then concluded that a Tightly coupled Hybrid OPC UA interface was preferable according to the IEEE 2660.1 standard. This means that the interface should have a client-server approach and be running remotely, a Tightly coupled Hybrid approach. However the authors also mention that this setup has a relatively low score, meaning that many of the other proposed practices are still viable, with testing needed to be done in order to pick the best one based on each specific scenario.

In [14], it is proposed that one of the key requirements in the design of interfaces for MAS is interoperability. This comes with other challenges associated, like re-usability and scalability. In an MAS, the authors identified two main types of interfaces, the interface between agents, which normally is provided through the framework of the agent-based system, and the interface between agent and device.

Leitão et al. [15] analyzed a study performed under the IEEE P2660.1 Working Group [16] and concluded that most approaches followed a two-layer convention. The upper layer contained the agents part of the MAS and the lower layer the hardware associated with the physical production system. These two layers can interact in two ways [15]:

- Tight coupling, where the two layers communicate either through shared memory or through a direct network connection. This communication is synchronous and more direct.
- Loose coupling, where the two layers communicate through a queue or a pub/sub channel. This communication is asynchronous and less direct.

These layers can also be hosted in different setups [15]:

- Hybrid setup, where the two layers run in different devices.
- On-device setup, where the two layers run in the same device.

This means that there can be four different interfaces, Tightly coupled Hybrid, Loosely coupled Hybrid, Tightly coupled On-device and Loosely coupled On-device.

A Tightly coupled Hybrid interface (Fig. 2.2) is characterized by having the upper layer where the agent operates running remotely and accessing the lower layer through an API. This API is responsible for translating the instructions given by the agent into commands the hardware can interpret. It is also responsible for the opposite, translating the hardware output, such as error codes or function results into data the agent can use. This approach is limited by the channel through which both layers communicate since both agent and device operate on two different computing platforms. This channel is affected by the amount of traffic in the network, more connections implies a lesser quality

of service, namely in response time [15].

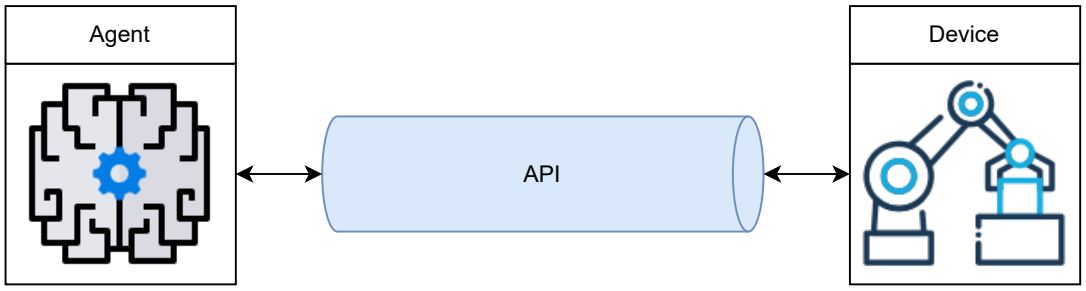


Figure 2.2: Tightly coupled Hybrid interface. Source: Adapted from [15]

A Loosely coupled Hybrid interface (Fig. 2.3) also sees both agent and device running on different computing entities. The difference is that instead of each agent having a direct connection to the corresponding device, they communicate through a message broker. Since the system still runs on two different computers it still suffers from the quality of the connection between layers, making this somewhat inappropriate for systems highly dependent on real time action. However, this approach sees better results in complex systems, where the agent layer needs to publish information to a large amount of devices at once. It also sees good results when it comes to scaling the system, since both layers are very independent of each other [15].

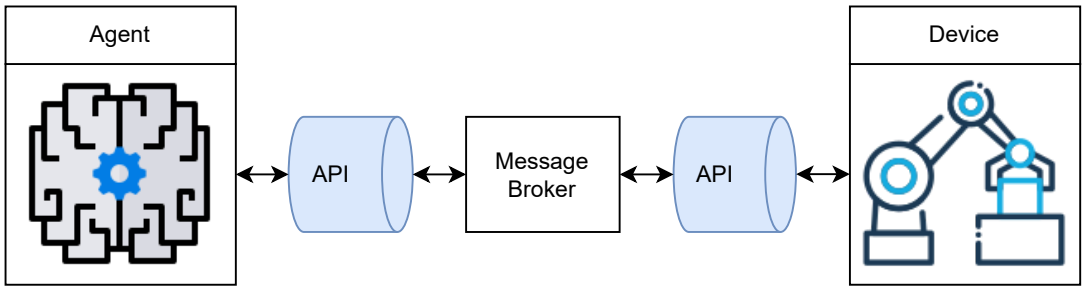


Figure 2.3: Loosely coupled Hybrid interface. Source: Adapted from [15]

A Tightly coupled On-device interface (Fig. 2.4) on the other hand follows an architecture where both devices share the same physical platform and can be done in two different ways. The first one, and far less common, has both agent code and device code compiled into a single binary running in the same computing element. This solution provides far better results in very demanding real time applications, however it also removes some flexibility from the system and is far more complicated to design due to the lack of development tools. The second option has the computational resources shared through a software library, where communication is done through software functions while abstracting some elements. This option still holds good results in real time control, but not as good as the first option [15].

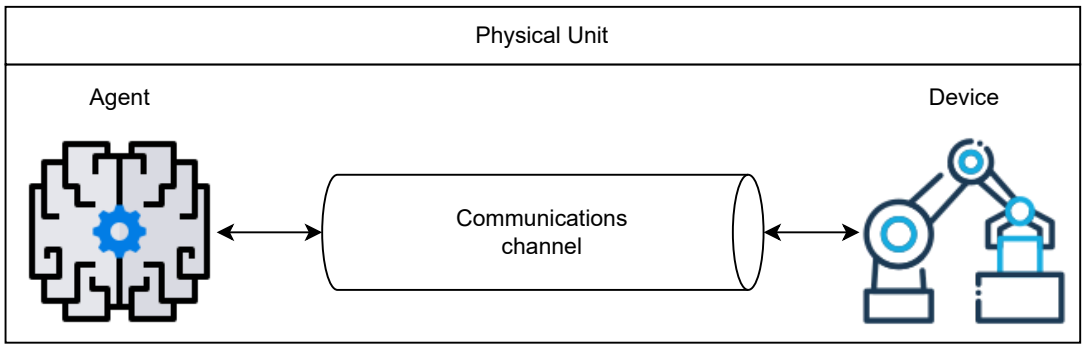


Figure 2.4: Tightly coupled On-device interface. Source: Adapted from [15]

Finally, a Loosely coupled On-device interface (Fig. 2.5) is characterized by having the agent embedded in the device and communication is done through a broker. Both layers share a physical unit but do not share computational resources. The utilization of a broker between the two layers offers some flexibility, since the agent and hardware are less dependent of each other. This comes with the caveat that the real time response of the whole unit is dependent on the performance of the broker [15].

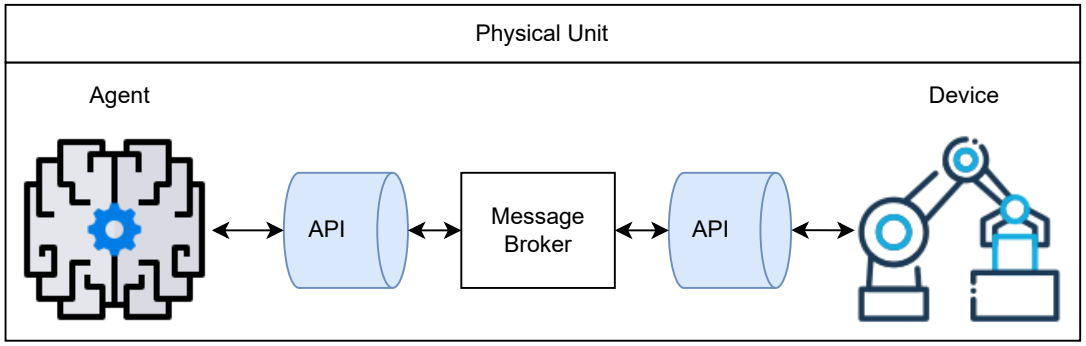


Figure 2.5: Loosely coupled On-device interface. Source: Adapted from [15]

The most common programming language to codify agents is Java, most likely due to the existence of JADE, followed by C++ [15]. JADE helps developers in the implementation of MASs with the FIPA specifications. It also allows deployment for different machines, due to Java supporting multiple devices [17]. For the device part, pre-existing hardware is used in the majority of cases because it can be integrated into an MAS by using protocols such as OPC UA [15], which is a platform independent data exchange standard. It allows for both server-client and publish/subscribe communications, as seen in the following section [18].

2.2.2 OPC UA

Another way to integrate hardware into an MAS it through the use of already made tools. The Open Platform Communications Unified Architecture (OPC UA) was created based on Open Platform Communications Classic (OPC Classic), which in turn is based on the COM/DCOM protocol for the exchange of data. OPC UA is an evolution of OPC Classic but with extra functionalities, like added security, extensibility and platform independence. This last feature allowed it to run on many more platforms such as cloud-based servers, micro-controllers and PLCs [18]. As mentioned in Section 2.2.1, it is a recommended way to implement an interface for an MAS. OPC UA can be used with as a Tightly coupled or Loosely coupled interface, because it supports both direct client-server connections and pub/sub message transmissions, making it a strong option to integrate hardware into an MAS.

An OPC UA server is needed, and it can be hosted anywhere on the network. Cyber-physical entities can connect to it using its address, and it supports encryption and users with different levels of permissions for added security. A server hosts a group of files and folders, called nodes. Each node can be accessed independently of other nodes, and values can be written to and read from a node. A node can represent anything, from a machine to a single sensor. OPC UA also supports subscription based communications and events, to lessen the load of the system on a network [18].

Because OPC UA already implements communication protocols and communication infrastructure, as well as an information format, all participants in the network know how to communicate. This means that the MAS can be running on any kind of platform or be programmed in any kind of language, increasing system flexibility. Many modern PLCs already provide an embedded OPC UA server facilitating their integration into a new system [19].

2.2.3 Modbus

Another way to integrate hardware into an MAS is by using Modbus. Modbus is an industrial communications system that has been around since 1979. It follows a master/slave architecture, where the master is usually an application capable of acquiring data and the slave a PLC. This master application can be substituted for an agent from an MAS, integrating it with the slave hardware. Modbus supports standard TCP-IP and UDP. It is simple, has high levels of compatibility and is decentralized due to the use of master/slave communications, making it flexible. Modbus could be integrated with any programming language of choice, by using software libraries to interpret and send commands to the Modbus layer [20].

2.2.4 MQTT

MQTT is a widely used protocol for the Internet of Things (IoT). It is a pub/sub protocol, with a minimal network bandwidth and a small code footprint. It is dependent on a MQTT broker, which serves as a hub to the messages flowing between clients. A client is any entity part of the MQTT network, and they can both publish messages or subscribe to topics. A topic is an identifier that comes with every message published to the broker and all clients that currently subscribe to a topic of an incoming message will receive that message [21].

It has seen a lot of use by, not only the manufacturing industry, but also in logistics, smart home applications and more, making it a valuable tool in the integration and communication of smart devices.

2.3 Practical Uses

Adoption of industrial oriented MAS has been slow. According to Karnouskos and Leitão [9], the technology was still in its infancy almost two decades ago, with an incremental progress at best being made since then. In [14], Karnouskos et al. claim that agent-based applications in the industry is still limited. This is because despite the potential shown, these systems have not been implemented in real-world applications, where they would have the chance to evolve and leave the prototyping phase as new research is being done to make them more suitable for these applications.

There are, although, many research prototypes of MAS used for an industrial applications. Some of them are explored in this section.

2.3.1 Bottling Plant

For the design of the bottling plant in [8], a research paper [22] was first done by Marschall, Ochsenkuehn, and Voigt, with the collaboration of multiple partners from different backgrounds. This was done to define the base requirements for the CPPS as well as the associated MAS. These requirements are:

- Easy Scalability and Functional Expansion;
- Manufacturer-neutral Resource Representation;
- Robust Production Control by the Product;
- Lot Size One without Identification.

Summarizing, the system needed to be easily scalable and it must be able to expand its functions to handle changes in production, it must be able to represent the resources in the CPPS as a generic and manufacturer independent representation, products must be

able to handle their own production steps, handling errors and reacting robustly to those errors and finally be able to produce lot sizes of one without needing an identification system for each individual product.

In consequence of these requirements, Marschall, Ochsenkuehn, and Voigt designed a base solution consisting of two generic agents, a Product Agent (PA) that represents individual products being manufactured, in this case the beverage bottles, and a Resource Agent (RA) that represents the resources used to manufacture the beverage bottles.

The MAS was made using JADE, and as such all agents in this system are FIPA compliant and communicate through FIPA Requests and the FIPA Contract Net.

Each agent inherits from a generic class called Agent. The RA and PA then inherit from this class, with added functionalities and variable fields. The PA is an agent with the capabilities of performing autonomous and goal-driven behaviours. The RA is an agent capable of controlling the physical resources by using sensor data and messages with hardware instructions.

A PA differs from the generic Agent by implementing a configuration file "ProductConfig". This file is in the XML format and has information on the product represented by it. It also has a "PlanningModule", which is essentially a "StateMachine" with all the products processing instructions.

Like the PA, the RA also mirrors the Agent class. It must be generic in order to be implemented on multiple resources, so for each "ResourceType" there exists a "ResourceConfig" file which is loaded onto the RA in order to implement its interface. To give an example, if the resource has the "ResourceType" "Machine", the "ResourceConfig" file "MachineConfig" must be loaded.

The authors identified five different "ResourceTypes" by classifying many resources from renowned machine manufacturers. RAs not only include robots, transport systems and stations but also databases, as a data management method. The authors recognize that not all types of possible resources for a CPPS have been considered. This means that for every new resource type that needs to be added to the system, a new "ResourceConfig" must be created in order to integrate the new RA into the system. In addition, a new resource that communicates differently from the ones already in the system would need a new interface, and thus a new "ResourceConfig" would also need to be created, even if the new resource performs similar functions in the manufacturing plant.

In [8], Marschall et al. created the service oriented bottling plant using the industrial agent system designed in [22], with positive results. To allow for extensibility of the system

by additional resources a new agent class was created called InterfaceAgent (IntA). The "ResourceConfig" files for each type of RA now have a new field which contains an "InterfaceAgentConfig". This new IntA is instantiated by the RAs following the configurations of their respective "InterfaceAgentConfig" and it extends either a "DBLinkAgent", used to connect to a database, or a "PLCLinkAgent", used to connect to a OPC UA client. All the information, like server address, port and authentication, is stored in the "InterfaceAgentConfig" file. By using OPC UA, the system can now interface with the hardware in the manufacturing plant, through a Loosely coupled Hybrid interface. The authors recognize that according to the IEEE P2660.1 Working Group the scalability is considered weak, although they claim the flexibility is worth this loss in scalability.

To implement a new IntA, the following must be provided:

- The communications protocol and the address, ports and authentication;
- The way the interactions between the agent and resource should proceed;
- The rules for the interpretation of internal resource states.

Communication between the "PLCLinkAgent" and the machine is done through the use of simple commands. They specify the command to perform and the program type to use and must also include a unique name, the "NodeID", which identifies the node of the given input on the OPC UA server, the data type, all possible values, the read/write direction and the description. The program type is chosen based on the size of the bottle and the command has to be one of the five commands already defined:

- "NoCommand", in case no action is needed;
- "ProductInPosition", in case the product is in position and ready;
- "ExecuteProcess", in case the process should start;
- "ProductRemoved", in case the product needs to be removed from the machine/station;
- "PrepareMachine", in case the machine needs to be prepared for a process to start.

All commands have a number code associated to them to facilitate communications and at any time the "PLCLinkAgent" can retrieve the state of a machine by observing the "NodeID" with the machine state code. In Figure 2.6 it is possible to observe the state machine representing the interactions between the "PLCLinkAgent" and a machine. To handle manufacturer specific machine state codes, the authors mapped said codes onto generic MAS states, with the possibility of having multiple codes mapped to a single state. This was done to make the system capable of handling machines from different manufacturers without sacrificing flexibility in the MAS.

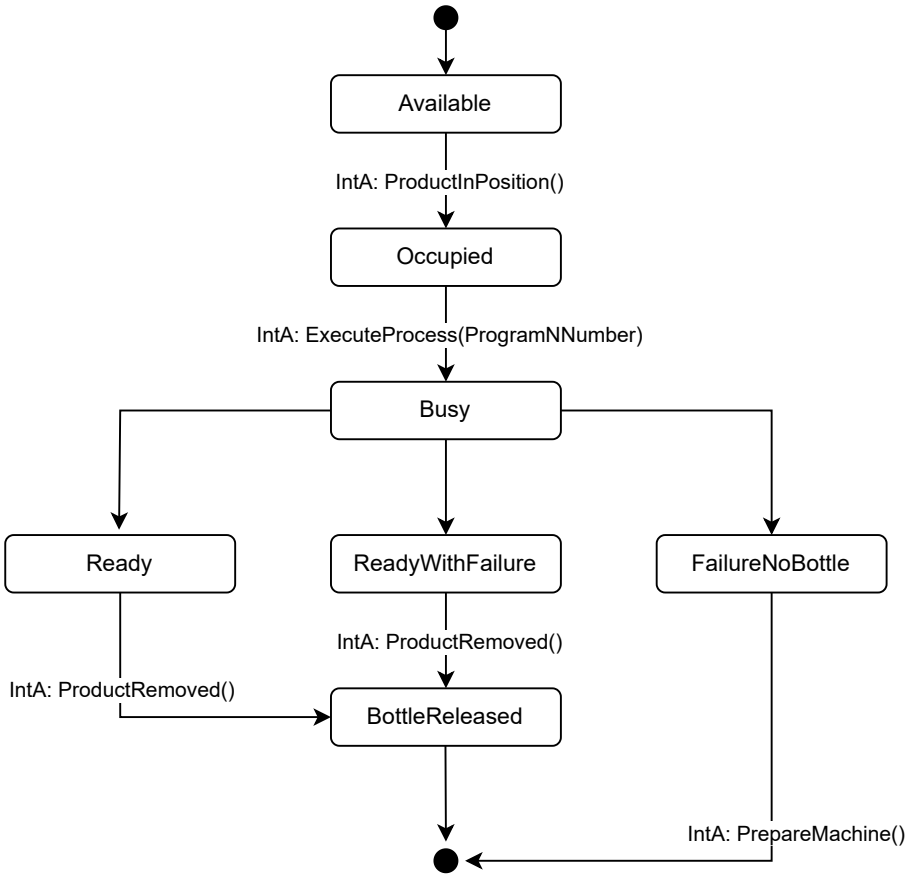


Figure 2.6: Interactions between PLCLinkAgent and PLC. Source: Adapted from [8]

The use of OPC UA makes this system very flexible. New hardware that needs to be implemented in the system can be configured to use these commands through the use of a PLC. The use of generic states make it scalable and configuration files also help fulfilling this necessity. However, it is still dependent on these files, with individual configurations needed for different manufacturers and machine types. The system also needs to be adapted to recognize the machine states from the new implemented hardware.

Nevertheless this system performed as intended, producing customized beverage bottles according the customers specifications. It is a good example of an MAS based CPPS, flexible, scalable, robust, with decentralized control and autonomous intelligent agents.

2.3.2 Agent-based Plug and Produce CPPS

Rocha et al. [23] have created a Plug and Produce CPPS. It is capable of integrating new agents on the fly, as the system operates. First, the authors divided the system into three layers. The upper layer is where the MAS operates, called the fog layer. The middle layer is where the interface between the MAS and the hardware is, called the edge layer. And

finally, the lower layer is where the hardware components of the CPPS are, called the physical layer.

The agents were also categorized into PA and RA, performing similar functions to the ones in Section 2.3.1 and in addition the authors also considered Transport Agents (TAs) which abstract all resources whose function is to move a product from point A to point B. They also considered a Deployment Agent (DA) tasked with managing the existence of all other agents. This DA should create a new agent or remove an existing one whenever a physical resource is plugged into or unplugged from the system.

To accomplish this the authors considered the grouping of a physical resource with its agent a Module. Modules are the components of the whole production system, and they can be plugged and unplugged at any time. The system need to be able to operate to the best of its abilities at all times. In Figure 2.7 an example of one of these Modules is shown.

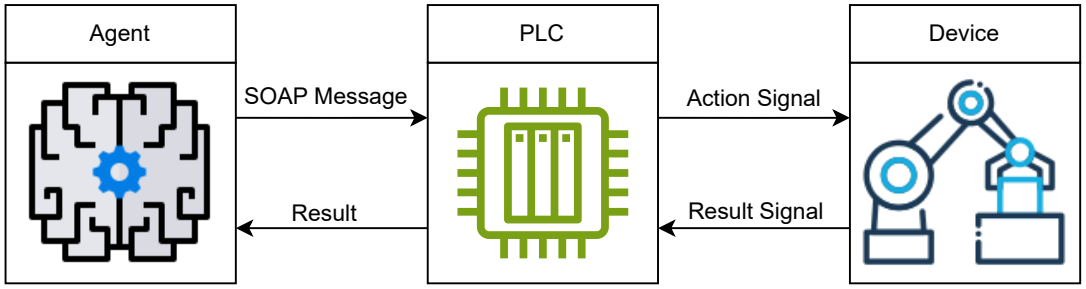


Figure 2.7: Plug and Produce RA. Source: Adapted from [23]

For the interface between hardware and agent, PLCs were chosen. These PLCs are able to communicate using Device Profile Web Services (DWPS). For the DA, a Java class was implemented using the Web Services 4 Devices - Java Multi Edition DPWS Stack (WS4D-JMEDS) framework, which searched for the devices in the network and obtained information about them. It was able to detect all devices connected to the network and add and remove them as needed.

Each resource is able to perform certain procedures on the products, represented in the MAS as skill which RAs perform on to PA. This is how the authors simulate the system virtually, whenever a product needs a certain procedure to be performed on itself, the corresponding PA asks an RA for that skill. This is relevant because the system may or may not have a resource able to perform a specific skill. In the case of a PA that needs an non-existing skill to be performed, it waits until an RA capable of performing the needed skill to be plugged into the system.

The MAS was developed in the JADE framework, all agents are therefore FIPA compliant and communicate through FIPA Requests and FIPA Contract Net. More precisely, the FIPA Requests are used for PA-TA communications and the FIPA Contract Net used for PA-RA communications. Whenever a new PA enters the system, it asks through the FIPA Contract Net which RAs are can perform the needed skill. After getting responses from all the RAs, the PA picks the best one and receives its location. It then sends a FIPA Request to the TA to transport it to this location. After arriving, it then requests that the skill be performed to the RA.

This system was used to simulate a simple conveyor belt line with brushing capabilities. The authors where able to successfully plug and unplugged Modules from the system during its operation. The DA correctly connected and disconnected hardware components from the system and deployed and kicked agents from the system accordingly. This shows that an MAS built from the ground up with these functionalities is very powerful in its scalability, and although this was only a prototype it shows a lot of promise for a dynamic system.

2.3.3 PRIME

Rocha, Barata, and Santos [24] have done a demonstration on the PRIME architecture as an agent based framework with plug and produce functionalities. PRIME is a project developed thanks to the European FP7 program, and it proposes a solution to allow plug and produce using any kind of computational devices. This means that it is no longer needed to restrict a manufacturing plant to specific controllers to provide to it some sort of reconfigurability and flexibility. It allows any kind of controller or to be integrated into the system while still using the same framework.

All agents in this framework were developed using JADE, therefore all agents are FIPA compliant. This adds to the plug and produce functionality of the system. The PRIME agent system is composed of eight different agents:

- Prime System Agent (PSA) is the highest level agent in the framework. It manages the current state of the system;
- Production Management Agent (PMA) is responsible to combine all resources and tasks in the same space to abstract certain functionalities;
- Skill Management Agent (SMA) works in tandem with a PMA, combining the lower-level skills into higher-level ones according to pre-defined rules, that the associated PMA then provides to the system;
- Component Agent (CA) is the agent that abstracts the hardware in the CPPS. It is able to read and write data to and from the hardware;
- Local Monitoring and Data Analysis agent.

All devices to be integrated into the system were categorized into three groups according to their characteristics:

- Fully intelligent resources, capable of running the necessary agents locally, typically a machine with the ability to run the Java environment, setup in a Tightly or Loosely Coupled On-device architecture;
- Semi-intelligent resources, capable of announcing their existence to the system and of reconfiguring themselves but without the ability to run the Java environment, setup in a Tightly or Loosely Coupled hybrid architecture;
- Passive resources, without any computational abilities and dependent on a controller to connect them to the main system.

For the first type of device, PRIME was able to very easily connect to it. The device ran all the necessary components to enable communications and to expose itself to the network. It ran the necessary agents related to the hardware locally and the main framework was able to configure the hardware by interacting with the local agents, which in turn interfaced with the device. This is the type of architecture preferred by PRIME, since it provides all services autonomously [24].

For second category of devices an INICO PLC capable of running DWPS was needed to connect the device to the framework since they can't run the agents locally. An auxiliary computer running the DWPS software was responsible for detecting the PLC and connecting to it. The necessary agents running on this computer launched the hardware related agents whenever they detected a new device running DWPS, and these local agents were able to connect to the main PRIME network [24].

The last category of devices is the most complicated one because they have no easy way to interface with the main system. In this case a more primitive PLC was used to simulate this limitation. An auxiliary computer running the JADE framework with all necessary agents is needed to create this interface and the system communicates with the PLC on a case-by-case scenario, with each PLC possibly needing different configurations. When the relevant agent detect a new device, it launches a new agent to interface with this device. The new agent then uses a case specific library to interface the PLC using standard protocols [24]. This last option is not flexible and uses a case-by-case configuration, making it the least desirable in a system.

3

Architecture

In this section, the designed architecture for the proposed solution is explained. Starting with an overview of the system, the main architecture is presented, followed by a few usage scenarios. Then each component of the system is identified, how they work and how they are connected through the interfaces they use to communicate with other components. Normal system operations are overviewed and the supporting Multi-Agent System that was built to showcase the integration solution is explained. Every agent is presented in detail and a full system architecture is pictured at the end.

3.1 System Architecture

The main objective of this architecture is to bridge the gap between software and hardware. More specifically, to allow for a cyber-physical entity to interface with any kind of hardware in a flexible manner. To allow this flexibility, the system needs to be modular to an extent, enough to allow compatibility for many types of hardware, but not so much to make it hard to work with. A main entity must allow for the interfacing with the modular part of the interface, to enable support of multiple physical entities.

In addition, some supporting architecture is also needed to deploy the cyber-physical entities. This architecture must provide the main interface entity with a list of all integration modules available, so that it is able to load them.

These modules must then be supplied with the right configurations so that they are able to interface with the hardware. These configurations are also provided to the main entity by the supporting architecture, but are then sent to the modules.

The system proposed in this work then consists of two main components, a Module Engine (ME) and the Link Libraries (LLs), with a deployment entity capable of providing these two components with the right resources. The Module Engine is the main entity that operates between the layers of software, in this case the agent, and hardware. It allows the agent to interface with any kind of hardware by loading Link Libraries.

These LLs are what actually communicate to the hardware below, and must be able to use any kind of communication protocols. Due to their modularity, any LL can be used at any point, independent of the characteristics of the agents above them. They are made with flexibility in mind to allow for the integration of any kind of hardware.

The ME must be equally as flexible to allow for switching on the fly, during system operations. This allows for a more flexible and adaptable MAS, since communications protocols can be switched fairly easy, the system becomes more robust also. To accomplish this, the LLs need to be loosely linked to the ME.

As described previously the auxiliary architecture must provide the ME with a list of all the available LLs. It must also provide the LL with the correct configurations so that they can interface with the hardware. This could be done by passing all necessary resources to the agent on launch, and then the agent passes them along to the ME and LLs. This support architecture can be a simple entity that, upon deploying the agents, supplies them with the correct resources that are in turn passed to the ME and LLs. In this case, the deployment entity approach was chosen, but it would be possible to deploy an agent using the ME through other means. As long as the ME is supplied with the resources it needs to operate, it is able to perform its function. In Figure 3.1, the three main layers of our cyber-physical entity are shown, along with the deployment entity. There is an agent, which will take care of the decision making, the ME and LL which will provide an interface between agent and device, and the hardware itself, that will actuate on the physical world and provide sensor information to the agent above. It should matter not what kind of agent or hardware the agent is using, with the Module Engine, it must be capable of interfacing with it.

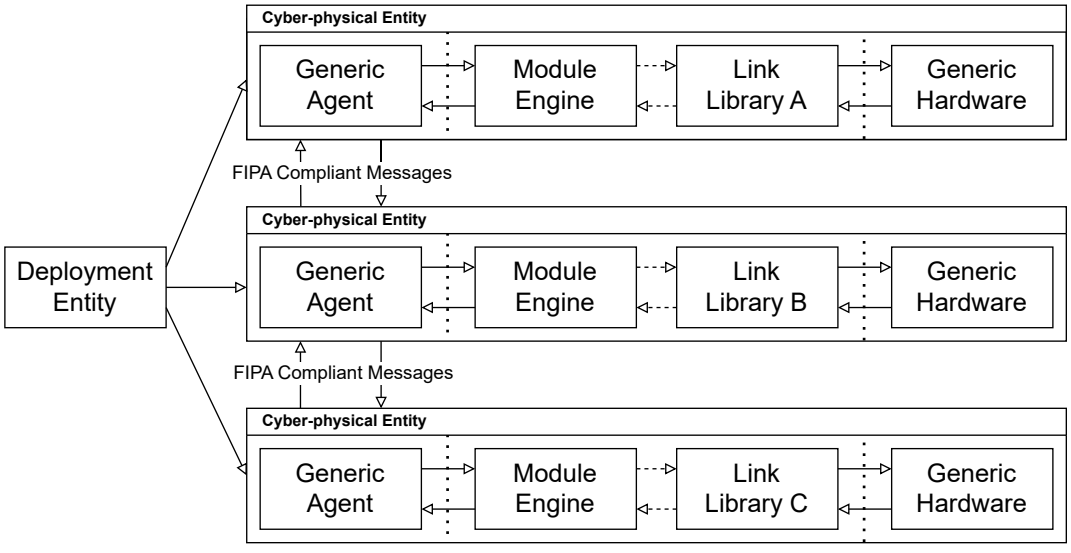


Figure 3.1: System architecture.

To summarize, the main objective of this project is to facilitate the integration of agents with their hardware, through the dynamic instantiation of Link Libraries by the Module Engine and by allowing the LLs to be reused by many kinds of agents. This would also facilitate development of new Link Libraries, since the architecture is prepared to work with new LLs from the get go.

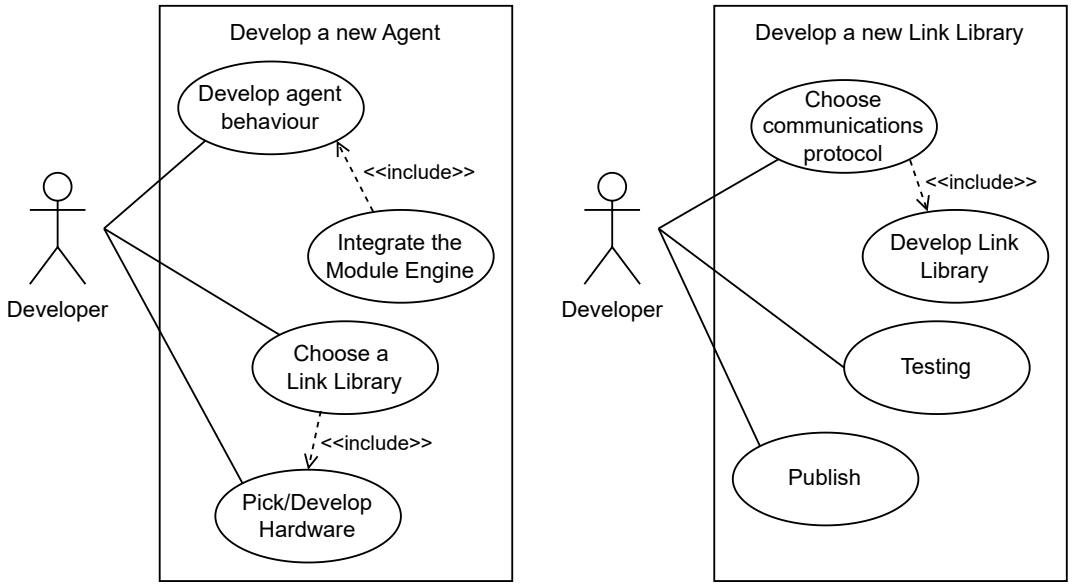
3.2 Usage Scenarios

This system has three main usage scenarios. The first is when a developer is creating a new agent to add to either a new system or a previously existing one. The second is when a developer wants to create a new LL to integrate a new type of hardware, or to use a different communications protocol. The third is when the already operating MAS runs into an hardware problem, and needs to use other types of hardware to reduce system downtime. This scenario can also be applied when a new agent is integrated into the already operating MAS, since it is in part what is happening when an agent needs replacement.

When a developer is creating a new agent, they need to make sure to use the Module Engine together with the agents that need to interface to the hardware. For obvious reasons, those agents that do not use hardware do not need the ME. They also need to make sure that the LL they wish to use to communicate with the hardware is already developed. If not, then they need to create it. The creation of new Link Libraries will be explained in another scenario.

The agent should be able to call the ME at any point during its operation, whenever it need to instruct the hardware. It should also be able to retrieve the result of the operation from the hardware. Figure 3.2(a) shows a diagram representing this scenario. The development of the agent is unrelated to the hardware, since the ME allows a more loose connection between the two. This is one of the advantages of the Module Engine. They can both be done in parallel to speed up development time.

To develop a new Link Library a developer only needs to pick a new protocol and start development. As long as they respect the interfaces and methods for an LL, better explained in Chapter 4, the ME should be able to load it. In addition, the hardware also needs to implement the same communication protocol implemented by the LL. If the hardware supports HTTP requests, for instance, the LL would need to implement a way to communicate through HTTP requests. When development is complete, this new LL can be published in some software distribution system, GitHub for instance, to be freely available to other developers wishing to use it. This scenario can be seen in Figure 3.2(b).



(a) New agent development scenario. (b) New Link Library development scenario.

Figure 3.2: Deployment Agent activity diagram.

Finally, performing maintenance on a system using the ME reduces system downtime, since if and when there is a fault, new hardware can easily be integrated. The Module Engine should allow this, and since Link Libraries are more flexible than traditional hardware integrations, they can be replaced easily by selecting a different LL from the already available ones. If there is not an adequate LL, a new one can be developed. Since they are relatively small, it might be faster to create a new LL than to create a new traditional interface for the hardware. It also follows that integrating new agents into the pre-existing MAS is as easy, since both processes share similarities, as shown in Figure 3.3.

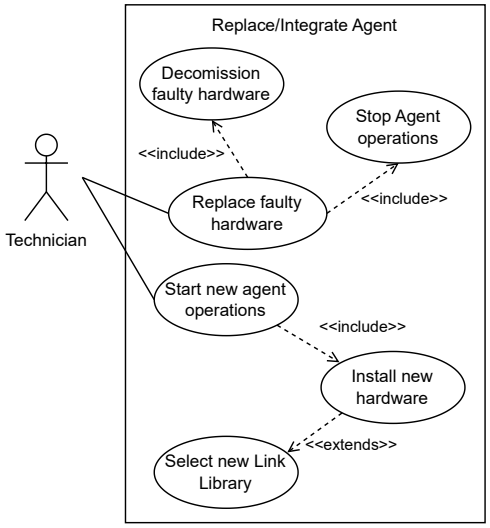


Figure 3.3: Agent replacement/integration scenario.

3.3 System Components

The developed system is to be inserted between agent and hardware layers to allow for a more flexible interface. The cyber-physical entity of which the agent is part of is composed of four main components. The agent itself, the Module Engine tasked with loading the Link Libraries, the LL capable of interfacing with the hardware, and the hardware represented by the agent. The agent, the ME and the LL can be considered the cyber part of the cyber-physical entity, with the hardware being the physical part.

In Figure 3.4, a Deployment Entity is also represented. This is the entity tasked with launching an agent using the ME and also provide it with the initial parameters. Once again, this entity could be replaced with any other system, as long as the ME receives its parameters, it should operate normally. These parameters allow the ME to know what Link Libraries exist, which one is to be used and also give the LL its configurations needed to establish a connection to the hardware. Both the marketplace file and the LL type are parameters used by the ME, to load an LL. The configurations need to be passed to the Link Library, as they are LL type specific.

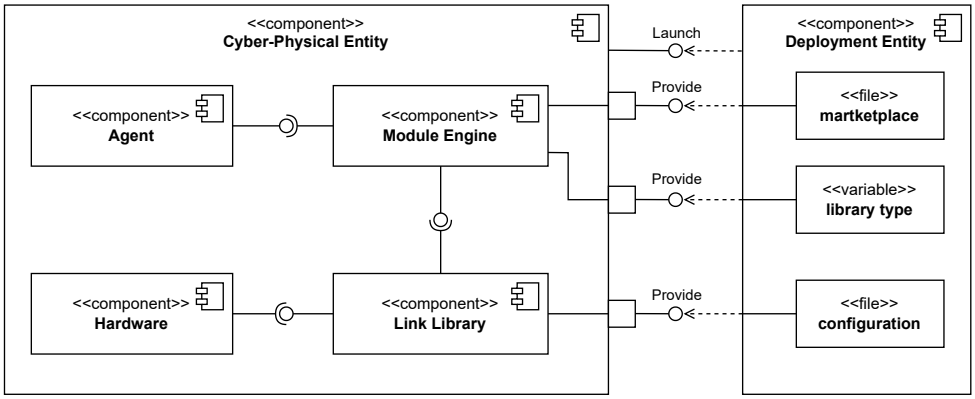


Figure 3.4: Component diagram of a cyber-physical entity using the Module Engine.

Because the Link Libraries are modular, these could be designed and implemented by other developers working with the Module Engine, wishing to create LLs with new protocols. To create a new one, a few specifications need to be followed in order to make sure the LL is able to communicate with the ME without problems. The LL must establish the connection with the hardware upon being loaded, through the protocol it implements. It must be able to close this connection at any point as well, since these LLs can be switched arbitrarily. Lastly, an LL needs to be able to communicate to the hardware through the protocol it implements. This means that the hardware would also need to implement the same protocol in order to establish a connection. It would also be possible to develop an LL capable of directly interfacing with the hardware through a more specific communication channel, by hosting the agent on the same device as the hardware, for instance. As long as

a Link Library implements it, it should be possible to use any communication channel. No information is exchanged exclusively between the loaded Link Library and the Module Engine, which makes development easier, since no protocols need to be followed in that regard.

The Module Engine simply serves as a loader and interface between the agent and the Link Library. All messages sent to the LL by the agent need to go through the ME, and they will arrive at the LL untouched. From the point of view of the agent, it is as if it is communicating directly to the LL. All data that flows from the agent to the Link Library must be in the format of a string of text. This LL can now transform the message in any way if needed, to allow for the correct usage of the protocol, in order to communicate with the hardware.

In this architecture, the marketplace is a simple file that holds the location and names of the Link Libraries. It must be organized in pairs, each LL name must be associated with an LL path, to allow the ME to load it. The marketplace could be developed into a more complex application that fetches the Link Libraries from a remote database, akin to an online platform for the distribution of packages. However, to reduce the project scope, this simpler design was chosen.

3.4 Module Engine Operations

The first entity that launches when the system is started must be the deployment entity, since this is the entity that will launch the cyber-physical entities in the system. It will deploy the agents using the Module Engine, and provide them with the parameters it needs to operate. A cyber-physical entity needs to create its own instance of the ME upon deployment, and give it the three parameters received from the deployment entity. Therefore, the ME would need to be included in its development process.

As explained before, the ME needs the marketplace file, where all available Link Libraries are listed, to select the right one. It is picked based on the LL type it also receives. Finally, after loading in the correct LL, it provides it with the configurations file.

The Link Library must now read this file and search for the configurations of the protocol it is implementing. It is possible to include more than one type of protocol in each configuration file. That is, a single configuration file may include different configurations for different protocols, but never more than one group of configurations per protocol. This file may include things like server addresses, ports, namespaces, topics, etc. Anything that the LL needs to establish a connection through the protocol it is implementing must be included in the configurations file. Since this LL can be created by other developers, it offers a lot of liberty in what it can do. As long as it follows the specifications described

previously, it should operate without problems.

Once communication with the hardware is established, the Module Engine will wait until a new command arrives from the agent. To accomplish this, an agent only needs to call the ME and provide it with the command. Once it does, the ME will pass that command downward to the LL, which will pass it along to the hardware. This process is needed to ensure modularity. Any LL can be associated with any agent, so the way to achieve this is to have an interface in the middle, the Module Engine, to pass instructions along.

Once the command is executed by the hardware, the result is passed along through the inverse path. From the hardware, to the Link Library, to the Module Engine and finally to the agent. This whole sequence of events is depicted in Figure 3.5. It is also possible to disconnect an LL by calling the right method. The ME would need to be restarted to change the LL, since it loads it as part of setup.

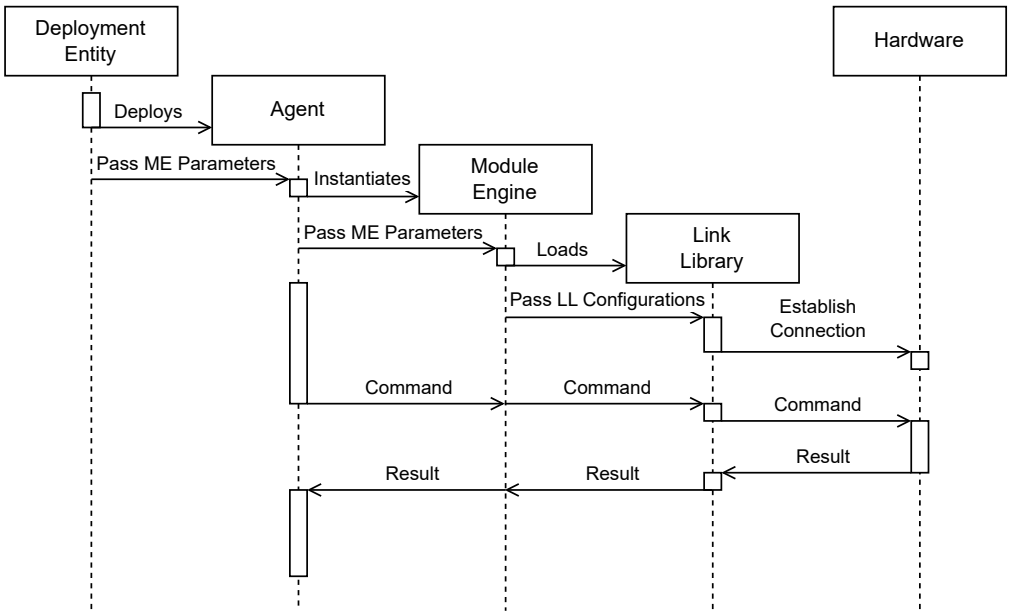


Figure 3.5: Sequence diagram of Module Engine operations.

The ME will need a method to parse the marketplace file and extract from it the name and path to the location of the LL, sorting them into a lookup table, for faster access. It would also need a method to load a Link Library given its type and provide the loaded LL with its configurations.

Two methods to utilize the LL are also needed, to execute a command and receive its result, and to stop the LL and disconnect it from the hardware.

On the Link Library side, it would need a starter method that is run when it first loads, to initialize any needed fields and establish connection to the hardware. It needs a method to send instructions and receive its result, and a method to stop operations and disconnect. Both of these methods are called by the ME.

The only messages sent between ME and LL are the commands the agent sends to the hardware. This interface should not change any command whatsoever, it simply serves as an interface. It is as if the agent is communicating directly to the hardware below, as illustrated in Figure 3.6. The LL could potentially convert the command to something the hardware understands, if needed, but that is up to the developer creating the Link Library.

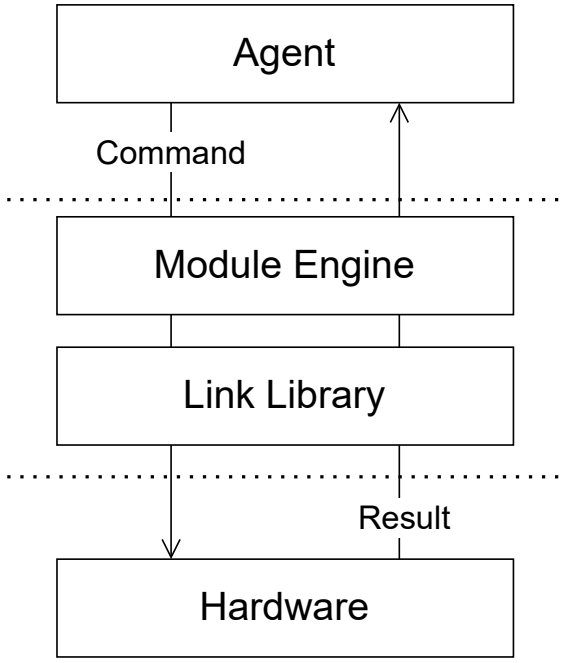


Figure 3.6: Cyber-Physical Entity internal communications.

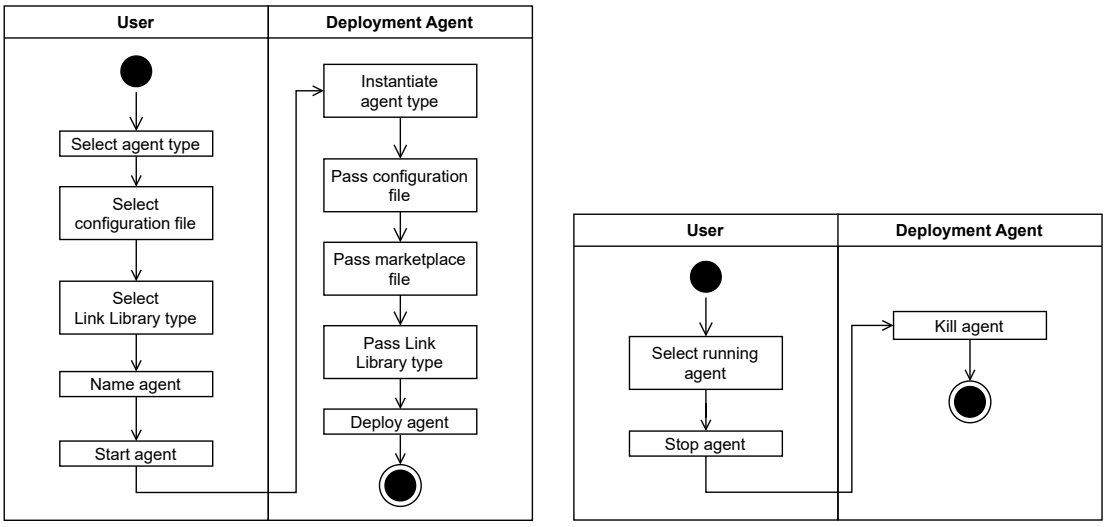
3.5 Multi-Agent System

To showcase the functionalities and perform tests on the Module Engine, it was necessary to develop an Industrial Multi-Agent System (MAS). This Cyber-Physical Production System is composed of three main types of cyber-physical entities, with two other entities performing more of a management role, used for agent deployment. The two management entities are not considered cyber-physical entities because they do not have a physical counterpart and therefore do not use the ME.

The developed entities are:

- The Resource Agent (RA), that represents any kind of physical component capable of performing processes, like a robotic arm or a bottle filling station;
- The Transport Agent (TA), that represent any kind of physical component capable of transporting products from one location on the shop floor to another, components like a conveyor belt or a Automated Guided Vehicle (AGV);
- The Product Agent (PA), that represent any kind of product to be manufactured by the Industrial MAS;
- The Deployment Agent (DA), that will launch RAs and TAs and provide them with the necessary parameters. This is the entity seen in Figure 3.4;
- And the Product Manager (PM), that will launch PAs and provide them with their production sequence.

When the system is first launched, the agents that start up immediately are the Deployment Agent (DA) and Product Manager (PM), since both of these agents are responsible for the launch and management of all other agents. Both of them need to be capable of receiving input from a human user through a Graphical User Interface (GUI). The user creates the necessary agents through the DA by providing it with the LL type and configuration file. The DA is capable of launching both RAs and TAs because these are the agents that need the Module Engine to operate as mentioned previously. Figure 3.7 presents the process of deploying a new agent (3.7(a)) and stopping a pre-existing agent (3.7(b)). The marketplace file is not provided by the user, but could instead be provided by some kind of web application. For this work however, it is provided locally and the DA has access to its contents directly.



(a) Deployment of new agent.

(b) Termination of running agent.

Figure 3.7: Deployment Agent activity diagram.

The Product Manager is simpler in its activities, since its only task is to launch Product Agents. A user only has to start the agent through the GUI of the PM. When a PA is started, it does not need any other external parameters. Figure 3.8 presents this simple operation. Since the PM does not terminate the PAs, it only has the functionality to deploy agents.

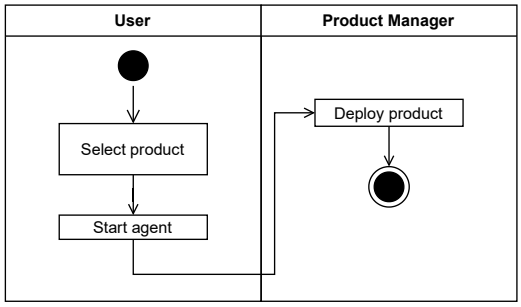


Figure 3.8: Product Manager activity diagram.

After deployment, Resource Agents and Transport Agents will instantiate the Module Engine and pass it the marketplace and configuration files, along with the LL type. Then they will proceed to register themselves in a Yellow Pages Service, which is a way for agents to search for other agents with specific characteristics. This service works a little bit like a phone book, presenting all registered agents along with their agent ID, a unique identifier that corresponds to each agent. Any agent can access the Yellow Pages and search for agents with certain capabilities, called skills. These skills show what actions an agent can perform. For example, an agent with a skill called "Move_to_Storage" might move itself or a load to storage, or an agent with the skill "Staple_tag" might be able to staple a tag on a piece of clothing, and so on. A production sequence is list of the skills a product needs to be performed in order to complete it fabricated. In the designed system, Product Agents can use the Yellow Pages to look for RAs and TAs capable of performing the needed skills.

When all RAs and TAs have been launched and their initial setup completed, the system is now ready to work. PAs are launched as new products enter the production line, and after getting their production sequences, they will search the Yellow Pages to find a RA capable of performing the first skill. When they find it, they will issue a Call for Proposals from all relevant agents through the FIPA Contract Net. This interaction protocol was developed by FIPA, and it works as follows:

In this protocol the agent that starts the communication is called the Initiator, and all other are the Participants. The Initiator sends a Call for Proposals or CFP message to all Participants preselected by the Initiator. After receiving the message, the Participants can either accept the call by sending a Proposal, or refuse altogether. On refusal, this particular Participant is out of communications from now on. Proposals might include some data to help the Initiator decide which Participants it wants to keep communicating

with. Upon deciding this, the Initiator will send an Accept Proposal message to the desired Participants, Rejecting all other Proposals. Finally, the Participants whose Proposal was accepted might perform some process and inform the Initiator of the result, with a Failure message or a Inform message. This interaction protocol can be visualized in Figure 3.9.

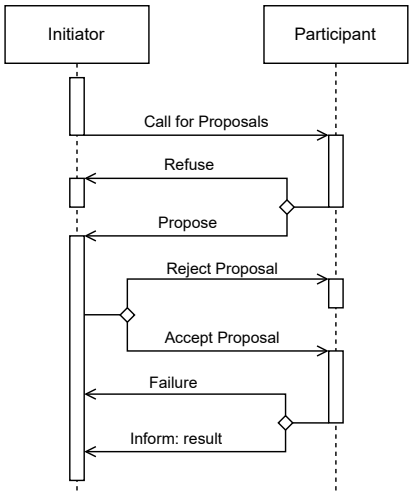


Figure 3.9: FIPA Contract Net interaction protocol. Adapted from [25].

After receiving the Call for Proposals, RAs will respond with a Proposal. This simply signifies that the agent is available to perform the needed skill, and it does not contain any extra data. Then the PA, the Initiator, will Accept the first Proposal on the responses list for simplicity. Finally the selected RA will respond with an Inform message, in which the contents of the message contain the location of the RA on the shop floor. This location will be used by the PA to ask for transportation from a TA. An example of a communication through the FIPA Contract Net can be seen in Figure 3.10. In this example, two RAs have the relevant skill for the PA. It selects the first one and rejects the other. Then the RA Informs the PA of their location.

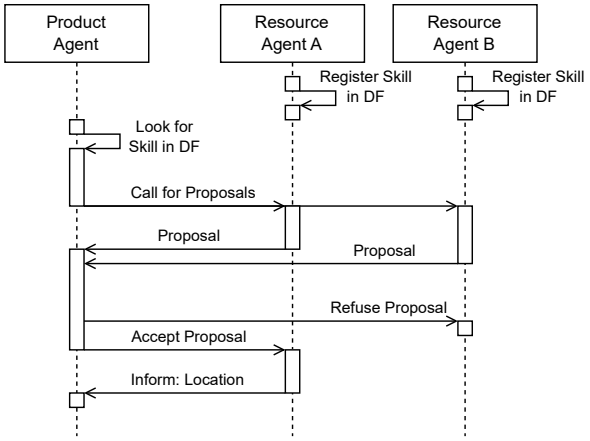


Figure 3.10: FIPA Contract Net protocol between a Product Agent and two Resource Agents.

Upon finding a Resource Agent, the Product Agent now needs to be transported to its work station. For this it needs a Transport Agent. So the PA will once again look into the Yellow Pages for a TA, by searching for a skill once again. The physical system used in Chapter 4 to simulate a real environment only uses a single TA. So instead of asking for an agent through the FIPA Contract Net, the agent can skip straight away to the next step, which is to ask for a skill to be performed through a FIPA Request. This protocol is also one created by FIPA, and its less complex than the FIPA Contract Net:

This protocol also includes an Initiator, but only one Participant. This is a one to one communication. The Initiator starts by sending a Request to the Participant. At this point the Participant may Refuse, and communications are terminated. If it Agrees however, it will start performing the desired process immediately. Upon completion, it will notify the Initiator with either a Failure or Inform message. This protocol is shown in Figure 3.11.

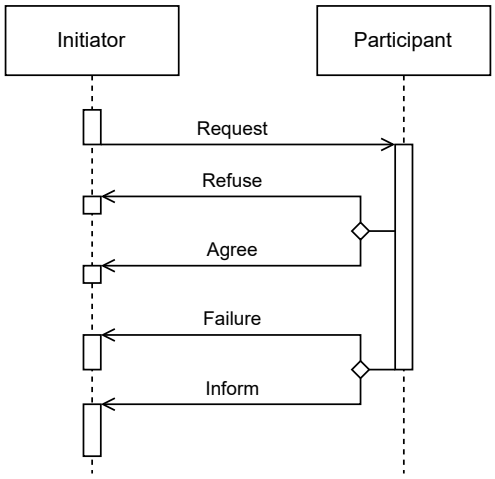
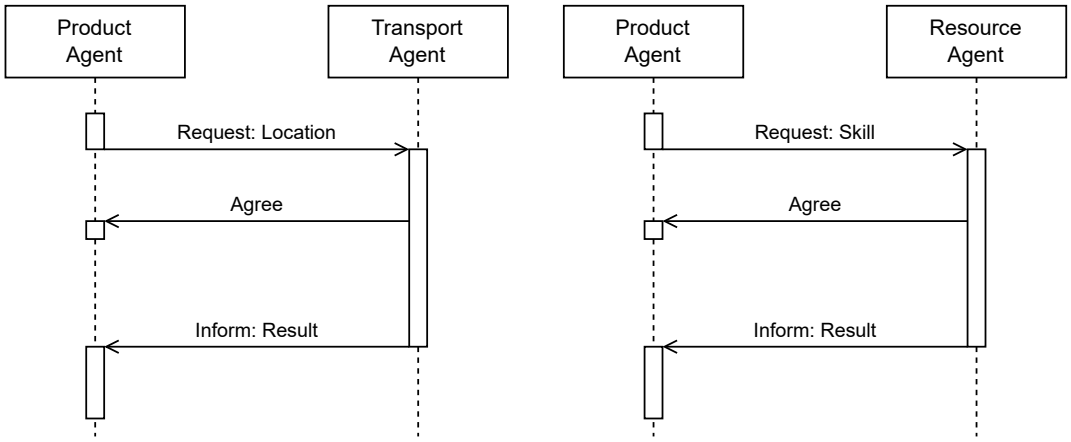


Figure 3.11: FIPA Request interaction protocol. Adapted from [26].

The PA starts a FIPA Request with its starting and ending positions, so the TA knows from where the PA departs from, and what is its destination. After Agreeing with the Request and before the communication terminates, the TA will start the transportation procedure by moving the PA from its starting position to its destination. When this is completed, the TA will send the Inform message to the PA signalling the transportation is complete. After arriving at the location where the previously found RA is located, the PA will use the same protocol to Request the skill from the RA. After Agreeing, the RA will start performing the skill on the product. When complete, an Inform message is sent to the PA signalling the end of the operation. Both of these sequences of messages are shown in Figure 3.12. In 3.12(a) the FIPA Requests protocol between a PA and TA is shown, and in 3.12(b) between a PA and RA.



(a) Product Agent and Transport Agent. (b) Product Agent and Resource Agent.

Figure 3.12: FIPA Requests between agents.

When the RA finishes its skill and informs the PA, the PA will check if its production sequence is complete. If it is, it will Request transportation from a TA to storage. If the sequence is not complete, it restarts the process by checking the Yellow Pages for agents capable of performing the next skill, Calling for Proposals, and so on, repeating the process. The whole evolution of the MAS can be visualized in Figure 3.13. It only shows the full interactions between agents, their actions and decisions without the Module Engine.

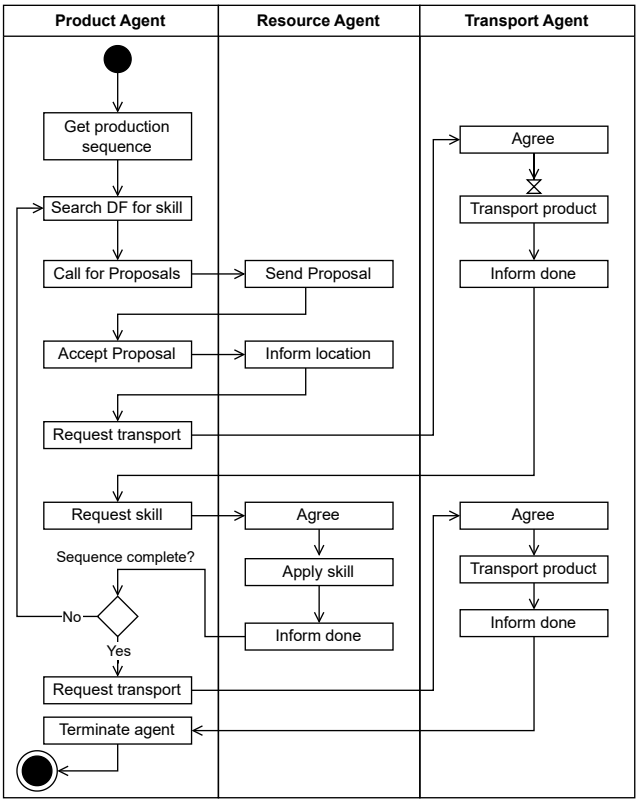


Figure 3.13: Activity diagram of the Industrial Multi-Agent System.

3.6 System Overview

Now that all parts of the system have been explained, it is now time to do a brief overview of the behaviour of the system has a whole. When the MAS is launched, the first two agents that start up immediately are the Deployment Agent and the Product Manager. Then a user needs to manually launch the Resource Agents and the Transport Agent and select the right configurations for each agent.

When these agents are launched, they will register themselves in the Yellow Pages Service with their skills and instantiate their Module Engine, which will in turn load the corresponding Link Library. These LLs will establish connection to the hardware. After all of these agents are deployed and ready to operate, the user can now launch the Product Agent.

Upon being launched, the PA will look at the Yellow Pages and it will find the RAs capable of performing the first skill in its production sequence. Then it will establish contact with all of them through the FIPA Contract Net. After receiving all Proposals, it will select one and refuse the others. In the Inform message, the PA will receive the location of the station where the RA is located.

The next step is to Request transportation from a TA to this location. The PA will start a FIPA Request with its current location and its destination. The TA will answer this Request to signal it received the message and will immediately start the process of moving the product. For this, it will send the command through the Module Engine and through the Link Library, to the hardware. Once the hardware finishes executing it, it will return the result back up through the LL and through the ME to the agent.

The TA will now notify the PA that transportation is complete. The PA then starts another FIPA Request, this time to the previously chosen RA. This agent will execute its skill by using the same process as the TA. Through the ME and LL down to the hardware. After the result arrives back at the agent, it will notify the PA. If this is the last skill in this products production sequence, the PA will now Request another transportation, but this time to storage, terminating the agent and ending its production. If, however, there are still skills in the production sequence, then the process restarts. The PA will search again for a PA capable of performing the new skill in the sequence and so on. In Figure 3.14, this whole process is shown, from start to finish.

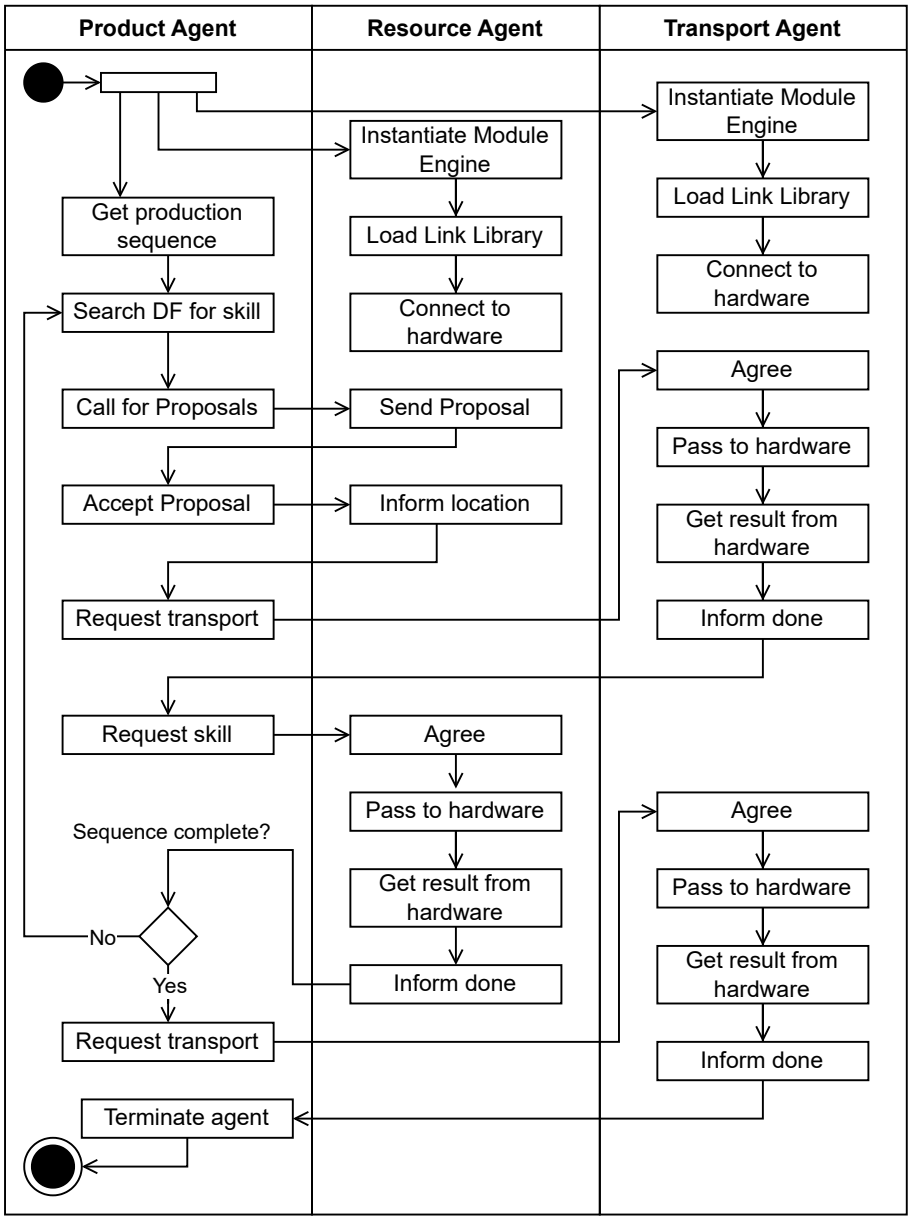


Figure 3.14: Activity diagram of the complete system.

4

Implementation

Now that the proposed architecture of the system has been laid out and well defined, it is time to implement it. First the tools used are identified and each class was implementation is explained, their data models and methods. Then the different modules in the system that communicate through interfaces are identified, an explanation is done on how a human operator can interact with the system, what behaviours each agent makes use of and the developed Link Libraries for hardware interfacing. Finally, the system operations and what behaviours and methods are called for each operation are also explained.

4.1 System Implementation

The implementation needs to start with the deployment agents, since these are responsible for launching all other agent types. The Deployment Agent (DA) is tasked with deploying Resource Agents (RAs) and Transport Agents (TAs). The DA needs a Graphical User Interface (GUI) to allow a user to launch these agents with the right configurations. These must include the agent type to be launched, the type of Link Library the agent must use and its configurations. Like the DA, the Product Manager (PM) also needs to launch agents, more specifically, Product Agents (PAs). This should also be done through a GUI but this one should only show buttons per product type, and some information on the already deployed PAs.

The RAs and TAs will operate somewhat similarly to each other, with the RAs needing an extra step before a skill executes. They will register themselves in a registry of agents called the Directory Facilitator (DF). This DF is the Yellow Pages Service mentioned in Chapter 3. This is mainly so that the Product Agents can find the right agent for the operation they need to accomplish. For skill execution, RAs and TAs are dependent on the Module Engine.

The Product Agents need to be constantly on a loop. They look at their production sequence and search for a RA capable of performing the current skill. Upon finding it, they will request transportation to the station. Upon arrival, they will call for the skill to be performed on them. If the production sequence has been completed, they request transportation out of the production line. If not, the process must repeat until this condition is met.

The Module Engine will need to operate between the layers of agent and hardware. It needs to be able to use its configurations to load any developed Link Library. It must also be capable of relaying messages from the agent to the hardware and vice versa. Multiple Link Libraries need to be developed in order to test whether or not the ME is capable of switching LLs during runtime.

4.1.1 Implementation Tools

For the implementation of the Module Engine framework and accompanying MAS, the Java programming language was selected, more specifically version 21.0.2 of the OpenJDK. As mentioned in 2.2.1, JADE was built with the FIPA specifications in mind and its Java version is well supported, so this framework was chosen to implement the Multi-Agent System.

The JADE framework provides a lot of tools for agent development, communication and management. It provides a lot of classes and methods useful for agent setup, communication, DF registration and more. Since the Java language was going to be used for the MAS and is one of the best supported in the world, the Module Engine and the Link Libraries were also developed using it.

As mentioned in Chapter 3, three main cyber-physical agent types were developed, Resource Agents (RAs), Transport Agents (TAs) and Product Agents (PAs). Along with these, two more agents were created, Product Manager (PM) and Deployment Agent (DA), with the purpose of launching and managing the other three agent types. All of these agents extend an interface "Agent" provided by JADE.

This interface contains a lot of useful methods and variables, although not all of them are used in this MAS. The methods used are the "setup" method, executed once when an agent is launched, and the "takeDown" method, executed when a agent is terminated. These methods must be overwritten to provide the agent with instructions on launch and termination.

Because the agents are launched through JADE, the class constructor cannot have any initial arguments. To launch an agent with arguments, the method "getArguments" present in every agent can be used. It returns a generic object array a developer can then use to retrieve the arguments an agent is launched with.

JADE also provides a lot of other classes that define agent behaviour. These classes must be defined inside the agents class to add new behaviours. Some of them must be used in order to make use of the different JADE functionalities, like the FIPA Contract Net. Others simply exist to add a bit more flexibility during development.

The behaviour classes used in this project were:

- The "OneShotBehaviour" class, that adds a single behaviour to the agents behaviour sequence. It is executed once, and then is excluded from the sequence;
- The "ContractNetInitiator" class, that allows an agent to start interacting with other agents as the Initiator in the FIPA Contract Net protocol. Once it finishes communications, it is excluded from the behaviour sequence;
- The "ContractNetResponder" class, that allows an agent to respond to messages as one of the Participants in the FIPA Contract Net protocol;
- The "AchieveREInitiator" class, that allows an agent to start interacting with anoter agent as the Initiator in the FIPA Requests protocol. This class is also excluded from the behaviour sequence after communications are done;
- And the "AchieveREResponder" class, that allows an agent to respond to messages as a Participant in the FIPA Requests protocol.

4.1.2 Deployment Agent

Starting with deployment, the Deployment Agent was designed to allow a human user to deploy and terminate agents during the execution of the MAS. In its constructor the functionalities of the GUI are defined and some initial values are set. This class extends the "Agent" class, and only makes use of the "setup" method. All other functionalities are called on button presses, through events.

The "selectedAgent" field specifies which type of agent (RA or TA) is to be launched. This can be changed through a radio button on the interface.

The "xmlMarketplace" field is loaded during "setup" with the method "getMarketplaceLibraries", using the file pointed to by the "marketplaceXMLPath" String. It holds the path of the XML file that contains the available Link Libraries.

The "agentContainer" field holds a reference to the container where the agents deployed will be hosted. Finally, the "xmlConfigPath" is a user loaded value that is used to pass the LL configurations file.

In Figure 4.1, some of the classes the agent uses to draw the GUI are shown. These classes are part of the "javax.swing" package, useful to draw graphical interfaces. The "ContainerController", used to create a container where other agents are deployed, is a JADE class. Also shown are the auxiliary "Constants" class, that stores constants useful

for the correct operations of the MAS. This class will be explained in more detail in Section 4.1.5.

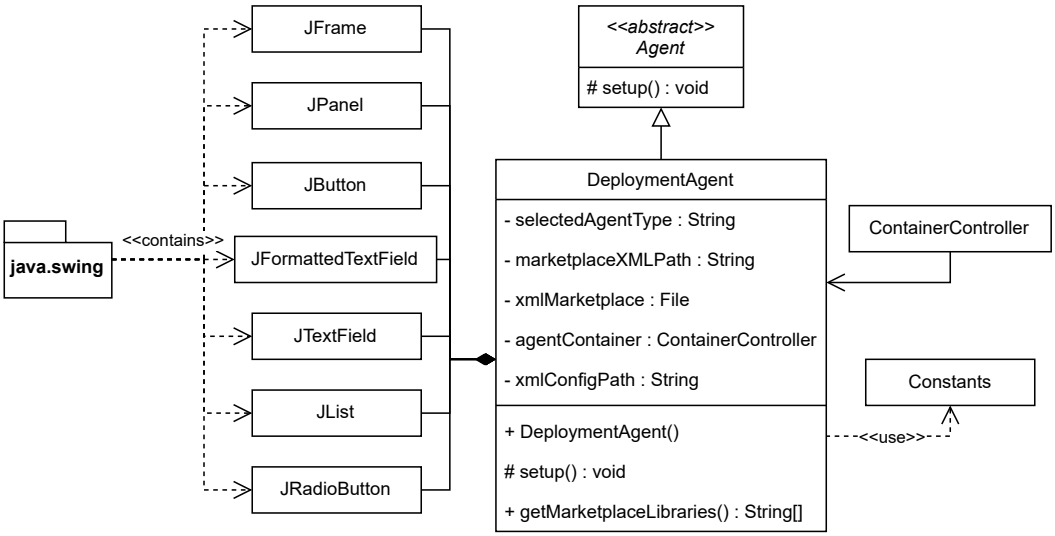


Figure 4.1: Deployment Agent class diagram.

4.1.3 Resource Agent

This agent is launched by the DA because it is dependent on the parameters provided by it. The Resource Agent class also extends the "Agent" abstract class, and overrides the "setup" and "takeDown" methods. It makes use of the "addBehaviour" and "getArguments" methods, as well as the "ContractNetResponder" and "AchieveREResponder" classes.

It makes use of the auxiliary "Constants" and "DFInteraction" classes, which will be explained in 4.1.5 and 4.1.6, respectively. It has two objects of type File called "xmlConfigFile" and "xmlMarketplaceFile", given as a parameter by the DA, that store the corresponding files. The String "libType", also given as a parameter by the DA, contains the type of LL this agent is using and the String "location" contains the position of this agent in the physical system.

Finally, the object "moduleEngine" of type ModuleEngine holds the ME instance this agent instantiates, and the ArrayList of Strings "associatedSkills" holds the list of all skills this agent is able to perform. This last object is initialized during setup, with the configurations provided by the DA as well.

The "requestResponder" class extends the "AchieveREResponder" class and the "contractNetResponder" class extends the "ContractNetResponder" class, explained in 4.1.1. Figure 4.2 shows a class diagram of the agent. In this Figure, the Module Engine and all subsequent classes are omitted, as they will be explained in 4.1.9 in more detail.

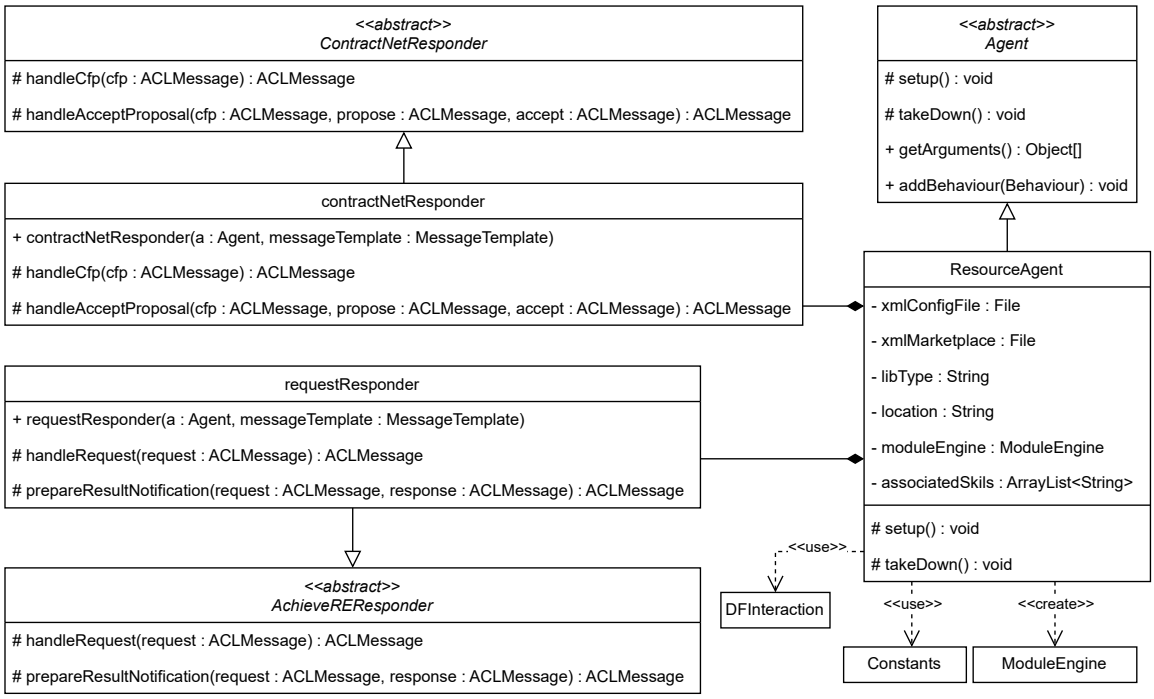


Figure 4.2: Resource Agent class diagram.

4.1.4 Transport Agent

Also launched by the DA, the Transport Agent class is very similar to the Resource Agent. It also extends the "Agent" class and contains both "setup" and "takeDown" methods.

The only differences are in the variables it uses and the classes it implements. It uses the "getArguments" method provided by JADE to get the parameters set by the DA. It also needs the "xmlConfigFile" and the "xmlMarketplaceFile" for the same purposes, since it also makes use of the ME. The String "libType" defines which LL to use, like in the RA, and it also has the ArrayList of Strings "associatedSkills" to hold the list of skills and an object "moduleEngine" that holds its instance of the ME.

The only exception is the variable "location", since the Transport Agent does not have a static location in the physical system. This class also makes use of the "Constants" and "DFInteraction" classes.

It implements a single "requestResponder" class which extends the "AchieveREResponder" class, used to respond to FIPA Requests, provided by JADE. This is because this agent does not make use of the FIPA Contract Net, therefore does not need any of the classes that enable its use.

Figure 4.3 has a representation of its implementation. Once again the classes related to the ME have been omitted.

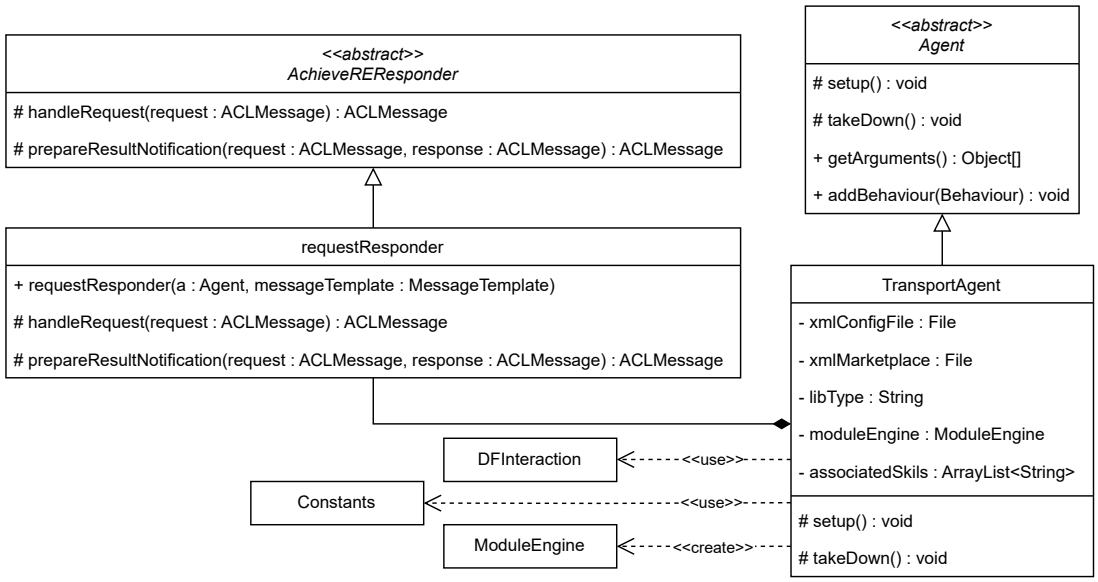


Figure 4.3: Transport Agent class diagram.

4.1.5 Constants

To help define all of the constants needed for the MAS, an auxiliary class of constants was created. This "Constants" class also contains a few methods to help with information retrieval. It is mostly composed of String fields. Other classes can reference it to check information about the system. All of these are implementation specific, and define the system used for testing in Chapter 4.

Figure 4.4 shows a representation of this class, as it is solution specific. Generic names for each type of constant are shown to shorten the size of the diagram, with the letter "X" being used as a placeholder for names of skills, stations, products, etc.

The Strings "SKILL_X" define the type of skills available in the whole system. The Strings "STATION_X" hold the RA types and the "TRANSPORT_X" holds the TA types. "PROD_X" represents the product types available. "LOCATION_X" fields hold the value for all locations in the system. "STATION_X_SKILLS" and "TRANSPORT_X_SKILLS" list the skills those agents can perform. Finally, "PROD_X_SKILLS" contains the list of skills a specific product needs to complete their production and "PRODUCT_TYPES" holds a list of all product types.

The methods help with information retrieval. Given an RA or TA name, "getStationTransportSkills" returns a list of all skills that agent is able to perform. With a name as parameter, "getStationLocation" gives the location of the station in question. "getLocationStation" does the opposite, it returns the agent name at the location passed to the method. Lastly, "getProdSkills" returns the list of skills of the product type passed as a parameter.

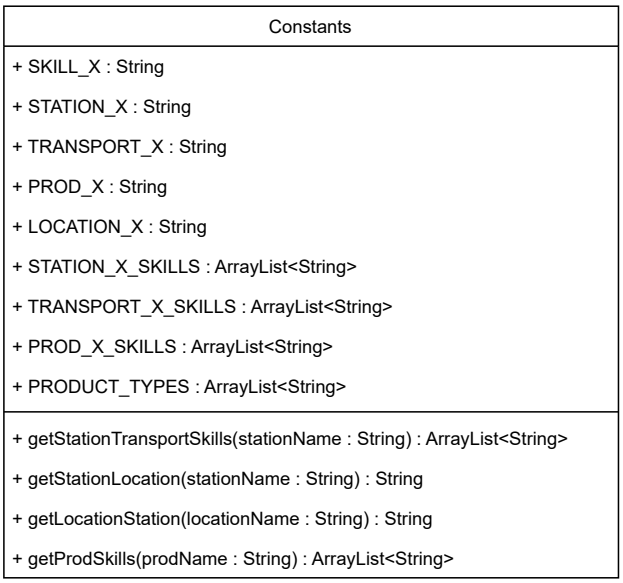


Figure 4.4: Constants class diagram.

4.1.6 Directory Facilitator

The "DFInteraction" is an auxiliary class. It provides methods that can register, remove or search information on the DF, which works as a registry for agents. In it, agents can register themselves, along with the skills they provide for the MAS. Other agents can then search agents by the skills they perform, and establish contact with those they find appropriate for the task, in order to request skill executions. Figure 4.5 shows the diagram of the auxiliary class implementation. The method "RegisterInDF" has two version, one allows for the registry of an agent with a single skill, the other for an agent with multiple skills. The "DF-Service" class is implemented by JADE and it is what allows for the interactions with the DF.

Resource Agents and Transport Agents register themselves in the DF during their setup, with the skills they are able to perform. During production, Product Agents can use this registry to look up agents capable of performing their needed skills, and establish contact with those agents.

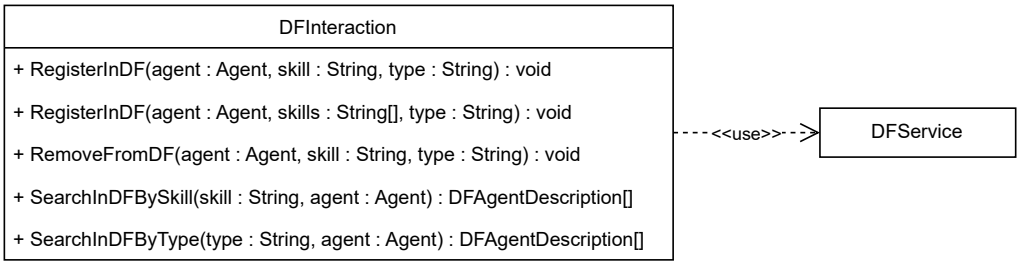


Figure 4.5: Directory Facilitator class diagram.

4.1.7 Product Manager

The Product Manager (PM) is another deployment entity. It also presents a GUI to allow a human operator to launch Product Agents, although it cannot terminate them. It operates similarly to the DA. This class also extends the "Agent" class, and also only makes use of the "setup" method, the other functionalities called on button presses.

It generates a button per product type based on the information present in the ArrayList of Strings "productTypesList". This filed is populated by referencing the "Constants" class, which holds all the product types present in the MAS.

The "productID" is an integer appended to the name of each agent launched under the PM, because JADE does not allow agents with the same name to exist. The "products" ArrayList of Strings holds a list of product agents that have been launched so far.

In Figure 4.6, the classes that it uses to draw the GUI are shown, once again the "ContainerController" used to instantiate a container where Product Agents are launched. The "DefaultTableModel" class helps with the definition of the GUI, and is a class in the "javax.swing" package.

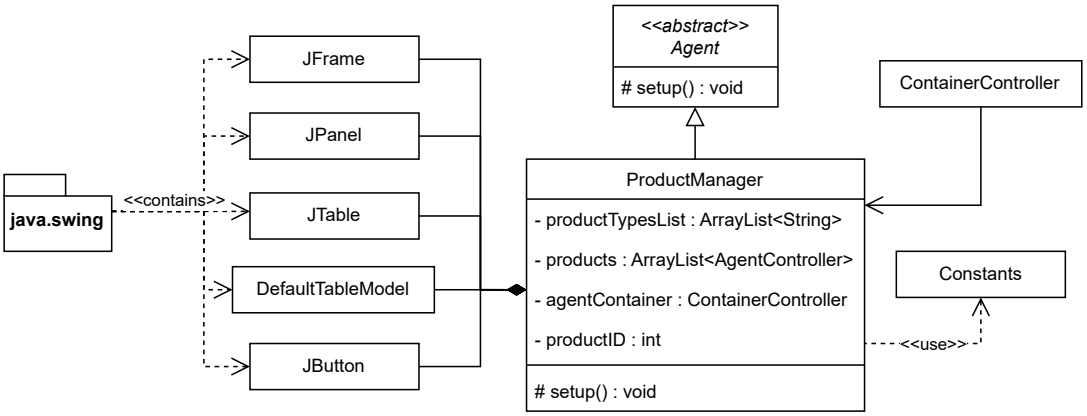


Figure 4.6: Product Manager class diagram.

4.1.8 Product Agent

The Product Agent class extends the "Agent" abstract class and overrides the "setup" and "takeDown" methods. It makes use of the "addBehaviour" and "getArguments" methods, as well as the "OneShotBehaviour", "ContractNetInitiator" and "AchieveREInitiator" classes. It also uses the auxiliary "Constants" and "DFInteraction" classes explained before.

It has an ArrayList of Strings called "executionPlan" to store the whole skill sequence, an int called "step" to store the current step in that sequence and a String "location" that stores the agents current location on the physical system.

The "executeNextSkill" class extends the "OneShotBehaviour" class, the "contractNetInitiator" class extends the "ContractNetInitiator" class and the "requestTransportMove" and "requestStationSkill" classes extend the "AchieveREInitator" class. These classes and methods are all represented in Figure 4.7, along with the variables they use.

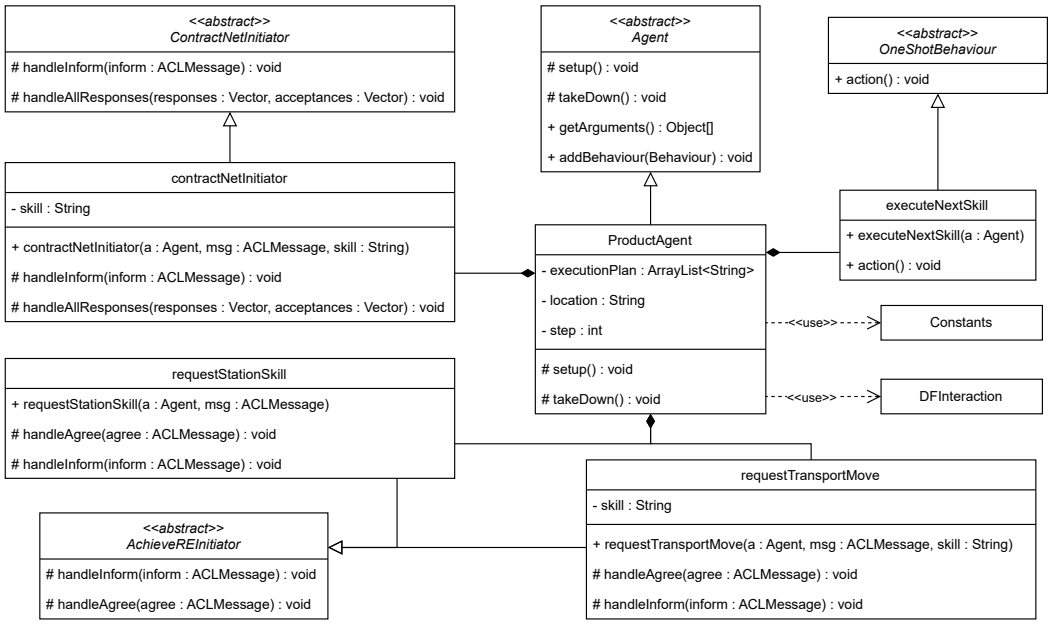


Figure 4.7: Product Agent class diagram.

4.1.9 Module Engine

With the whole MAS already defined, the hardware interface is now going to be explained. The Module Engine class is the main framework that was developed for this. It contains a generic object "linkLibrary" that holds the currently loaded Link Library. This object needs to be generic since, at the start of runtime, the ME does not know which type of LL will be loaded.

The method "parseMarketplaceXML" does exactly that, it parses the marketplace file with all the names and paths of all available Link Libraries and places them in the "classesToLoad" Hashmap. The name is used as the key, since it is unique, and the path as the value. This marketplace file is in the XML format, and holds both the name of the LL and the file path of the class that implements it. Evidently, if a Link Library has not been previously registered in the marketplace file, the Module Engine will not be able to find it, and therefore, load it. Currently, this file needs to be created and maintained by the developer, although a more complex solution could be implemented, making use of a package distribution application to download and update LLs.

These Link Libraries are loaded inside the ME by using the Reflections feature of the Java language. It allows for a program to inspect itself, and more importantly, to load classes and call their methods during runtime. This is what allows the ME to load any kind of LL at any point, while the MAS is running. This is important, because normally all the classes Java makes use of need to be compiled. However, since the LLs that might end up being used may or may not have been created by the same developer, or exist at the time of compilation, the ME needs this feature to accomplish its goal of being modular and flexible.

The method "createObject" takes the String "libType" from the agent that contains the type of LL to load. This LL is then fetched from the "classedToLoad" Hashmap and attributed to a generic object of type "Class", or "Class<?>". This is then loaded using Reflections by creating a new object of that class and passing along the XML configurations file received from the agent as a parameter.

To execute a skill the method "executeSkill" is called with the skill as the argument, which will in turn get the method "ExecuteSkill" from the "linkLibrary" object and place it in a "Method" type object. This method is then invoked to execute the skill, which is passed to the LL also as an argument, and its return message is returned as a String.

Finally, the method "shutdown" is used to disconnect the hardware from the Link Library, and is usually called when the agent, and consequently the ME, is terminated. Figure 4.8 shows how this class is implemented, along with an LL, This one implements the HTTP protocol, but it could have been any other like MQTT, OPC UA, etc.

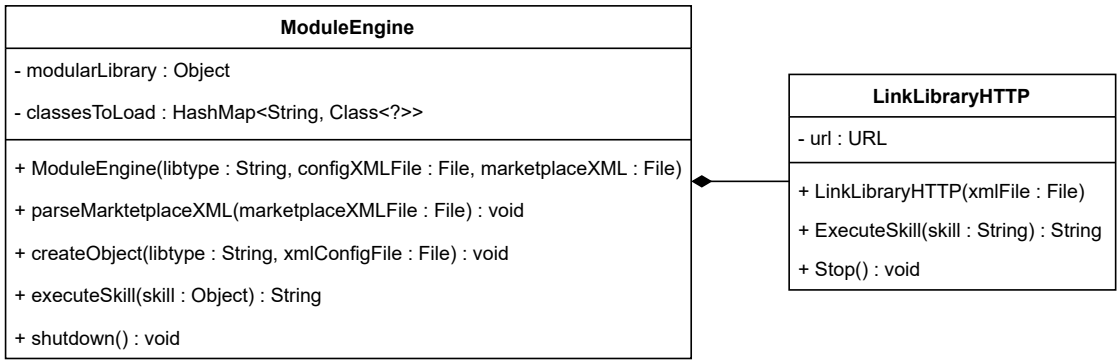


Figure 4.8: Module Engine class diagram with exemplary Link Library.

4.1.10 Link Libraries

To showcase the functionalities of the ME, three different Link Libraries were developed, each one implementing a different communication protocol. An abstract class "LinkLibrary" was extended to implement the "LinkLibraryHTTP", "LinkLibraryMQTT" and "LinkLibraryOPCUA" classes.

The "LinkLibraryHTTP" was implemented with the classes and methods provided in the "java.net" package. It communicates through HTTP Requests. When it receives a message from the ME, it will relay it to the hardware through a POST message. It will now wait until the response of this POST gets returned, with the result of the operation in it.

The "LinkLibraryMQTT" is dependent on the "org.eclipse.paho.client.mqttv3" package to implement its MQTT protocol. When the LL is started, it will immediately try to connect to the broker specified in its configurations, and immediately subscribe to a response topic, also present in the configurations. When a skill needs execution, the LL publishes the

skill in the requests topic, also specified in the configurations. Then, it will wait until the response topic receives a message, which it will return as the result to the operation.

Finally, the "LinkLibraryOPCUA" used the "org.eclipse.milo.opcua" package to implement an OPC UA communication. It will connect to the OPC UA server in the configuration file, and subscribe to the response node of the corresponding device. When a skill needs to be executed, the response node is cleared to make sure the result is read properly. Then the skill is written on the requests node and the LL will wait until the response node value changes. When it does, the requests node is cleared, so it is ready for the next communication, and the result is returned to the agent.

All Link Libraries must extend the "LinkLibrary" class, because this is the basis of an LL and it defines the methods on which the Module Engine depends on for correct execution. All further Link Libraries also need to take this base, to ensure correct integration with the ME.

Figure 4.9 has a representation of these classes and the respective packages they use to implement their communication protocols.

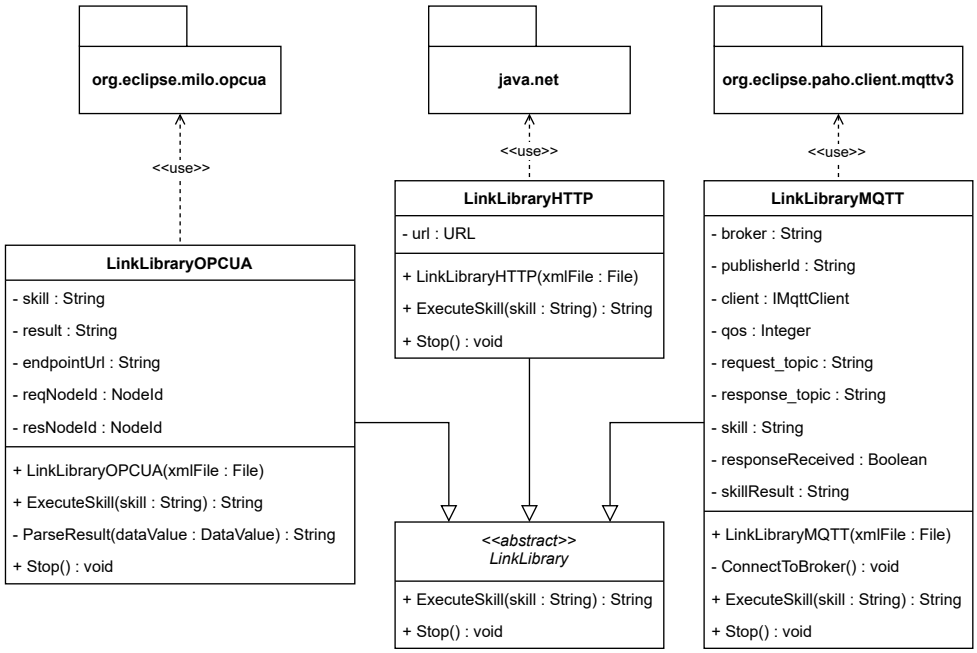


Figure 4.9: Link Library class diagrams.

All developed Link Libraries were registered in the marketplace file, one LL per XML tag, each tag with two attributes. The first attribute is the exact name of the class and the second attribute the file path that points to where the given LL is located. With these two attributes, the ME is capable of finding and loading the correct LL. In order to use these Link Libraries however, the hardware that would work underneath the agent would also need to implement these three protocols in some way. In addition, a configuration file must always be provided to the LL for it to communicate properly.

4.2 Interfaces

In this Section, the three interfaces between entities in the MAS are explained. Starting with the human to agent interface, for agent deployment. Then agent to agent interfaces, for MAS operations. Finally, agent to hardware for skill execution.

4.2.1 Human to Agent

As mentioned before, there are two agents with Graphical User Interfaces. The Deployment Agent and Product Manager both present a human user with an interface for agent deployment.

On the left side the DA interface has a button to open a configuration file and a text box where the path to the currently chosen file appears. Then it has a text field where the agent name is written and two radio buttons where the agent type can be selected, Resource Agent and Transport Agent. Finally there is a list of all available LLs that are fetched from the marketplace file and a button that starts the agent. On the right side there is a list with the currently running RAs and TAs. These agents can be selected by clicking on them and stopped by pressing the stop agent button below the list. Figure 4.10 shows this interface.

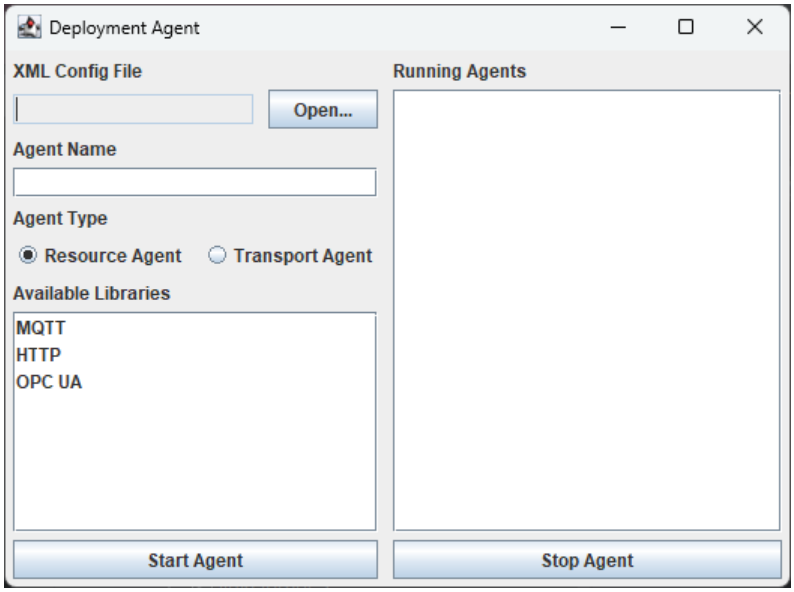


Figure 4.10: Deployment Agent Graphical User Interface.

The PM is more simple. It has buttons equivalent to the number of product agents specified in the "Constants" class and a list with the already launched agents. These agents have an ID represented by an integer, their product type and the skill sequence they need executed to complete the production process. This interface is shown in Figure 4.11.

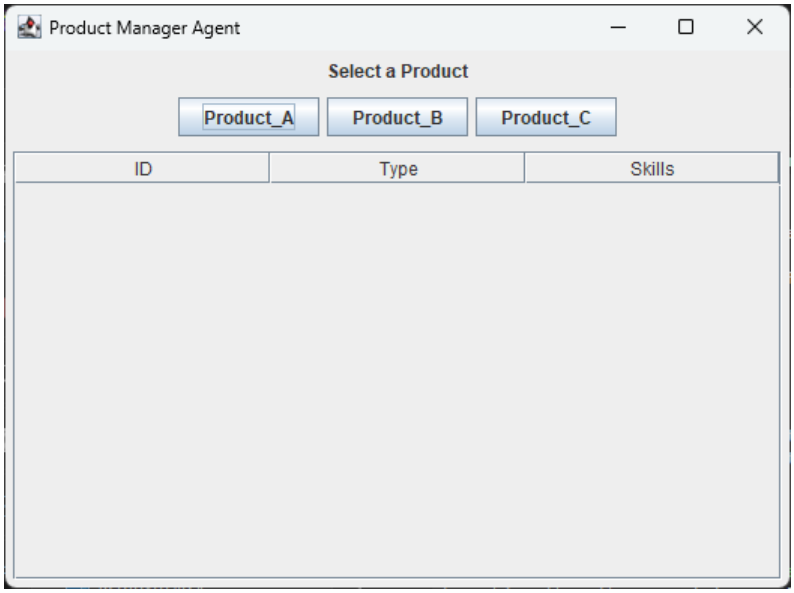


Figure 4.11: Product Manager Graphical User Interface.

4.2.2 Agent to Agent

Agent to agent communication is done through ACLMessages. These have been defined by FIPA [27]. These messages have many parameters that help define communications. Table 4.1 shows the parameters used by the agents of the MAS, along with their utility.

Table 4.1: ACLMessage parameters.

Parameter	Purpose
performative	Type of communicative act
sender	Sender of the message
receiver	Receiver of the message
content	Content of the message

The performative of a message can take multiple values. For the FIPA Requests protocol, messages of type "request", "refuse", "agree", "failure", "inform-done" and "inform-result". The FIPA ContractNet protocol makes use of messages of type "Call For Proposals" or "CFP", "refuse", "propose", "reject-proposal", "accept-proposal", "failure", "inform-done" and "inform-result". These message types and their respective protocols can be seen in Table 4.2.

The sender and receiver parameters are pretty self explanatory, they hold the agent ID of both the sender and receiver of the messages. The content parameter holds the content of the message. For this MAS it can be a location or a skill, depending on which type of agents are communicating and at what stage a product is along its cycle.

Table 4.2: ACLMessage performative types

	Protocol	
Parameter	ContractNet	Requests
Request		✓
Refuse	✓	✓
Agree		✓
Failure	✓	✓
Inform-done	✓	✓
Inform-result	✓	✓
CFP	✓	
Propose	✓	
Reject-proposal	✓	
Accept-proposal	✓	

4.2.3 Agent to Hardware

To interface with the hardware, an agent must call the "executeSkill" method of the Module Engine. In its parameters it should send the skill as a String. The ME will then call the "ExecuteSkill" of the LL loaded by it. All Link Libraries must contain the method "ExecuteSkill", otherwise calling it would be impossible. This method is implemented by the abstract class "LinkLibrary", as described in 4.1.9.

The LL will now forward the skill through the protocol it is implementing, in whatever format it was designed for. A developer could reformat this message to whatever type they want, to adapt to the hardware if needed, but the LL must always return a result of type String. As long as these rules are obeyed, Link Libraries can be used in the way most suitable to the system they are in. The result is passed to the ME as a String, which is then passed to the agent.

Three Link Libraries were implemented, seen in 4.1.10. The HTTP LL works by creating an HTTP connection, every time a skill is to be executed, using the address provided in the configurations. It sends the skill as a payload in a POST request. It then waits for an OK message with code 200 as per the HTTP protocol.

This response must include the result of the operation that is converted into a String and passed upward to the ME. This LL does not need to disconnect from the HTTP server, since this protocol does not depend on a persistent connection.

The implemented MQTT LL needs more parameters to work. It requires an MQTT broker address, a Quality of Service (QoS) value, a request topic and a response topic. These topics are differentiated to allow for a simpler implementation of the LL.

When the LL is loaded, it immediately establishes a connection to the broker and subscribes to the response topic. This means that every time a response arrives, the callback function is called. This function simply stores the message as a String.

Whenever the "ExecuteSkill" method is run, the LL will publish the skill in the request topic. It then waits until the response topic gets a message. Upon receiving it, it will return it to the ME. When this LL needs to disconnect, it just disconnects from the broker.

The OPC UA LL is a bit more complex than the other two. It also needs a server address, or endpoint, and a namespace. This namespace identifies which container the node representing the hardware is. In this node, two variable nodes are found, one for incoming requests and one for outgoing responses. To summarize, the LL needs and endpoint address, a namespace, the identifier of the request node and the identifier response node.

When the LL is loaded, it immediately connects to the OPC UA server and creates two node objects locally with the namespace and identifiers, one with the request and one with the response identifier. It also creates a subscription to the responses node.

When a skill is to be executed, first the response node is cleared, to make sure the LL gets notified of a new message. Then the skill is written to the requests node. The LL waits until a response arrives and when it does it saves it and clears the requests node for the next cycle of communications. The result message is sent to the Module Engine to be returned to the agent.

4.3 Multi-agent System Operations

With the whole system now defined, a review on how it operates is going to be presented. Before the system can be started, the marketplace file needs to contain the names and paths of the Link Libraries the MAS is dependent on.

When the MAS is first executed, both the Deployment Agent and Product Manager are launched. These agents will run their own setups.

The PM will run its "setup" method. It will look into the "Constants" class and find what Product Agent are setup there and create buttons that correspond to each PA. It will setup the container where product agents will be deployed and draw the GUI.

The DA will also run the "setup" method. It will try to find a marketplace file and list the Link Libraries there listed by running the "getMarketplaceLibraries" method. Then the agent container is created and the interface will be setup with it own default values and drawn to the screen. The system is now ready to launch agents.

Figure 4.12 starts when the system is first executed. It shows the steps and methods until it is operational. Since no more agents are running at this point, only the DA and PM are shown.

Before any product can be produced however, a human operator needs to deploy the Resource Agents and Transport Agents that compose the system.

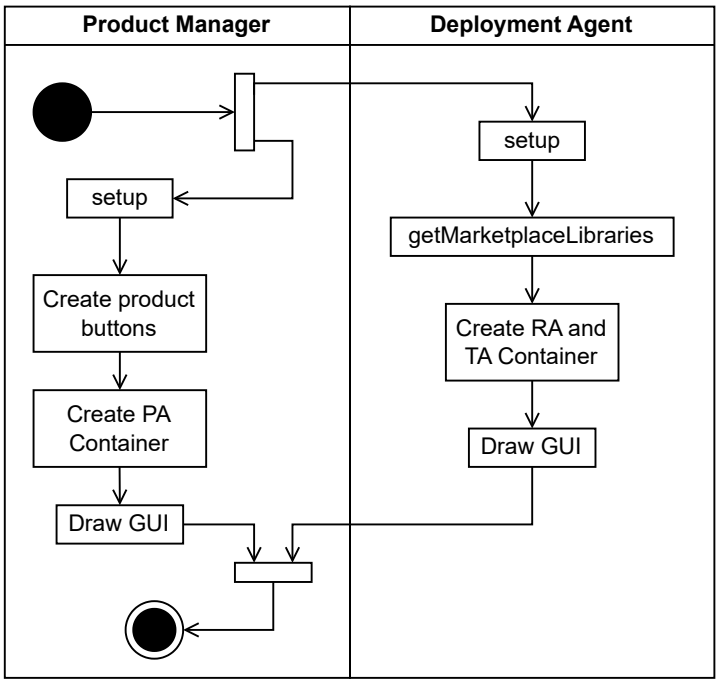


Figure 4.12: Multi-Agent System startup.

4.3.1 Initial Setup

Resource Agents and Transport Agents agents need to be deployed through the DA. From the available Link Libraries, the operator will chose which one needs to be launched with the agent to interface with the hardware. This LL must have been previously developed according to the specifications so it is compatible with the Module Engine, and its name and file path added to the marketplace file. Upon selecting an LL, the corresponding configuration file for this agent must be selected. Then the agent must be given a name and its type selected. Now the agent can be deployed by pressing the "Start Agent" button. This process now needs to be repeated for every agent, until all the agents have been launched.

When an agent is launched, its "setup" method is run. In it the agent will start the ME with the LL of the type selected, with the configurations provided to it. It will create a Link Library object by getting all the Link Libraries in the marketplace file with "parseMarketplaceXML" and create an LL object with "createObject". This LL will now connect to the hardware if needed, in its constructor. The agents registers itself in the DF using the method "RegisterInDF". Then the first behaviour is added to the agents operating sequence. In the case of the RA, it will be the "contractNetInitiator" and the "requestResponder". In the case of the TA, it will only be the "requestResponder".

Figure 4.13 shows this process for either a Resource Agent or Transport Agent. In the case of the RA, the "contractNetInitiator" behaviour needs to be added as well. The DA is omitted here for simplicity, since it would only deploy the agent.

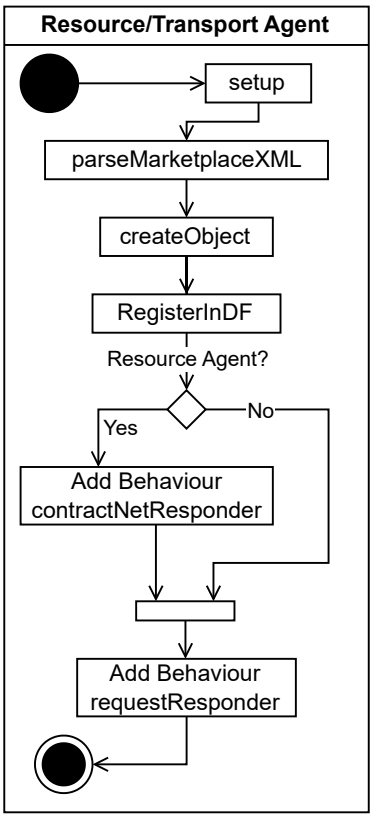


Figure 4.13: Agent startup.

With the MAS now built, new products can be launched by pressing the corresponding button in the PM.

4.3.2 Launching a Product

When a product is deployed, it will get its production sequence from the PM and set its own location as the starting position. It then will add the "executeNextSkill" to the behaviour sequence. This behaviour is executed immediately, its "action" method run, and it will search in the DF, using "DFInteraction", for an agent capable of performing its first skill. Upon finding it, it proceeds to send a Call for Proposals to all found agents.

For this the "contractNetInitiator" class is added to the behaviours and communications are established. Upon receiving a message, the RA runs "handleCfp" which generates a proposal. The PA receives it in "handleAllResponses", picks one if there are multiple and answers it. "handleAcceptPorposal" from the RA Informs the PA of its location. Finally "handleInform" in the PA looks for a transport agent in the DF.

Now the product will ask the found TA for transportation using the "requestTransportMove" class. This starts the FIPA Requests protocol and after the TA gets the first message through "handleRequest" it creates an Agree message that is forwarded to the PA and immediately starts the "prepareResultNotification", which executes the skill through the ME and provides a result as an inform message.

The Module Engine, on receiving the skill in its "executeSkill", will execute the "ExecuteSkill" method in the LL. Depending on the Link Library, the message might be sent through different channels, explained in 4.2.3. When the skill finishes execution, the result is sent back to the TA, which Informs the PA of it completion.

The PA now updates its location and initiates another FIPA Requests communications with the class "requestStationSkill". This follows the same logic as the transportation requests, but with a Resource Agent instead.

After being informed of the skills execution, the "handleInform" method increments the "step" field, which represents the execution step in the skill sequence", an checks if there are more skills to be executed. If there are, it adds a new "executeNextSkill" to the behaviour sequence and the process restarts. If there are not, the transport agent is requested again through "requestTransportMove", but this time to the deposit location in the MAS, defined in the "Constants" class. After the move is complete, the agent will terminate itself.

In Figure 4.15, at the end of this chapter, normal system operations can be observed. The diagram specifies which class executes what method. If no class is specified then it is the agent class. The ME has been initialized at this point and only needs to execute skills. All agents have been registered to the DF and the PM as been omitted since it would only launch the Product Agent.

4.3.3 Removing Agents

When a Resource Agent or Transport Agent needs to be removed from the MAS, the agent needs to be selected from the DA window and the "Stop Agent" button pressed. This will stop the corresponding agent by running its "takeDown" method. This method will in turn run the "shutdown" Module Engine method, which will run the "Stop" LL method.

The LL will disconnect from the hardware and the agent will remove itself from the DF. Finally, the agent will be terminated. This process is shown in Figure 4.14.

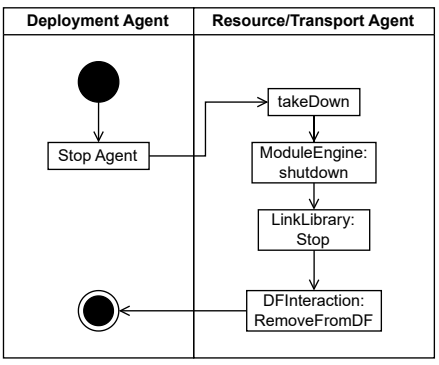


Figure 4.14: Agent termination.

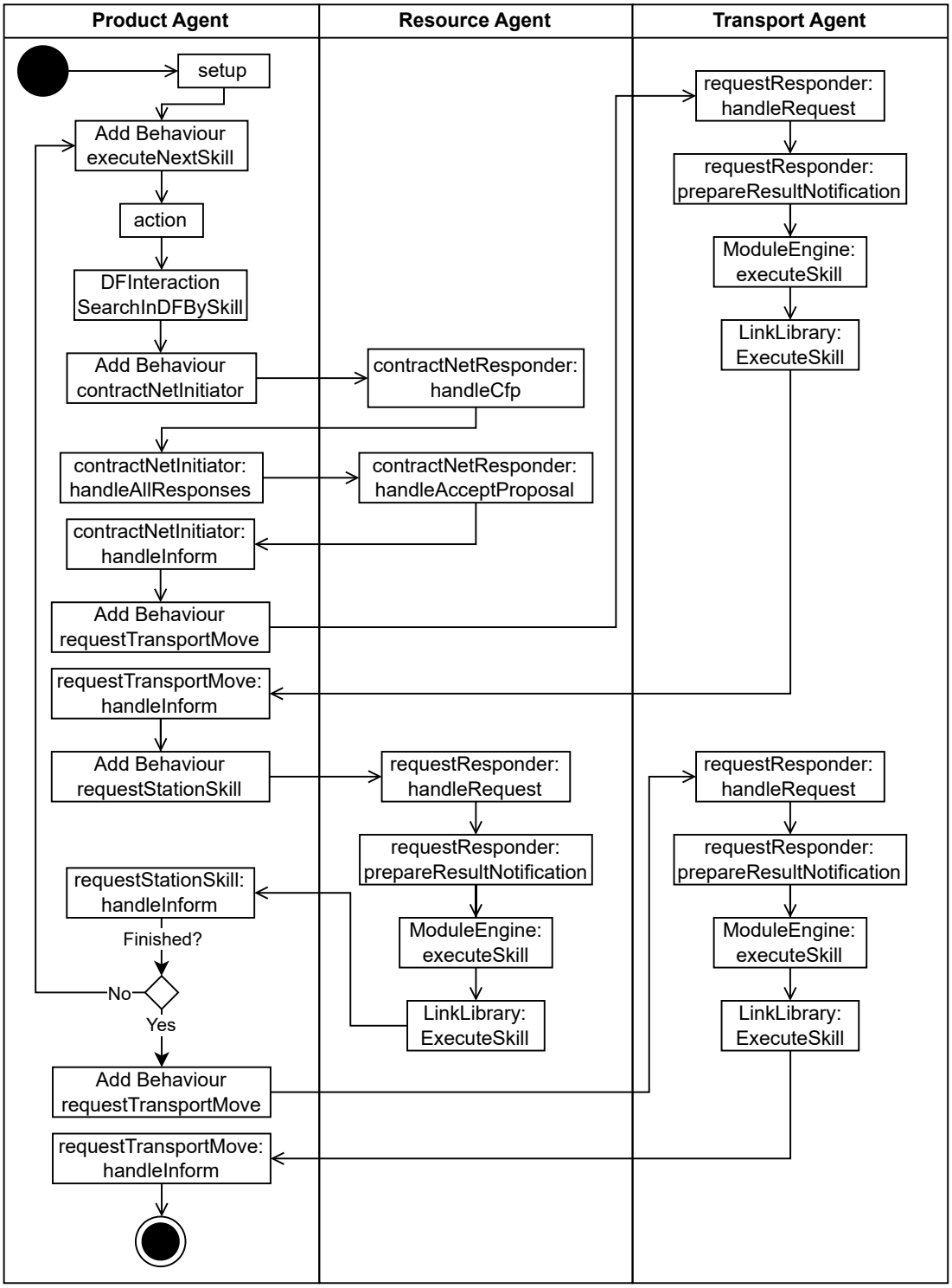


Figure 4.15: Multi-Agent System operations.

5

Tests

With the implementation done, it is time to test the system. First, a few performance tests were executed to ascertain the efficiency of the Module Engine when compared to a standard implementation. Agent deployment times and skill execution times were measured and compared. A brief explanation of the physical system used to simulate a production line is given. Then the tests on this system are described. Finally, a few deployment and skill execution tests are described to ascertain the efficiency of the ME.

5.1 Performance Tests

The performance tests were done on a machine with an AMD Ryzen 7 5700X processor and 32 gigabytes of RAM.

5.1.1 Deployment Test

The first test is the deployment test. In it, an increasingly amount of agents are launched to measure how long it takes to launch each agent. An agent using the Module Engine and a normal agent are compared to ascertain how much the ME impacts agent launch times.

This test was repeated three times, the first a single agent of each type is launched, the second ten agents of each type are launched, and the third a hundred agents are launched. Measurements are made by starting a timer when the "setup" method of an agent starts, and then stopped once the setup finishes. An agent running the Module Engine should take longer since it needs to get the parameters from the deployment entity and needs to instantiate its ME and wait for the LL loads before it finishes setup. The comparison is made between an agent that needs to follow these procedures versus and agent that does not. The times are written to a file that gets read to extract the values and calculate results.

As expected, and agent using the ME takes more time before it is ready to operate. The single agent took around 15 milliseconds to launch. An agent without the ME took around 0.0016 milliseconds.

Ten agents with the ME took 17.5 milliseconds total, with an average time of 1.75 milliseconds for each agent while the agents without took 0.0018 milliseconds total, with an average of 0.00018 milliseconds per agent.

Finally, a hundred agents with ME needed 799 milliseconds, with an average time of 7.99 milliseconds per agent. The other agents needed 0.0658 milliseconds, with 0.000658 milliseconds per agent.

Although the launch times increased considerably, it must be taken into account that the agents with the Module Engine had a longer setup. This involves getting all the parameters needed to operate, instantiating the ME, finding and loading the LL. Even though the time it takes for setup to complete is higher, for an agent making use of the ME, it is still under acceptable values for deployment, since none have too great a magnitude.

Table 5.1: Deployment times.

Number of agents	with Module Engine		without Module Engine	
	Total	Average	Total	Average
1	15 ms	15 ms	0.0016 ms	0.0016 ms
10	1.75 ms	17.5 ms	0.0018 ms	0.00018 ms
100	799 ms	7.99 ms	0.0658 ms	0.000658 ms

5.1.2 Execution Test

The second test is the skill execution delay test. Here, a skill is executed through the Module Engine. A special Link Library was developed for this test, and its only function is to return a String to simulate the result of a skill. This result is then written on the console. The execution time of this operation is compared to the time it takes for the system to write the same message to the console, without going through the ME.

This test was repeated sixty times, the five best and worst results excluded from the measured values to control for variations. The average time was calculated and compared. The operation without the ME takes an average time of 0.012576 milliseconds. The operation with the ME takes an average time of 0.028976 milliseconds, also less than a millisecond.

The difference between executing with the ME is around 0.0164 milliseconds, when compared to executing without. It takes almost double the time for the message to be written. This was expected since there are more operations occurring with the ME. Even though execution time does increase, it still is well under a millisecond, so the impact caused by the Module Engine and Link Libraries is not huge, making it a viable option for most applications.

Table 5.2: Execution times.

	with Module Engine	without Module Engine
Time	0.028976 ms	0.012576 ms

5.2 Case Study

The MAS was simulated on a physical system composed of a conveyor belt and two processing stations. The conveyor belt is divided into four sections, each with their own sensor. This means that products can stop in the middle of any of the four sections. They are also independent, meaning that they can move and stop individually. The stations can move forward, backward, up and down, and their tool spins to simulate the execution of a skill. This model is illustrated in Figure 5.1.

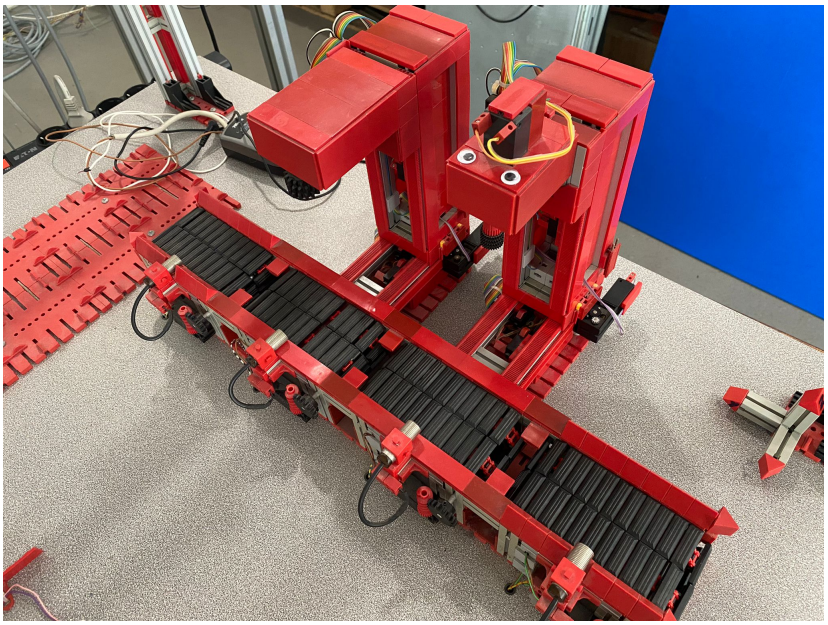
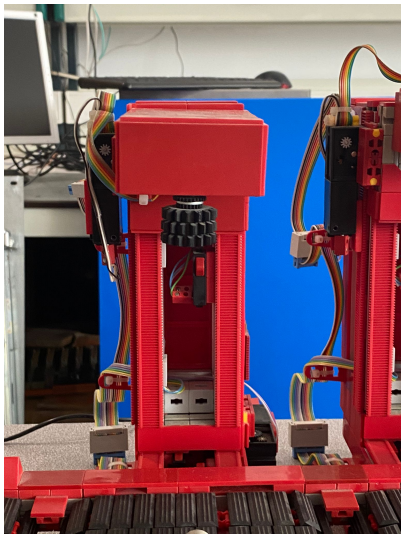


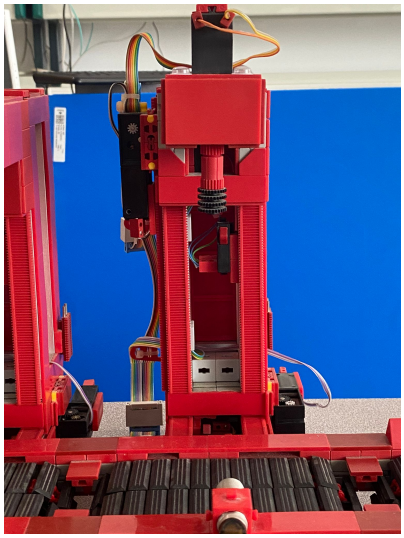
Figure 5.1: Simulation kit.

Each element of this system can be represented by an agent. The conveyor belt fits the definition of a Transport Agent and both stations can be Resource Agent. All of these entities were defined in the "Constants" class, the TA as "Conveyor" and both stations as "Station_3", for the station on the left (Figure 5.2(a)), and "Station_4", for the station on the right (Figure 5.2(b)).

Both stations are able to perform a skill. To reduce complexity, each station was attributed a single unique skill. "Station_3" is able to perform "Skill_A" and "Station_4" can perform "Skill_B". Both of these were also defined in the "Constants" class. These skills are registered by the respective agent in the DF. The act of performing the skill corresponds to the device moving forward, activating its tool for about three seconds and then moving to the starter position.



(a) Station 3.



(b) Station 4.

Figure 5.2: Kit stations.

The "Conveyor" agent is capable of performing the skill "Skill_Move", also defined in the "Constants". This is the skill with which the agent registers itself in the DF. When a Product Agent needs transportation, it must send a message to the "Conveyor" agent through the aforementioned channels in the format "CX#TOKEN#CY". Here, X represents the source location and Y represents the destiny location. The conveyor is split into four segments, numbered one to four from the left to the right. Each segment has a sensor that detects whether or not a product is on it. So the instruction "C1#TOKEN#C3" makes the conveyor turn the first, second and third segments to the right. Similarly, the instruction "C3#TOKEN#C2" makes the conveyor turn the second and third segments to the left.

A RevPi running an instance of NodeRED was used to control the system, its inputs and outputs connected to the conveyor and stations. A RevPi is a Raspberry Pi equipped with an shield board that allows it to interface hardware, like sensors and actuators. This RevPi was hosting the NodeRED instance, and it depended on an official RevPi NodeRED library to control the physical system.

NodeRED is an open source programming tool, capable of integrating hardware. It works by connecting nodes, which send messages to other connected nodes to complete processes. These groupings of nodes are called flows. Three flows were created, one for each cyber-physical entity. These flows are capable of receiving messages in HTTP, MQTT and OPC UA, and return the result through the same protocol. Figure 5.3 shows the developed nodes. It also shows the OPC UA server that was needed for OPC UA communications. The MQTT broker was hosted on a different machine.

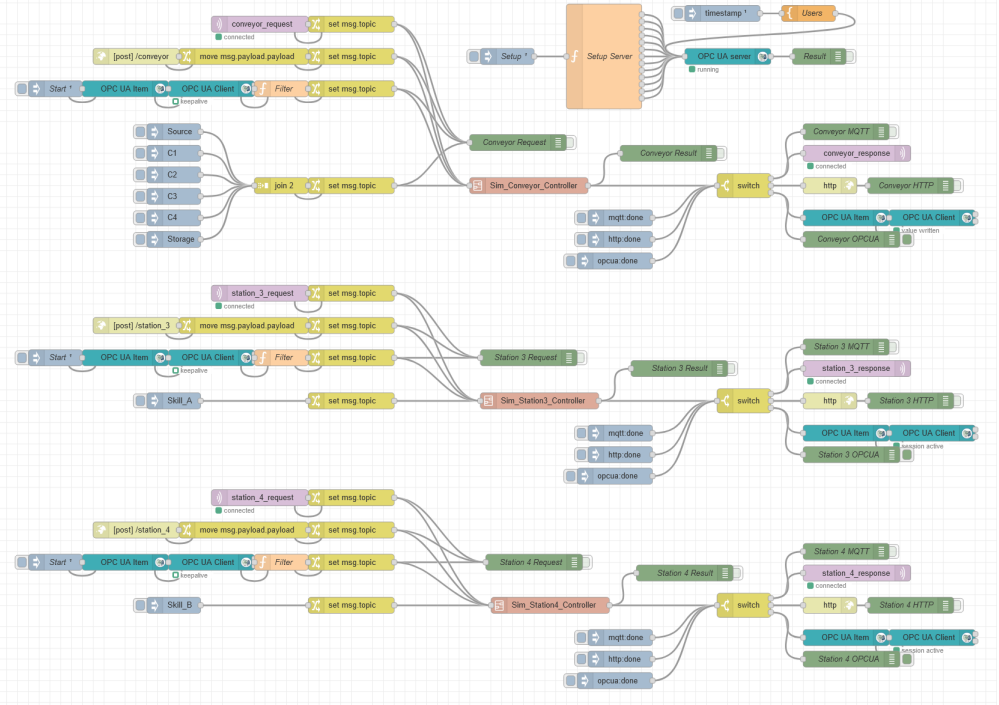


Figure 5.3: NodeRED flows.

Three configuration files were created, one for each cyber-physical entity. A single file contains the configurations needed for the three developed Link Libraries. Table 5.3 shows the configurations for the MQTT protocol and Table 5.4 for OPC UA. The address field is not shown as well as the configurations for HTTP since the only element therein is the server address.

Table 5.3: MQTT configurations.

	Station_3	Station_4	Conveyor
Quality of Service	2	2	2
Request topic	station_3_request	station_4_request	conveyor_request
Response topic	station_3_response	station_4_response	conveyor_response

Table 5.4: OPC UA configurations.

	Station_3	Station_4	Conveyor
Namespace index	1	1	1
Requests identifier	Station3_Req	Station4_Req	Conveyor_Req
Response identifier	Station3_Res	Station4_Res	Conveyor_Res

To simulate the system, both NodeRED and the MAS systems were launched. The Product Manager and Deployment Agent are immediately deployed, finish their initial setup explained in 4.3.1 and wait for agents to be launched. After this, the two Resource Agents were launched through the GUI, "Station_3" and "Station_4", with their respective configurations. Along with those agents, the "Conveyor" Transport Agent is also launched,

also with its configuration file. At first, all agents are using the LL that communicates through MQTT, and thus the configurations for this protocol are used. These agents are connected to the broker on launch, and will communicate to the corresponding topics.

After the agents were done with their initial setups, a product agent was launched. For the purposes of showcasing the systems capabilities, three different Product Types were created. These products are shown in 5.5, along with their production sequences and the sequence of Conveyor Belt sections they need to visit in order to complete their process. All of these values were also defined in the "Constants" class.

Table 5.5: Product Types.

Product Type	Production Sequence	Location Sequence
A	[Skill_A]	[C1; C2; C4]
B	[Skill_B]	[C1; C3; C4]
C	[Skill_B; Skill_A]	[C1; C3; C2; C4]

All three product types were launched, one at a time. Product A was first, and the system was able to complete the production sequence without any problems. The product first went to Station 3, the station applied the skill, and then moved on to storage. The other two products followed a similar result, their production sequence executed as planned. This means the Module Engine was working as intended. Even though it wasn't hard-coded to the MQTT protocol, it was able to use the Link Library that integrates it to communicate to the machines.

To further test the ME, "Station_3" was taken down and restarted, this time with the HTTP Link Library. The same procedure was performed, with the same result. No noticeable difference was observed in the three products sequences. The ME was once again integrating a new protocol.

The only difference noted was when OPC UA was used, the stations wouldn't respond as fast to the instructions. However, this was attributed to the fact that the RevPi was running both the OPC UA server and the NodeRED instance, overloading its processor. This could easily explain the delay observed. Despite this, the ME was also capable of integrating this protocol.

Many combinations of the three protocols were used, with the same results. The Module Engine was integrating all three protocols as if it was hard-coded with them. The Link Libraries developed were acting as interfaces between the ME and NodeRED, but this interface could be replaced at any point to integrate new hardware.

This outcome was expected, since through the use of the Reflections feature of the Java programming language, a class can be loaded during runtime as if the program was compiled with it. Some kind of delays were to be expected, since there are extra instructions running in the background due to the Module Engine serving as an intermediary between agent and Link Library, but their impact is minimal, since the ME is fairly lightweight.

6

Conclusion

The concept of Industry 4.0 revolutionized the manufacturing sector through the digitalization of manufacturing processes. Industrial Cyber-Physical System or Cyber-Physical Production Systems enable the transition to the Industry 4.0 standard. These systems are service oriented, can process Big Data and have cloud integration for storage.

They are also able to interface with the real world, by using sensors, and to act on it, by using actuators. In essence these systems are composed of two counterparts, a physical one and a digital one. This makes them very robust and efficient, since they rely on the digital version to extract information on how to act on their environment.

Industrial Multi-Agent System were suggested as a model for the implementation of a Cyber-Physical Production System due to the advantages they could bring to the industry, such as the decentralization of the system, allowing for the autonomous behavior of each individual agent to accomplish a common goal. This makes the system very robust and flexible because errors don't propagate throughout the different layers of the system and agents can join and leave the system as needed. They, however, have not seen practical uses outside research prototypes. This may come from the skepticism that they won't perform to the same capabilities as existing systems.

In this work, a method to facilitate the integration of Industrial Multi-Agent System was presented. The Module Engine and Link Libraries combo allow for a faster and easier development, when compared to traditional hardware interfaces. These Link Libraries could be developed to support all kinds of protocols and hardware, facilitating the integration of a Cyber-Physical Production System.

The prototype presented in this work shows a lot of promise, with minimal drawbacks to performance, it is a great alternative to the methodologies employed nowadays for the integration of hardware on a Multi-Agent System. It could be improved in many ways, like the ability to change Link Libraries without having to terminate an agent or by creating a web application capable of providing and updating Link Libraries remotely and automatically. Still, this kind of framework is a step in the right direction of the wide adoption of Multi-Agent System with industrial applications.

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