

## Article

# Communication and Control of an Assembly, Disassembly and Repair Flexible Manufacturing Technology on a Mechatronics Line Assisted by an Autonomous Robotic System

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**Abstract:** This paper aims to describe modeling and control in what concerns advanced manufacturing technology running on a flexible assembly, disassembly and repair on a mechatronic line (A/D/RML) assisted by an Autonomous Robotic System (ARS), two robotic manipulators (RM) and visual servoing system (VSS). The A/D/RML consists of a six workstations (WS) mechatronics line (ML) connected to a flexible cell (FC) equipped with a 6-DOF ABB industrial robotic manipulator (IRM) and an ARS used for manipulation and transport. A hybrid communication and control based on programmable logic controller (PLC) architecture is used, which consists of two interconnected systems that feature both distributed and centralized topology, with specific tasks for all the manufacturing stages. Profinet communication link is used to interconnect and control FC and A/D/RML. The paper also discusses how to synchronize data between different field equipment used in the industry and the control systems. Synchronization signals between the master PLC and ARS is performed by means of Modbus TCP protocol and OPC UA. The structure of the ARS consists of a wheeled mobile robot (WMR) with two driving wheels and one free wheel (2DW/1FW) equipped with a 7-DOF RM. Trajectory tracking sliding-mode control (TTSMC) is used to control WMR. The end effector of the ARS RM is equipped with a mobile eye-in-hand VSS technology for the precise positioning of RM to pick and place the workparts in the desired location. Technology operates synchronously with signals from sensors and from the VSS HD camera. If the workpiece does not pass the quality test, the process handles it by transporting back from the end storage unit to the flexible cell where it will be considered for reprocessing, repair or disassembling with the recovery of the dismantled parts. The recovered or replaced components are taken over by the ARS from disassembling location and transported back to the dedicated storage warehouses to be reused in the further assembly processes.

**Keywords:** programmable logic controller; modbus TCP; open platform communications; visual servoing system; wheeled mobile robot; industrial robotic manipulator



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## 1. Introduction

The continuous development of software and automation in industrial environments brings new concepts for communication, design and control for manufacturing technology. There is a growing need for high-speed robotic assembly and transport of small parts, which often means higher throughput and greater precision than can be achieved using human labor [1].

This study focused on the implementation, simulation and system design of the hybrid communication and control for the advanced flexible manufacturing technology presented on a laboratory system that integrates several subsystems and different field equipment and autonomous robotic systems (ARSs) [2]. A fully automated assembly line assisted by mobile robots is still in its early stages and is not yet widely used. ARSs are extremely flexible because once the facility map is built, they can travel from one destination to the next, autonomously avoiding obstacles along the way, unlike conveyor systems that have limited flexibility, and are quite expensive and time-consuming to reconfigure [3].

The objective of this research is to introduce a new perspective upon the framework of manufacturing technology design where implementation and setup was based more on engineering experience and less on simulations, investigation and validation methods to increase efficiency and to evaluate the performance of the manufacturing lines assisted by ARS [4].

The main elements of originality and contributions are concentrated in the following areas: task scheduling and assigning; planning and synchronization of A/D/RML assisted by ARS, RMs and VSS; Petri Nets modeling; hardware architecture design of the entire system to allow flexible manufacturing, communication concepts, supervisory control and data acquisition (SCADA) [5]; implementation and network topology, synchronization of signals from sensors and between subsystems, distributed control and image processing for precise positioning; VSS and real-time control for implementation of a fully automated manufacturing technology; improving the automation level; security; and increasing the efficiency by using the ARS IRM with VSS technology [6,7]. The presented flexible manufacturing concept allows the assembly of two different products and complete disassembly or repair of the products depending on the quality test. Disassembled components from the rejected products are recovered by ARS and placed back in the designated storage compartments. The recovery process implementation allows the reuse of the products subcomponents through reprocessing, technology that works automatically, completely independent without the operator intervention, increasing efficiency, productivity and safety [8].

The presented technology for flexible assembly, disassembly and repair with components recovery, consists of an assembly/disassembly mechatronics line (A/D/ML), a flexible cell (FC), which is an assembly/disassembly station with an integrated 6-DOF industrial robotic manipulator (IRM), and an ARS which is a WMR equipped with a 7-DOF RM and an eye-in-hand visual servoing system (VSS) [1,2]. Along with the communication concept and real-time implementation, several aspects will be discussed regarding the design of the flexible manufacturing technology, such as: task planning, hybrid modeling, simulation, sensors and actuators, interoperability between field level devices, synchronization, data acquisition, remote monitoring and control [9].

An assembly/disassembly and repair flexible manufacturing line (A/D/R/ML), consists of the following subsystems: IRMs, WMRs, workstations and manufacturing cells, component storage units, transporting system (conveyor belts) and monitoring, control and data acquisition systems, able to perform specific tasks for manufacturing technology such as product assembly, quality check and repair or disassembly operations with components recovery, including a reconfigurable manner that confers reversibility, repeatability, and last but not least, flexibility [3]. The main idea of flexibility added to a manufacturing line, a FML (Flexible Manufacturing Line), means a technology capable to automatically manufacture different products, in small or medium batches, without adding hardware changes or the complete redesign of the system.

The automatic control of all system components and automatic supervision, controls and diagnosis is performed with the help of two PLCs in a hybrid hardware architecture for controlling all the subsystems of the complete A/D/RML and managing the process and operation facilities, thereby coordinating control tasks as well as synchronizing the operations of the ARS with process timings [10]. On top of that, for controlling assembly/disassembly and repair for the flexible manufacturing line, the algorithm architecture is agent-based

control, in which the PLC from the FC station acts as a main control unit, or “master PLC”, for centrally managing both subsystems of the complete A/D/RML by means of synchronization and confirmation signals [11]. Therefore, master PLC synchronizes with subsystems PLCs to automate their respective areas and for operating and controlling locally their components, after confirmation from the main control unit is applied.

The presented hardware structure includes two Human-Machine Interfaces (HMI) as operator control panels for both major subsystems (A/D/ML and FC) and a SCADA application running on the Remote PC as the main visualization, control and data acquisition system. The information to perform the flexible manufacturing process tasks is obtained from the system using IO Field Devices such as sensors, cameras, measuring devices and transducers and is processed by the PLCs and interfaced via a communication link with Remote PC or SCADA [5].

Industrial development has been evolving rapidly, bringing new smart technologies to automation systems and becoming more dynamic and adaptable production systems. Visual servoing is a commonly used technology in combination with RM and works by processing and implementing the results obtained from several research fields such as real-time image analysis and processing, robotics, control theory and systems and real-time application design. Therefore, a visual sensor—an HD camera—is connected on the end effector, “the eye” of the RM, which allows the visual inspection and investigation of the working environment without contact with its elements. VSS behavior is mainly influenced by the type of visual features used to generate control law [12]. There are several VSS control architectures corresponding to the servoing systems; in this approach, the Hybrid Visual Servoing (HVS) architecture is used for driving the mobile VSS mounted on the ARS robot manipulator [13,14].

The rest of the paper is organized as follows: the proposed hardware technology of the A/D/RML assisted by ARS is presented in Section 2.1 describing FC, ARS and eye-in-hand VSS control architectures; in Section 2.2, Petri Nets modeling is presented and also task planning and scheduling for each of the flexible manufacturing operation; in Section 2.3, the communication concept of the A/D/RML assisted by ARS is described; real-time control results for assembly, disassembly and repair operations are shown in Section 3; Section 4 provides a vision of the experimental laboratory level A/D/RML assisted by ARS, discusses the real-time control results and highlights the laboratory tests limitations of the study and Section 5 is reserved for final conclusions of the approach from this research paper, draws the main research findings and gives an insight to future directions for research/recommendations.

## 2. Materials and Methods

### 2.1. A/D/RML Assisted by ARS Technology

#### 2.1.1. Hardware Structure of A/D/RML

An experimental A/D/RML assisted by ARS is developed at the laboratory level that works in real-time, for testing purposes and for the implementation of different methods and techniques for analyzing, optimizing and manufacturing line balancing, to study the actual technology and improve efficiency, reliability and precision. Figure 1 shows the basic design concept of the A/D/RML, consisting of 3 major subsystems, which operate, communicate and synchronize together by means of PLCs and SCADA and act as a single flexible manufacturing line that performs several tasks such as assembly, the disassembly of 2 different products with reprocessing, repair and components recovery functionality.

The main A/D/RML hardware components are:

- Flexible Cell—separate station with ABB RM IRB120 6-DOF and components storage units used for assembly, disassembly and repair of the workpieces, with handling, processing and transport capability;
- A/DML mechatronics line-based on laboratory mechatronic system Hera&Horstmann, used for the assembly and transport of the workpieces with checking and storage facilities;

- ARS—WMR PeopleBot equipped with an RM Cyton 7-DOF used for recovery, transport and return operations for the dismantled components.

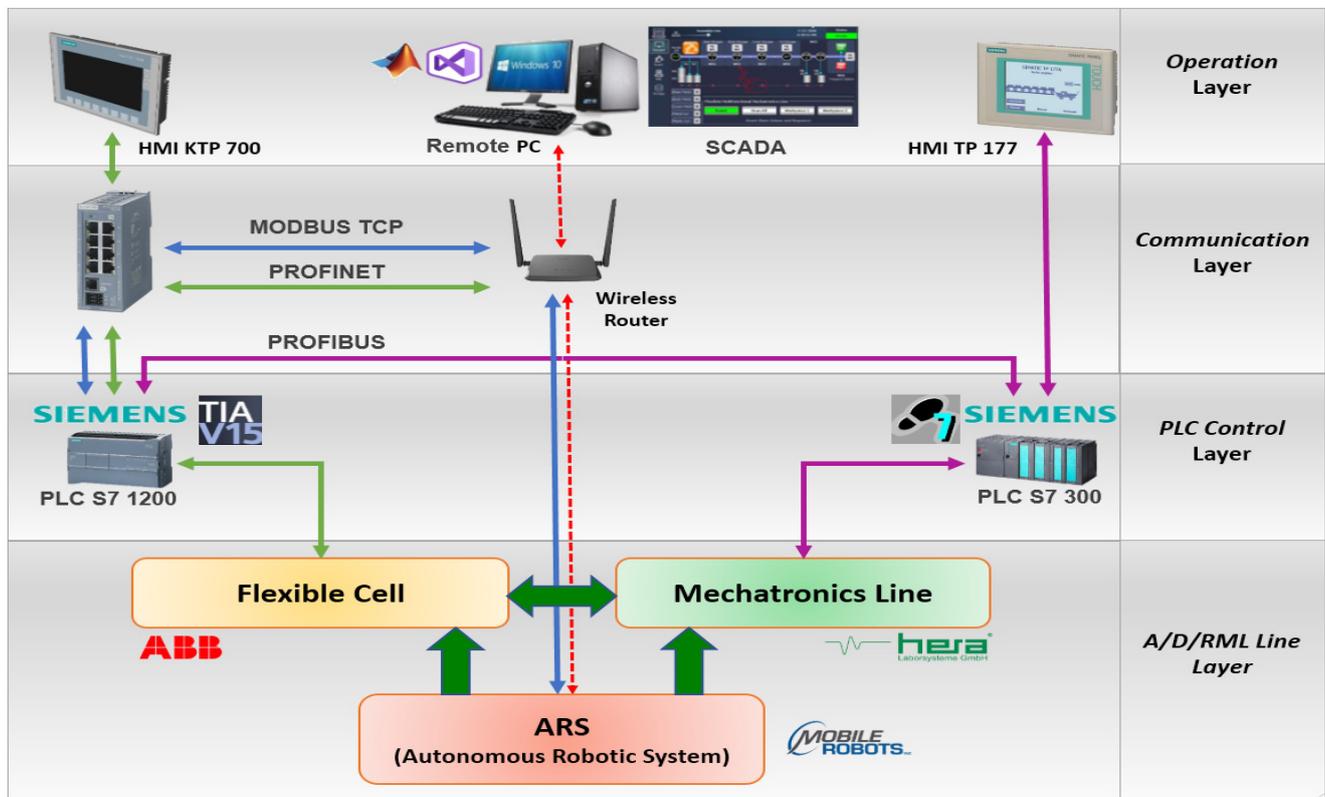


Figure 1. Structure of A/DML Hera&Horstmann and Flexible Cell ABB served by ARS.

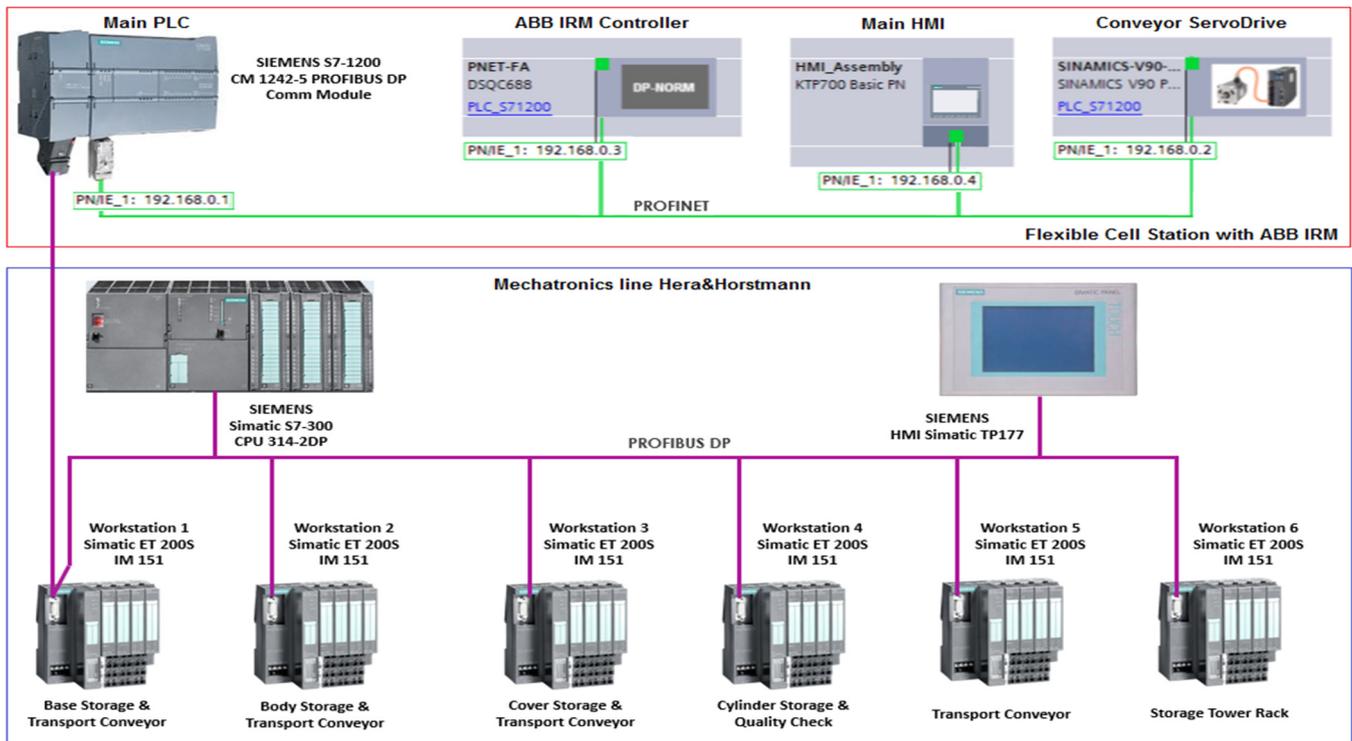
The A/D/RML, as described above, is characterized by a modular structure. The hardware structure consists of 2 Siemens PLC controlled subsystems/modules with specific tasks for all the manufacturing operations. FC is a RM pick-and-place station, Siemens S7-1200 PLC controlled assembly/disassembly station, positioned next to mechatronics line, which handles the supply of workparts, assembly and transport for workpiece product type 1 (WP1) on the manufacturing line, acting as a feeding unit and handles the disassembly and repair operation for workpiece product type 2(WP2) upon request. The Hera&Horstmann mechatronics laboratory line is a Siemens S7-300 PLC controlled subsystem that has a predefined role as a logistics unit that assembles individual workparts into workpiece product type 2(WP2), transports between workstations and stores the assembled workpieces on the final storage place—Storage Rack Tower.

The PLC-based hardware and software design architecture, as seen in Figure 2, is a hybrid structure that features both distributed and centralized topology:

- Distributed structure, by means of separate, individual PLC control for both FC and mechatronics line, to automate their respective areas with visualization and operation facilities;
- Centralized architecture, where the FC station PLC, besides the local control role, acts as “master PLC” for centrally managing both subsystems of the complete A/D/RML, having process and operation facilities, thereby coordinating, controlling and synchronizing the operations tasks with the ARS.

Each PLC hosts several routines for automatic control but the manual, initial task for choosing and starting the manufacturing process operation is made remotely from SCADA or locally from HMIs. The assembly/disassembly and processing/reprocessing routines are managed strictly through Siemens S7-1200 PLC from the FC, which acts as a Central

System that handles visualization and manages the overall operation of the complete A/D/RML [15].



**Figure 2.** A/D/RML PLC Network hardware structure.

In the mechatronics line, Siemens S7-300 PLC communicates with the I/O field via Profibus (magenta line Figure 2). The Profibus link is used for communicating and the control of the transporting conveyor belts drives, workpiece positioning and PLC to PLC synchronization methods as well as for handshake and signal exchange interface with the FC by means of a Profibus adapter. An additional HMI (Siemens TP 177) is connected for process visualization purposes only. FC communication is based on the industrial Ethernet network Profinet technology (green line Figure 2) for communicating with the main HMI (Siemens KTP 700), ABB IRB120 Robot controller and Intelligent Siemens Servomotor Drives Sinamics V90 with accurate positioning control functionality. The compatibility between the FC and mechatronics line, by means of communication, is performed as mentioned before, via a Profibus adapter to bridge/interconnect the 2 different communication technologies: Profinet (protocol based on the Industrial Ethernet) and Profibus (protocol based on serial communication).

For disassembly or repairing tasks, pick-and-place and transport actions are performed by the ARS with the help of the Cyton RM, which is equipped. First, the FC station with the ABB robot dismantles or repairs the workpiece by replacing the bad components and sliding them on a specific tray. Then, the ARS system will grab the recovered workparts for transporting and place them into the designated storage ML locations. Several synchronization signals will be needed between the master PLC and ARS by means of the Modbus TCP protocol, a standard communications protocol widely used in industrial automation. These signals will be sent when the FC station has ended the repair/disassembly action and the dismantled component (workpart) is released and ready for recovery by the ARS. Synchronization acknowledgment signals will be returned when ARS is busy handling a task such as reprocessing/transport or when placing operation job is completed and ARS becomes available again.

For the developed technology, at the PLC level, several algorithms have been developed by using Siemens programming packages such as TIA Portal, Step7 Manager, as

well as WinCC Flexible for the HMIs. SCADA is developed on the Remote PC and also in TIA Portal. In both PLCs, modular programming is used; functions or function blocks are created as an entity, providing a particular functionality or controlling a particular type of device in the system (ABB Robot, conveyors motors, storage, electrical and pneumatic actuators). During each scan, the PLC reads all local and remote inputs, executes every function in a predefined order (using IRQ) and updates all outputs at the end of each scan. PLC programs and algorithms are mainly programmed with Structured Text (ST) or Structured Control Language (SCL) which, according Siemens, corresponds to the IEC 1131-3 language "ST". SCL opens up several new constructs that are unavailable while programming in conventional ladder logic, including the FOR and WHILE loops as well as the CASE statement. These are particularly useful when dealing with large amounts of data in an array form. Using SCL also increases the readability of any sort of arithmetic calculation. The instances of Function Blocks are executed in the cyclical order in every PLC scan (10–12 msec time range). An additional part of the PLC program is the Modbus TCP link between master PLC from the FC station (S7-1200 PLC) and ARS. For that a Modbus TCP Server is configured and programmed, as shown in Section 2.3.3, in the Main Routine of the Siemens master PLC at the beginning of the scan, prior to the program execution, to establish and maintain a stable connection and a quick data exchange/synchronization signals with the ARS.

As shown in Figure 2, a separate Profibus communication link is used to interface data between both PLCs. This data must be sent and received between the master PLC and Siemens S7-300 PLC via the Profibus communication adapter.

#### 2.1.2. Flexible Cell with ABB RM

Flexible Cell (Figure 3) is an Integrated ABB iRB120-Robot Training Station that consists of the following major components:

- RM ABB IRB120 6-DOF, with electric gripper;
- PLC Siemens S7-1200 series, CPU 1214C;
- HMI Siemens KTP700, Color Basic PN;
- Switch Siemens, SCALANCE XB005;
- Conveyor Belt, Sinamics V90 Servo Drive;
- Compact stack storage units for each workpiece component (\*S1 to \*S4);
- Unloading trays for workpiece component disassembly (\*WH1 to \*WH5).

The communication link is made with Profinet, protocol standardized in IEC 61158 and IEC 61784, which uses traditional Ethernet hardware and software to define a network that structures the task of exchanging data with PLC and all the above-mentioned devices. For the FC hardware structure, the following profiles are applicable:

- Profinet-IO, interconnecting the PROFINET device with any other fieldbus or industrial Ethernet network. Uses cyclic data transfer to exchange data between PLC over Ethernet with HMI, PLC CPU and ABB Robot Controller;
- PROFI drive, implemented for drives application scenarios, used in FC station to control the conveyor belt with Sinamics V90 Servo Drive.

ABB Robot Controller has the hardware capability to communicate with third party devices via Profinet protocol by means of a dedicated board AnybusCC Profinet slave (DSQC 688) on the ABB Robot Controller DSQC1000 (main computer) (Figure 4). With the Profinet Anybus Device option, the ABB IRM controller can act as a slave on the Profinet network.

#### 2.1.3. Mechatronics Line Hera&Horstmann

The laboratory mechatronics flexible line, from Hera&Horstmann (Figure 5), incorporates five individual workstations with different tasks; each of them handle the line operations in different stages of the manufacturing process such as handling and transport-

ing on conveyor belts, loading and processing workparts with pneumatic workstations, sorting and testing products and storage in the dedicated warehouse unit.

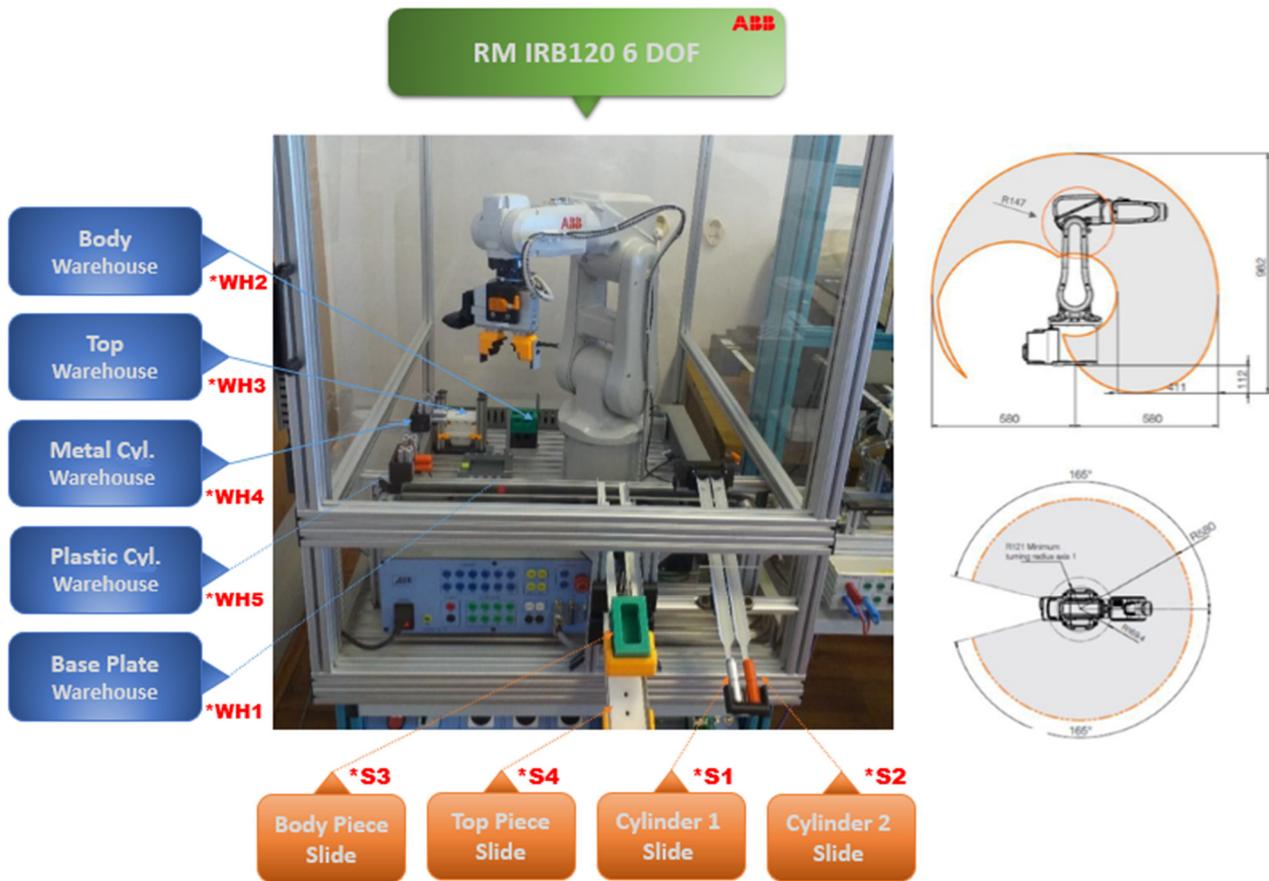


Figure 3. Flexible Cell Station with RM ABB IRB120 6-DOF.

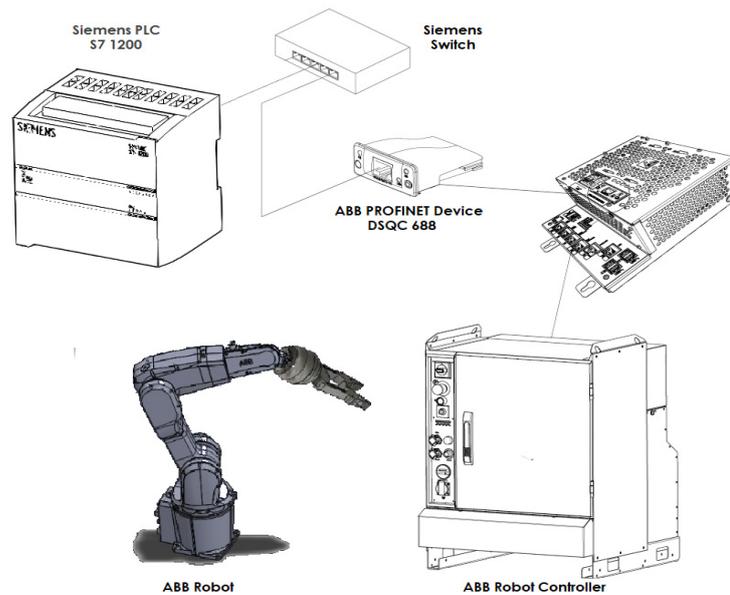
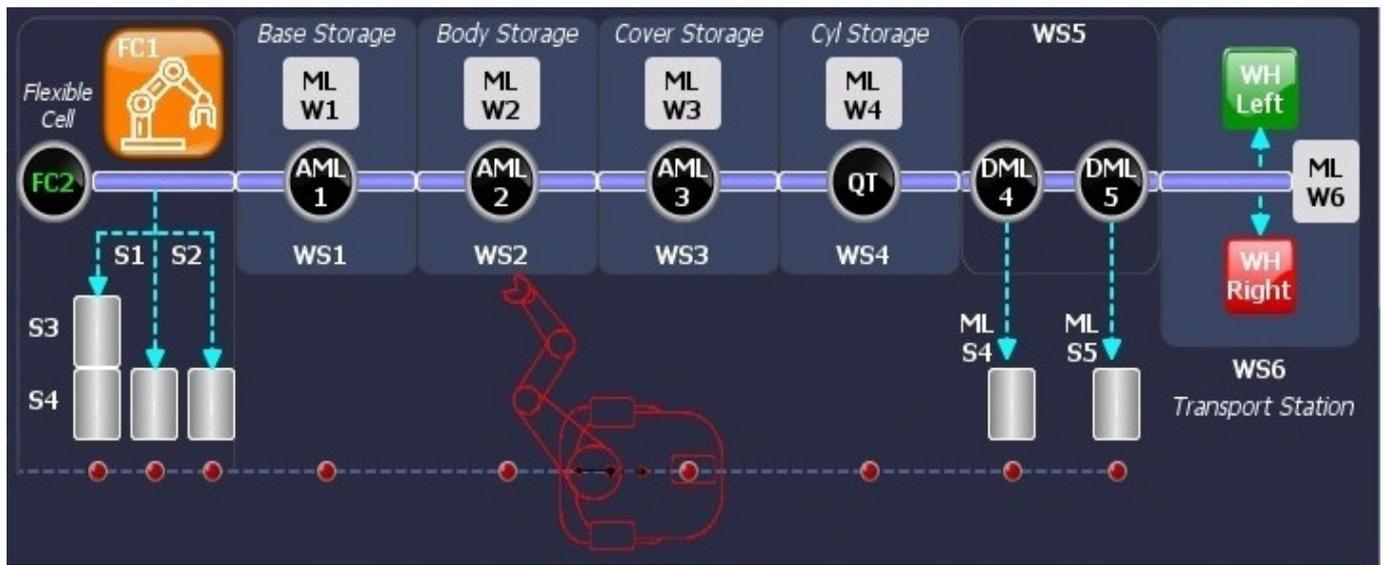


Figure 4. Profinet communication link between Siemens S7-1200 PLC and ABB Robot Controller.



**Figure 5.** Hera&Horstman assembly/disassembly mechatronics line.

The five-part workpiece enables the complete manufacturing process workflow operations such as assembly, testing, sorting, storage and disassembling. The workparts/components to be assembled into a single product are shown in Figure 6: workpart carrier (base platform), body, top or cover, metal cylinder and plastic cylinder. A/D/RML is a flexible manufacturing line by adding the capability of handling and processing batches of two different products, referred to as workpiece type 1 (WP1) and workpiece type 2 (WP2). WP1 is the workpiece with the triangular edges top part (Figure 6) and is assembled in the FC by ABB IRM. WP2 is the workpiece with round edges, top part (Figure 7a–c), and is assembled on the Hera&Horstmann ML.

The hardware structure of the ML presented on Figure 2 is based on a PLC distributed architecture, integrating the process peripherals such as signals and function modules in Remote I/O stations on the Profibus network, and consists of a Siemens Simatic S7-300 series PLC, processor type CP 314C-2 DP and Siemens CP 343-2 communication module for Profibus link.

Profibus DP interface uses predefined speed up to 12 Mbit/s and connects all 5 workstations and Storage Tower Rack, referred to as Workstation 6, through Remote IO's (Siemens ET200S communication modules), which improves adaptability and execution performance for the flexible assembly/disassembly technology framework inside this decentralized architecture design.

#### 2.1.4. Hardware Structure of the ARS

A/D/RML is served by an ARS, used for the recovery and transport/return operation of the dismantled components, which is a RM-equipped WMR. The ARS, shown in Figure 8, is composed of the following elements:

- 7-DOF Cyton 1500 RM equipped with an eye-in-hand VSS using a high-definition camera, both are connected to the Remote PC via Wi-Fi USB and synchronously communicating with the A/D/RML over Wi-Fi;
- WMR PeopleBot, which is a WMR with two driving wheels and one free wheel (2DW/1FW).

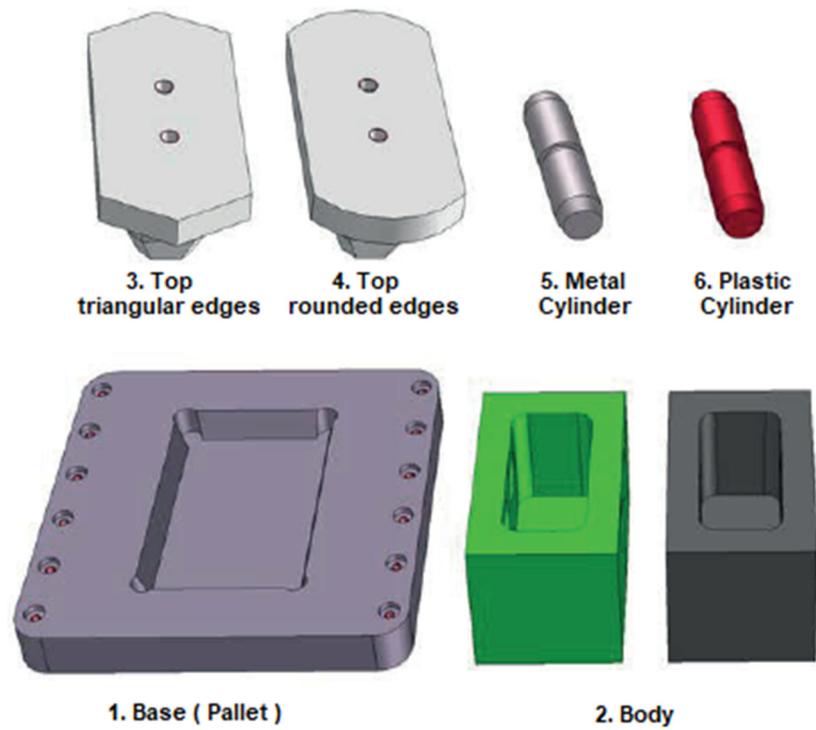


Figure 6. Five-part workpiece components.

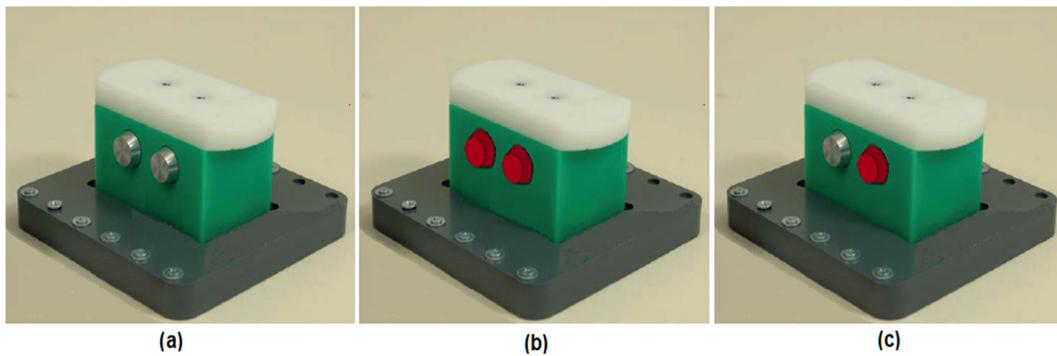


Figure 7. Assembled workpieces: (a) workpiece with metal cylinders; (b) workpiece with plastic cylinders and (c) workpiece with different cylinders.

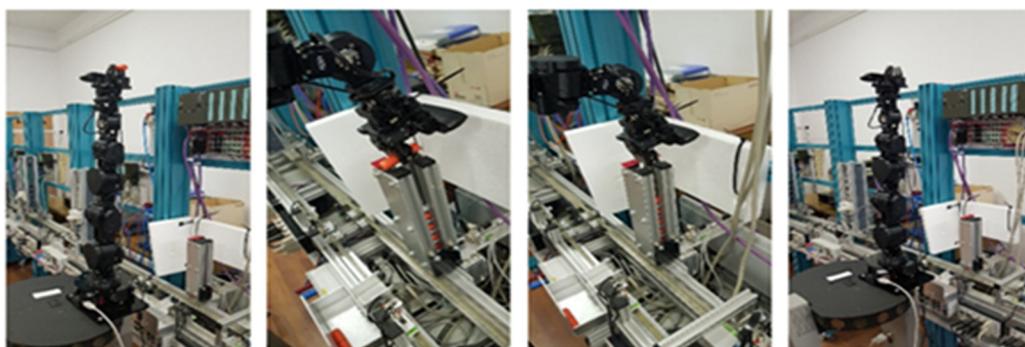


Figure 8. Real-time control of the ARS with RM Cyton.

The ARS is used to pick-and-place the recovered pieces with the help of Cyton 1500 RM in the appropriate storage depots if the assembled workpiece has failed the quality test and has been disassembled or repaired. The control of the ARS is carried out wirelessly

using a router that is placed inside the WMR through dedicated functions from Mobile Robots ARIA (Advanced Robotic Interface for Applications), running on the same Remote PC where Cyton RM is connected to.

#### 2.1.5. Eye-in-Hand VSS

In case workparts should be recuperated from the processed bad products, in disassembly and repair, synchronized tasks for pick-and-place actions are executed by ARS by grabbing the recovered dismantled components from the FC station trays. Therefore, ARS is equipped with an RM Cyton 7-DOF (degrees of freedom) with a gripper paddle and HD video camera on the end effector (Figure 8), connected both via Wi-Fi USB with the Remote PC.

For the moving and manipulation of the RM Cyton 7-DOF, signals from gripper video camera are processed, using eye-in-hand VSS technology. RM Cyton, ARS, HD camera and workparts (in this case, cylinders to be recovered) are shown in Figure 8. The eye-in-hand VSS is a system where the HD camera sensor is placed on the last link of the RM, also known as the end effector [1,2,12]. For this type of VSS, real-time computer vision information is processed with OpenCV on the Remote PC to control the motion of the robot in the workspace [16,17]. The objects tracking and the robots positioning are achieved using the comparison between the current visual features, extracted from the images captured by the camera, and the desired visual features. The obtained difference is used to minimize the error the actual configuration of the visual features, the real and the desired features extracted by the video sensor. VSS technology can make robots “smarter” and help to expand their fields of application. Rotational motions influence global image features, translating movements of the end effector result in movements in the eye-in-hand image. Therefore, image moments for the object detection algorithm are used in the Robot Vision fields due to its simplicity and efficiency in implementation. The image moments contain information about the target, the object to be handled, during the positioning task. Thus, ARS localizes and identifies defined objects in advance and decides by itself how to move the WMR on the spot and how to grip the respective part from the FC station trays.

### 2.2. Modeling the A/D/RML Assisted by ARS

The assembly, disassembly and repair automatic operations can be split up into a logical sequence of basic operational tasks, as seen in the figures below, algorithms that run parallel and synchronized with ARS transportation and positioning tasks assignments along the A/D/RML process. The technology on A/D/RML assisted by ARS and eye-in-hand VSS's basic design approach depends on aspects such as operation modes, operation lengths, distances and manufactured product types [3,5,6]. External events will be interfaced for synchronization between ARS and VSS. Therefore, prior to task scheduling, some assumptions have to be made for FC, A/DML, ARS and VSS in order to control the whole system. For each of the above-mentioned operations, a separate task scheduling strategy has been implemented. The hybrid aspect of the model (A/D/RML assisted by ARS) is given by the continuous aspect, variables associated with the distances covered by the movement of the ARS [2,18,19].

#### 2.2.1. Assembly Process Task Planning

The A/D/RML, as seen in Figure 9, due to the flexibility characteristic, can assemble and process two different products, referred to as workpiece type 1 (WP1) and workpiece type 2 (WP2). WP1 is the workpiece with the top part having triangular edges (Figure 6) and is assembled in the FC station with the ABB IRM. WP2 is the workpiece with top part having round edges (Figure 7a–c) and is assembled on the Hera&Horstmann ML.

The assembly of WP1 is made by the ABB IRM from the FC, picking and placing components in the right order (Figure 6): Base, Body, Top and two cylinders: metal type. Finally, WP1 moves along the Hera&Horstmann ML and is stored on the left side of the

WS6—this product is always considered to be good, with no quality check to perform, although HMI allows operator selection for assembly between plastic and metal cylinders.

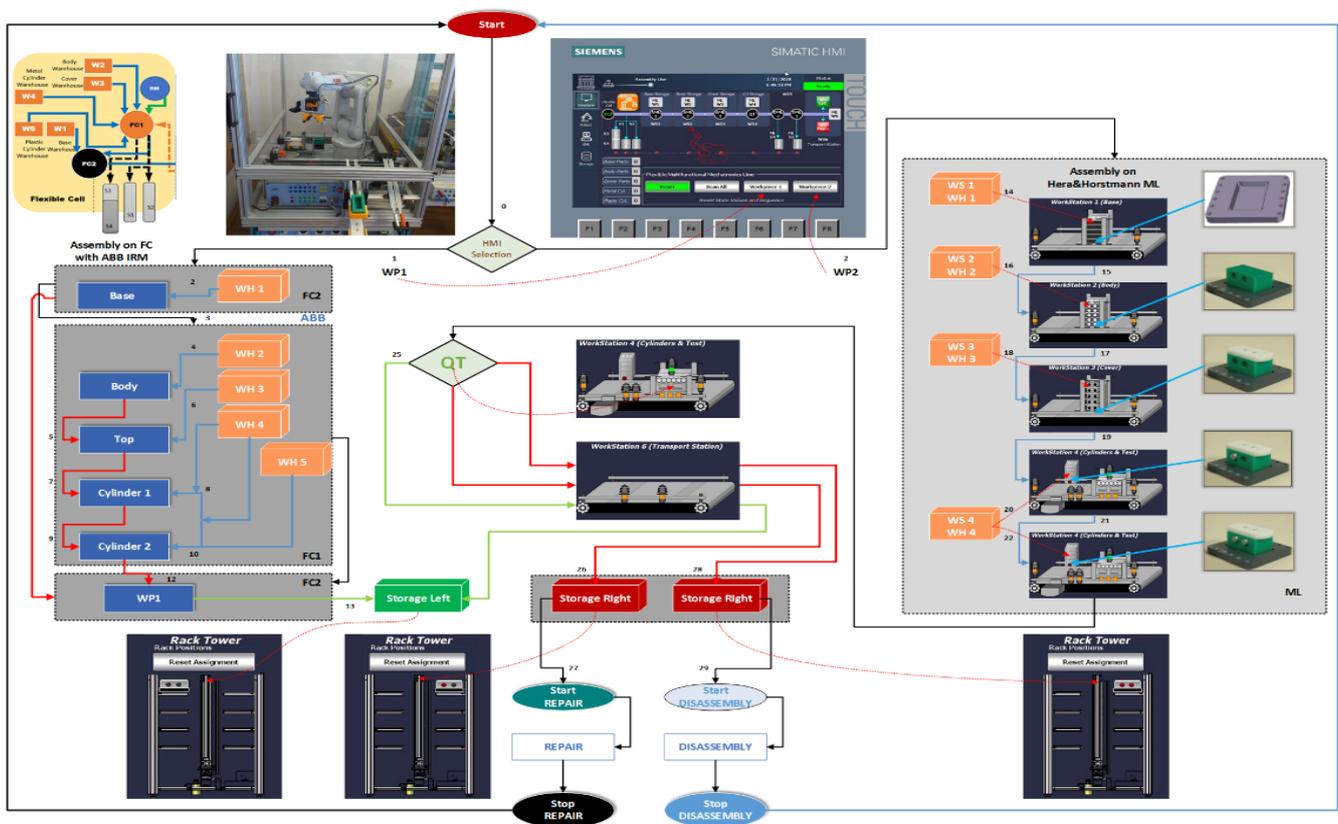


Figure 9. Assembly task planning.

The WP2 product is assembled with randomly picked cylinders and is subjected to the quality test (in mechatronics line, WS4 location, inductive proximity sensor for detecting metal cylinder). To evaluate the quality for the WP2 product, the convention is that an assembled product with both metal cylinders, it is considered of good quality and it is stored on the left side of the WS6 station. The WP2 product that contains both plastic cylinders (Figure 7b) is considered a bad product, unrepairable, and it is stored on the right of the WS6 station. This WP2 will be disassembled for component recovery. The WP2 product with different cylinder types (Figure 7c) is also stored on the right side of the Storage Rack and it will be repaired by replacing the plastic cylinder with a metal one.

### 2.2.2. Disassembly Process Task Planning

WP2 considered as scrap (two plastic cylinders, Figure 7b) is picked by the WS6 elevator and positioned and transported by the Hera&Horstmann ML back to the FC. The ABB IRM disassembles components in the established order: Cylinder 1 (left), Cylinder 2 (right) and Top and Body, letting them slide on the corresponding trays. The Base is transported back to ML WS1, where the piston pushes it into the storage warehouse. ARS takes over by grabbing each released component in order and transporting it to the appropriate storage on the Hera&Horstmann ML. The complete process of disassembly WP2 with recovering components is presented in Figure 10.

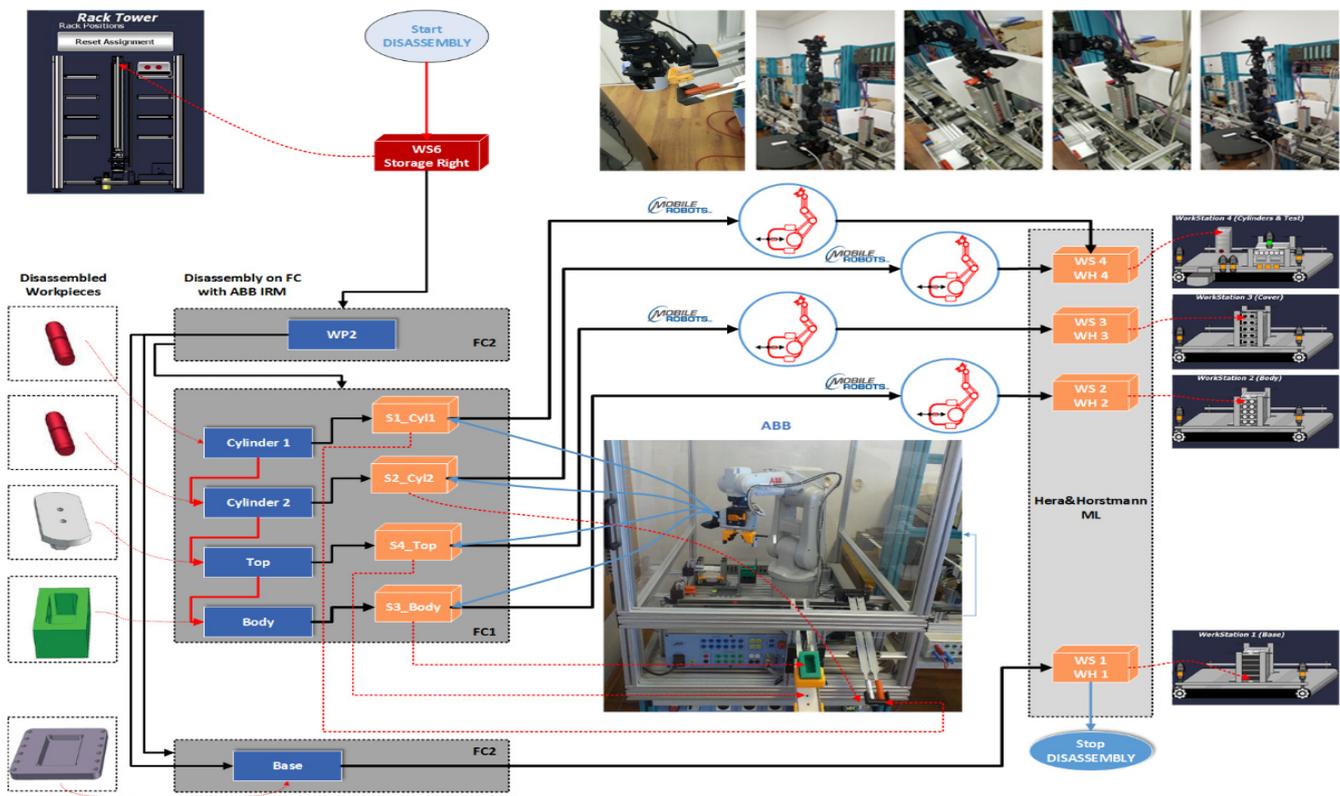


Figure 10. Disassembly task planning.

### 2.2.3. Repair Process Task Planning

When the assembled workpiece WP2 does not pass the quality test, the process handles it by transporting back from the storage unit (WS6 Storage Rack) to the FC where it will be considered for reprocessing, repair or disassembling—depending on the cylinder types (Figure 7). For repairing process (Figure 11) task scheduling consists of the following tasks:

- Process the WS6 FIFO stack of WP2 with failed quality test—bad product but recoverable (can be repaired);
- Transporting back the workpiece from the Storage Tower Rack to the FC. WP2, having cylinders of different materials (Figure 7c), is taken over by the WS6 elevator and positioned on WS5. It is transported along the Hera&Horstmann ML to the FC;
- The bad cylinder is processed in FC according to the quality state. The ABB IRM disassembles the plastic cylinder, letting it slide on the dedicated external tray compartment and replaces it with a metal one;
- Disassembled component is recovered by ARS. The recovered or replaced cylinder is picked by the ARS RM from disassembling the location tray;
- From this position, ARS handles the recovered plastic cylinder by transporting to the appropriate storage depot from Hera&Horstmann ML to be reused in the further assembly process.
- WP2, now having both metal cylinders, is a good quality product; it is transported from FC along the Hera&Horstmann ML to the WS6 station left side rack.

It is important to mention the following assumption: when on A/D/RML, there is a large volume for assembling, and at a certain moment due to the quality check stage, a bad workpiece may be detected; the repair or disassembly process has priority, so assembly is stopped until the bad workpiece is completely reprocessed. After that, assembly process is restarted for that volume of workpieces from the moment of stopping.

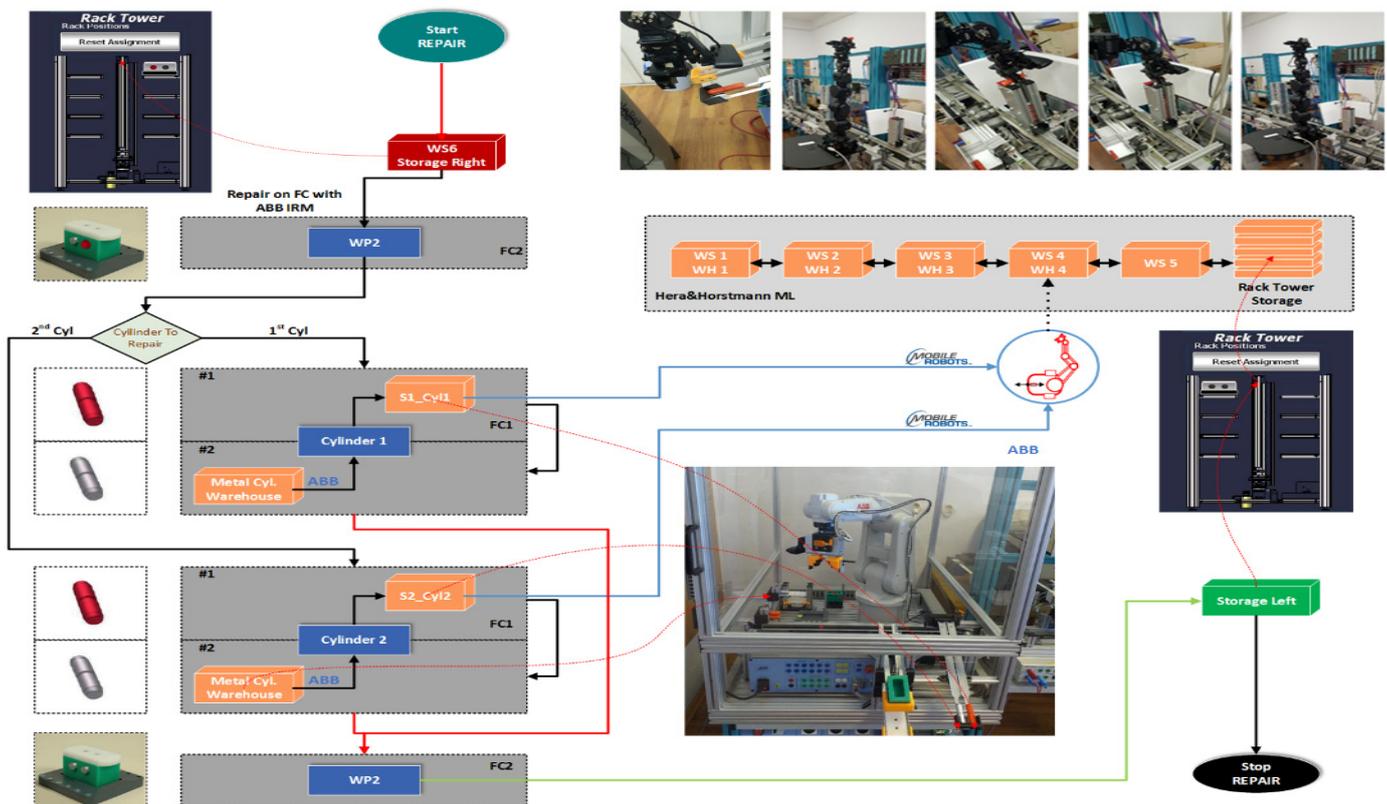


Figure 11. Repair task planning.

### 2.2.4. SHPN Model Structure and Simulation

The hybrid aspect of the model is determined by variables related to distances travelled by the ARS. These distances are considered between places where disassembly occurs and places where storage warehouses are located. These variables vary according to whether speed is constant or variable, a variation based on the ARS speed between A/D/RML locations. To develop a global assembly and/or disassembly model, we shall consider the hybrid aspect of the assembly/disassembly/repair process served by the platform. For modeling, we shall use Synchronized Hybrid Petri Nets (SHPN) [20], which integrates the discrete appearance of the assembly/disassembly process with the continuous appearance of moving of the WMR and components handling by the RM. The entire model is SHPN type as it is interfaced with external events for synchronization in a modeling/simulation approach useful prior to real-time control. SHPN morphology results in the integration of two PN models, each of which has a specific typology: SPN (Synchronized PN) and SHPN (Synchronized Hybrid PN). The simulation of the SHPN model (non-autonomous HPN model) is used to make and check the compatibility of the discrete dynamics of the ML with the continuous dynamics of the ARS and to be able perform together, synchronized without conflicts. The SHPN overall structure and the SHPN representation by modeling assembly, disassembly and repair operations for 2 different types of products (WP1 and WP2), performed by ARS equipped with RM, is shown in Figure 12.

These models describe the following automatic operations:

- Flexible assembly and storage of 2 different product types (SPN typology);
- Repair products and recover components (SHPN typology);
- Total disassembly of damaged products (SHPN typology).

Based on the SHPN model (Figure 13), Sirphyco simulation results for continuous and discrete places associated with displacements of ARS and FC with IRM are shown in Figures 14 and 15. PN Transitions, task scheduling presentation and steps for disassembly and repair operations on A/D/RML assisted by ARS are shown in Figures 16–18.

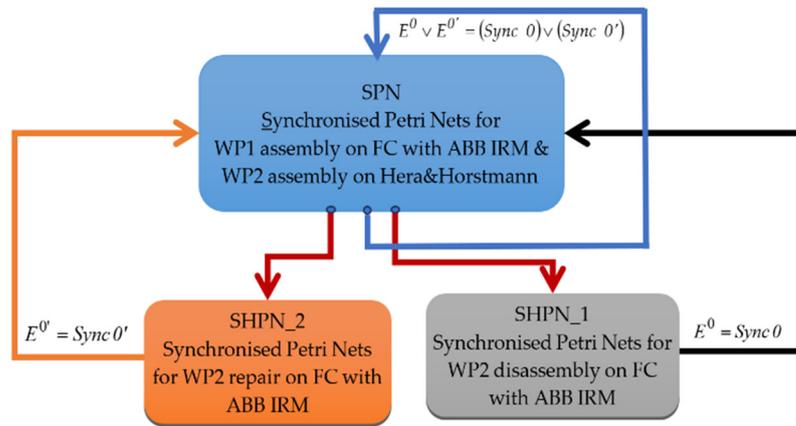


Figure 12. Synchronization and integration of SHPN Model.

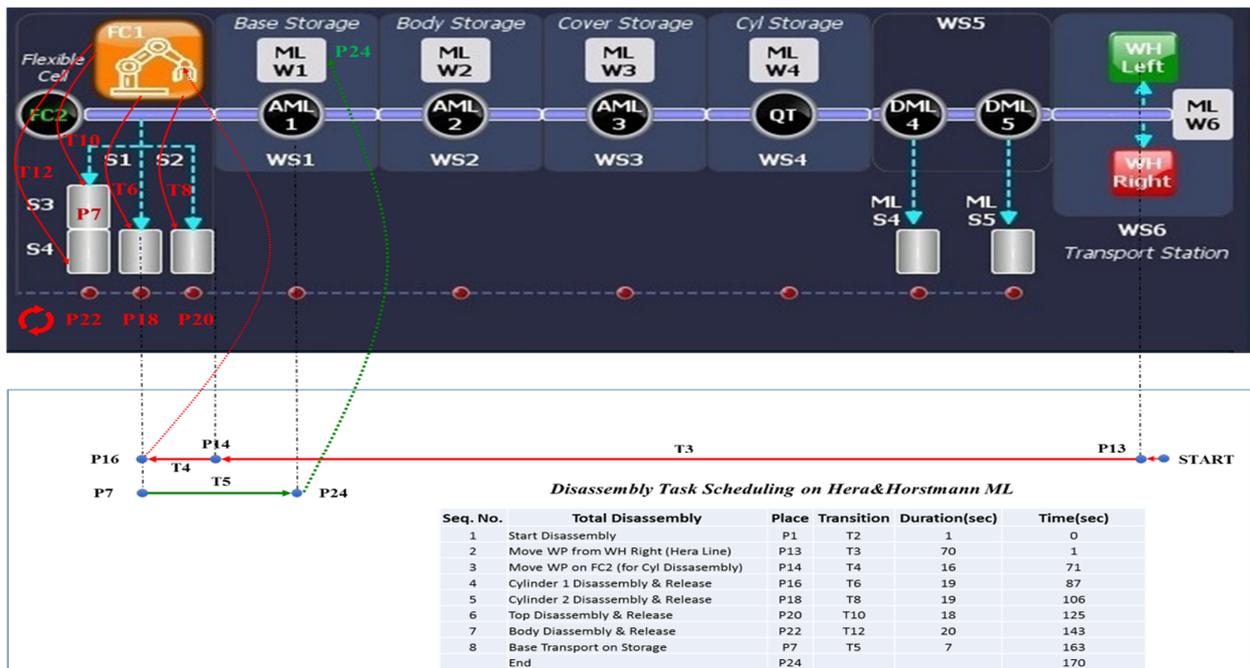


Figure 13. Task scheduling for disassembly operation on Hera&Horstmann ML.

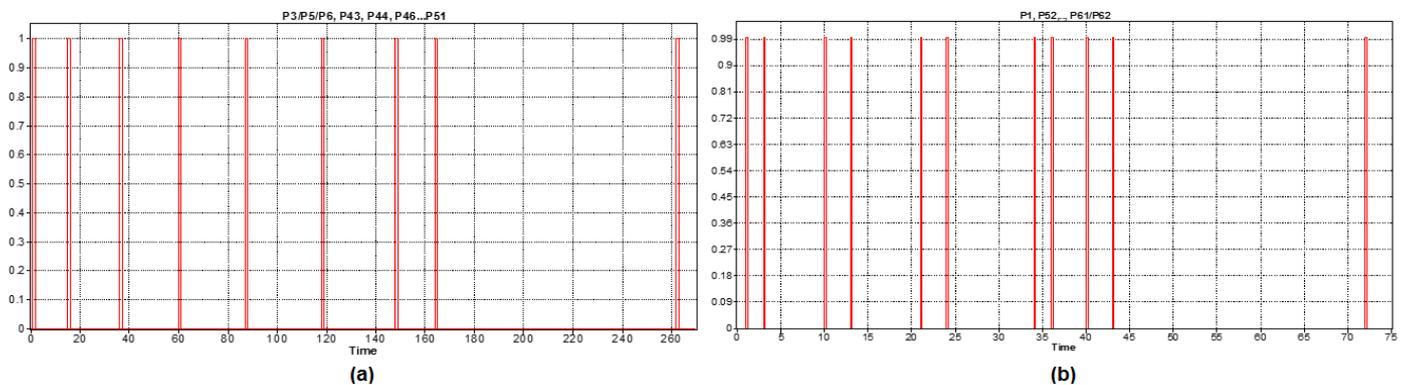


Figure 14. Monitoring signals for assembly operation steps from PN Sirphyco simulation: (a) WP 1, (b) WP 2.

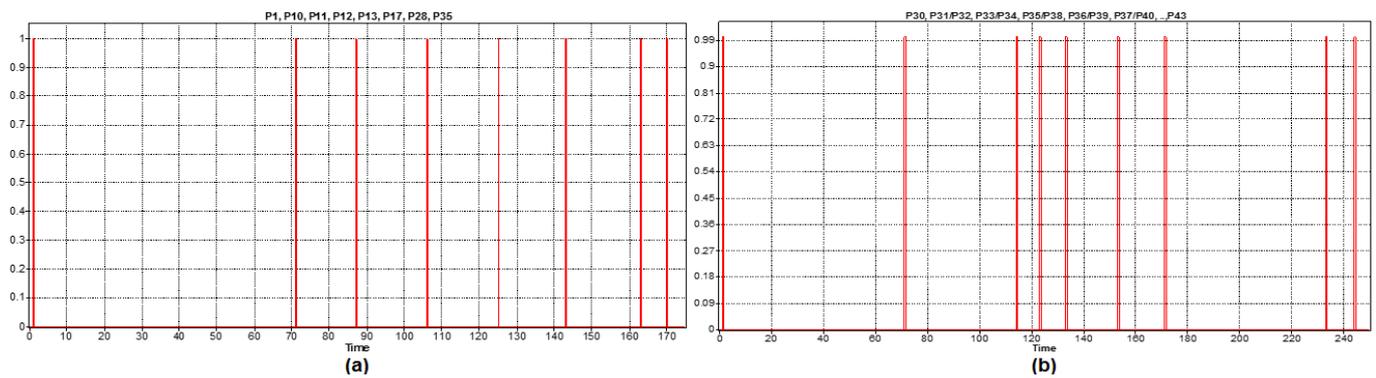


Figure 15. Monitoring signals in PN Sirphyco simulation: (a) disassembly WP2, (b) repair WP2.

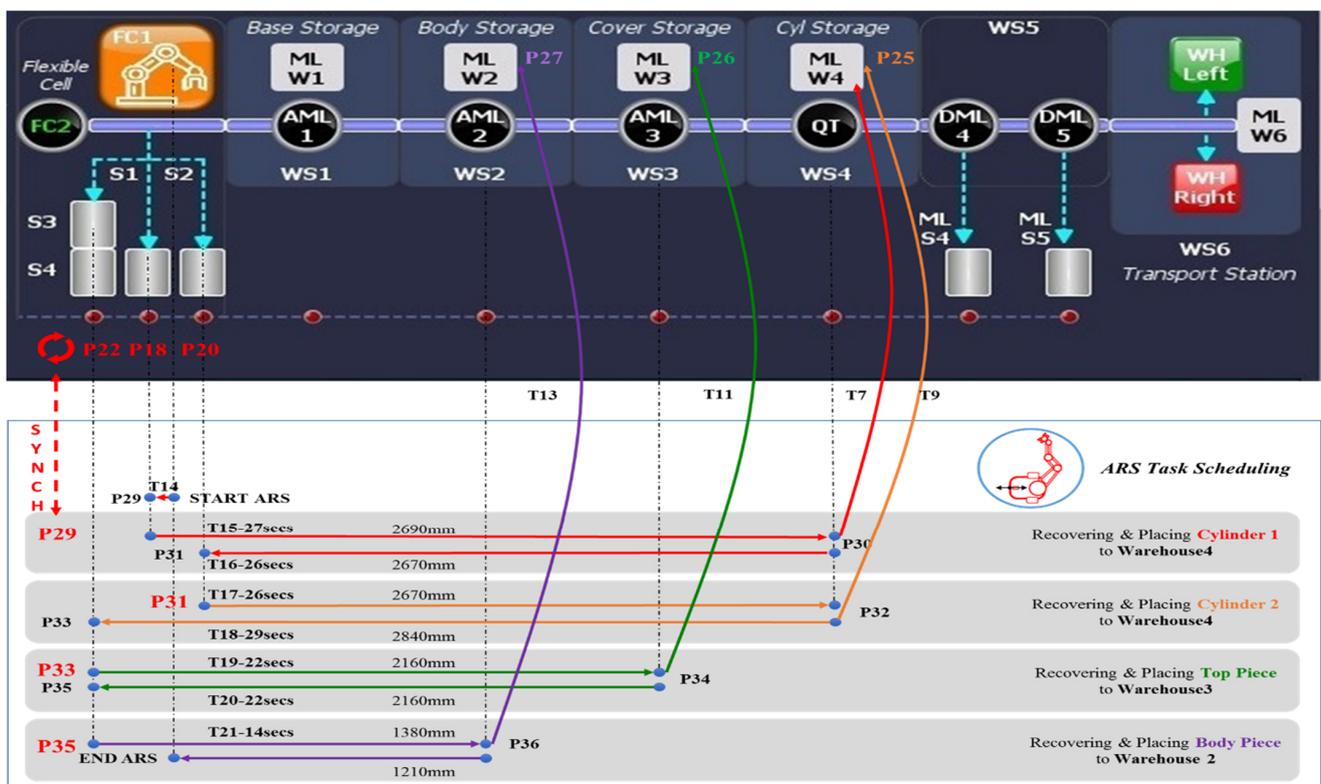


Figure 16. ARS task scheduling for disassembly operation.

### 2.3. Communication, Synchronization and Control Architecture of Multifunctional Flexible Manufacturing Technology

#### 2.3.1. A/D/RML Control Architecture and Network Topology

SCADA (Supervisory Control And Data Acquisition) systems are used in industrial settings to monitor and control field devices from a distance remotely.

The complete structure of the A/DML real-time control served by ARS is shown in Figure 19. The presented control strategy is a hybrid structure, which consists of two interconnected systems, that features both distributed and centralized topology, with specific tasks for all the manufacturing stages. Moreover, for sequence control and synchronizing of all the routines of the manufacturing line, the control algorithm architecture is agent-based type, managed strictly through Siemens S7-1200 PLC from the FC, which acts as a Central System communicating with all subsystems' PLCs to control the complete manufacturing process by means of signal interface for sending and acknowledging commands or actions. In this control setup, every subsystem or slave from the presented technology of A/D/RML

assisted by ARS is considered to be an agent, which includes a separate control, managed by a local agent software synchronized with the master PLC [11].

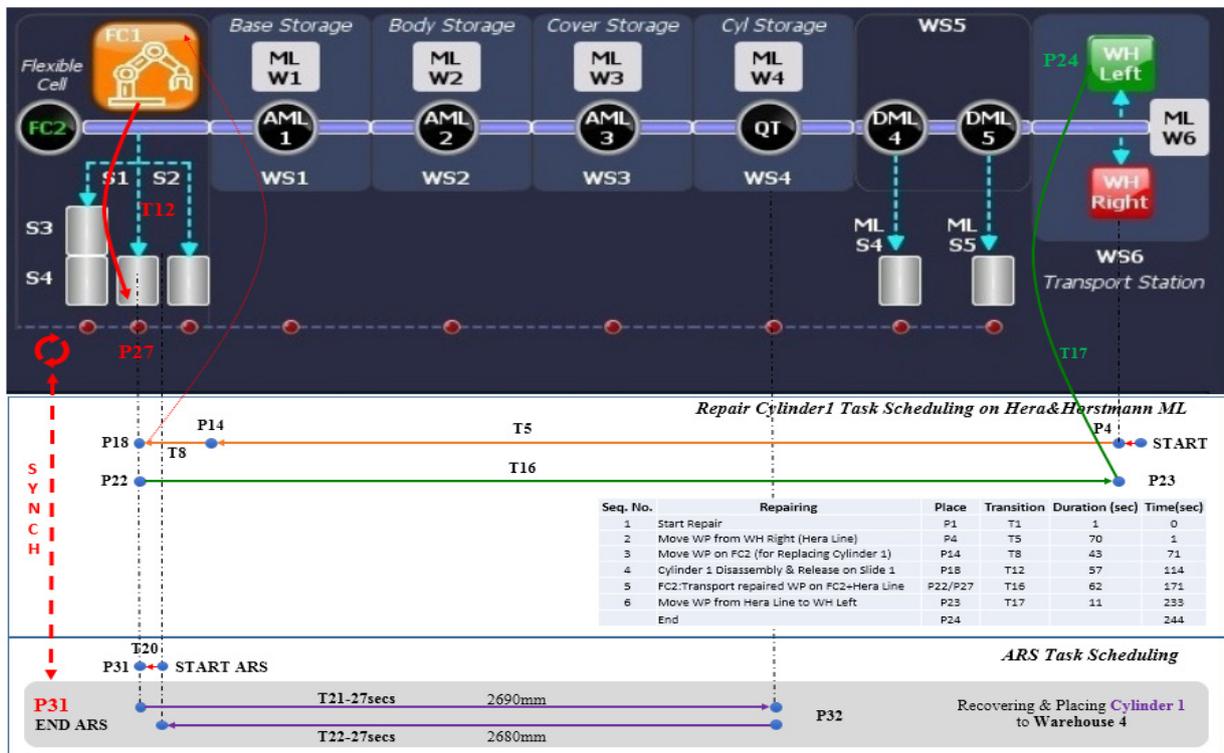


Figure 17. ARS task scheduling for repair/replace Cylinder 1.

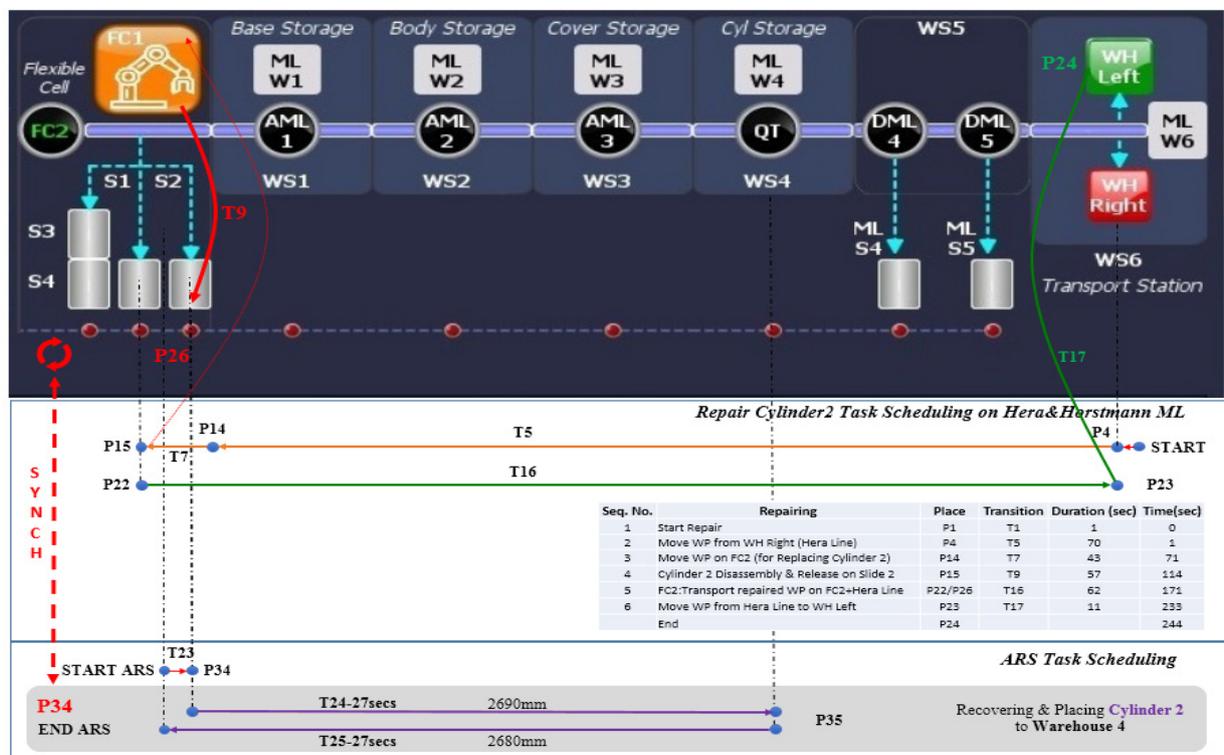
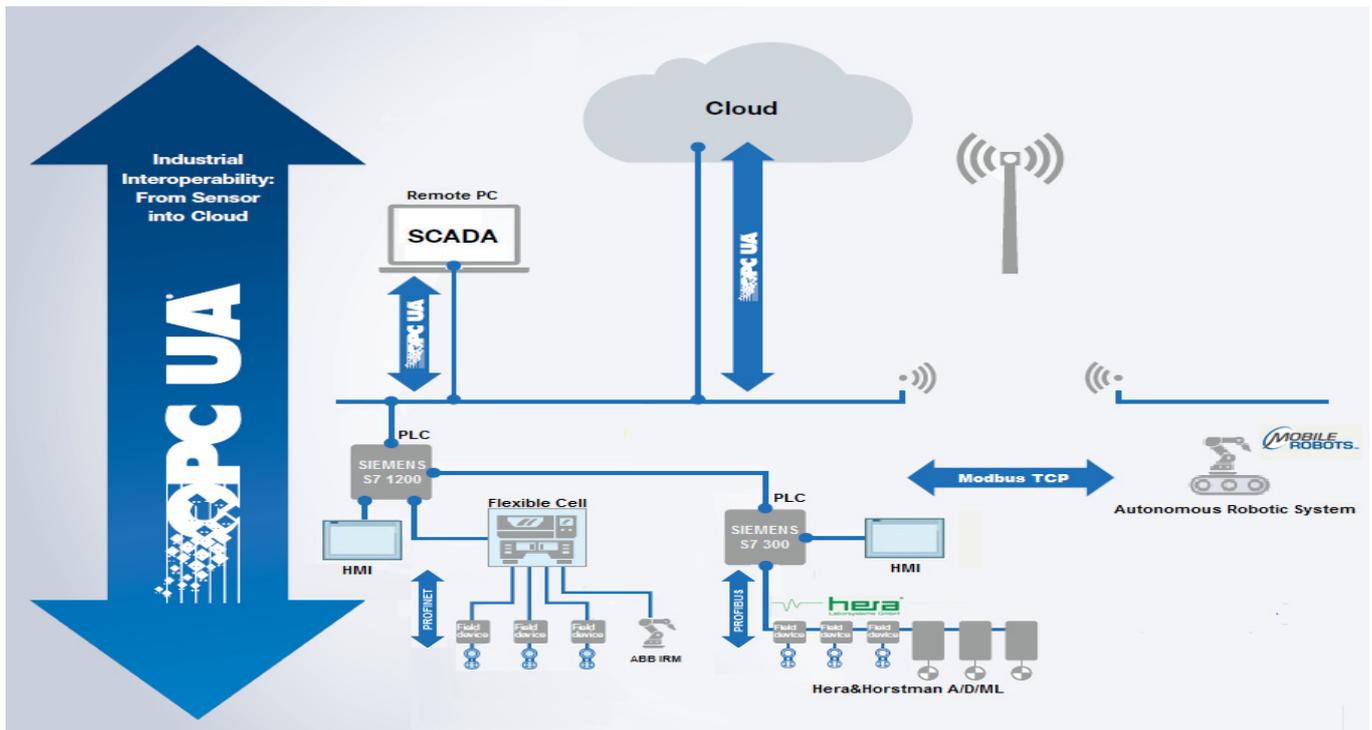


Figure 18. ARS task scheduling for repair/replace Cylinder 2.



**Figure 19.** Control structure of A/DML Hera&Horstmann and Flexible Cell ABB served by ARS.

Using SCADA system (Figure 20) along with both HMI's functionality (Figure 21) for controlling, real-time monitoring and visualizing the A/D/RML complete process, it integrates the following major functions:

- Data acquisition, to monitor and control all IO field-sensors from the lower layer of the automation process architecture, conveyor belt sensors, proximity sensors and speed sensors;
- Data communication, involving monitoring the automation process and interacting with all the devices/sensors from a single location via a communications network to bring remotely data from A/D/RML and ARS. A communication adapter (Figure 2) Siemens CM 1242-5 attached to S7-1200 PLC is used for connecting the newer generation Siemens master PLC from FC via the Profibus link to the mechatronics line. This module is used to connect and integrate SIMATIC S7-1200 into an automation solution as a Profibus DP slave. The CM 1242-5 works as a DPV1 slave in accordance with IEC 61158, handles data traffic completely autonomously and thus relieves the CPU of communication tasks. This communication module operates at two levels, the physical layer and data link layer, converting and regenerating the signal it receives or sends and supports cyclic communication for the transfer of process data between Profibus DP slaves and DP master (Mechatronics Line S7-300 PLC). Cyclic communication is handled by the operating system of the PLC;
- Data presentation display information in human readable format in the GUI, suitable for operator needs for easy control and fast response in case of alarms, a solution implemented for both the mechatronics line as well for the ARS and FC (see Figure 21);
- Control the field devices remotely, pending outputs and synchronization commands from SCADA Remote PC and transmitted via the network, improving operator and ARS fast actions and making a quick decision.

### 2.3.2. ARS Control Input Design

In this approach, the mobile part of the A/D/RML, referred to as ARS with PeopleBot WMR from Mobile Robots, will be used and has an odometric system, two driving wheels

and one rear freewheel. Additionally, an onboard embedded microcontroller is able to read the position information and send it, via WI-FI link, to a Remote PC according to a specific protocol. The SCADA application from the Remote PC computes the control input and sends it to WMR. Additionally, the Remote PC sends the data to the A/D/RML PLCs [21,22]. For controlling the ARS and WMR movements between the parking/grabbing and placing positions, dedicated functions from the ARIA (Advanced Robotic Interface for Applications) programming package are used and the TTSMC algorithm is implemented [23–26].

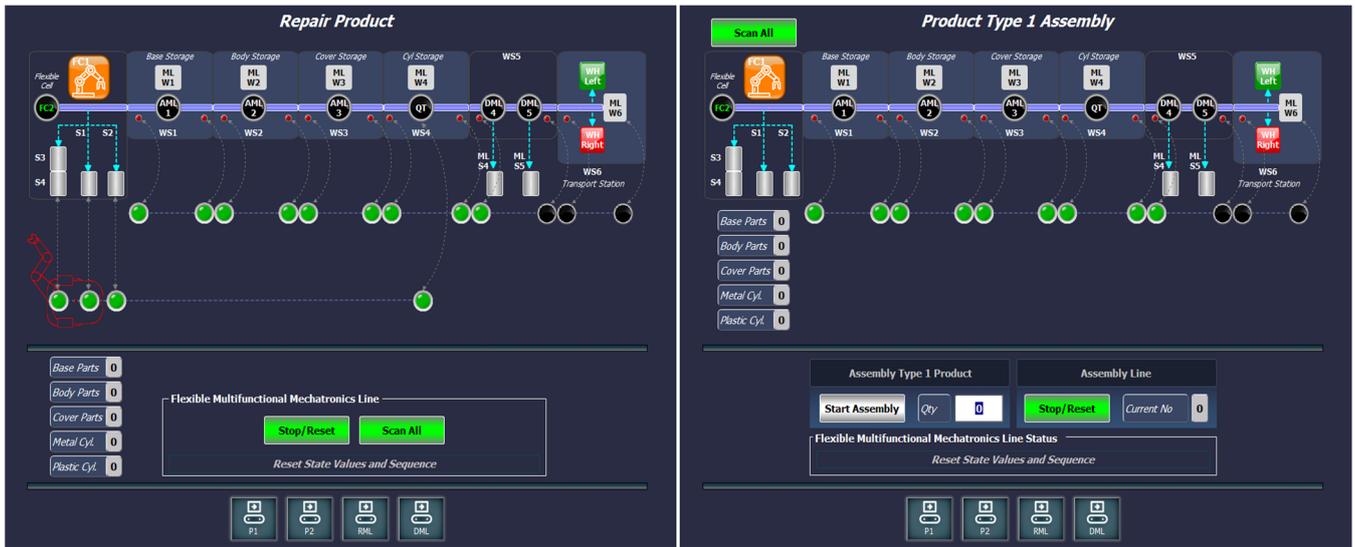


Figure 20. SCADA with Siemens TIA implementation for A/D/RML.



Figure 21. Control and visualization of A/D/RML via Siemens HMI (KTP700).

The ARS is equipped with 7-DOF Cyton 1500 RM and eye-in-hand VSS for picking up the dismantled workpieces from the FC trays in the case of a repair/disassembly process and transporting them to their proper storage warehouses. The control of the ARS is based on 3 control loops:

- Control loop for the synchronization commands between Main PLC and ARS Cyton RM using Modbus TCP signals (Figure 22). As designed, the communication link between the Cyton RM and the Remote PC is performed wirelessly using a USB over Ethernet adapter and a specific TCP/IP protocol;

- Eye-in-hand VSS algorithm, for the Cyton RM, handled wirelessly by Remote PC, for precise robot pick-and-place operations [27]. Cyton RM eye-in-hand VSS control algorithm has been realized using the open-source OpenCV library specialized in image processing;
- ARS WMR control algorithm, for moving the grabbed recovered workparts from the FC and place them on the dedicated storage units on ML, is based on TTSMC [28] with functions from Aria Mobile Robots. Communication with the FC is performed wirelessly using TCP/IP protocol.

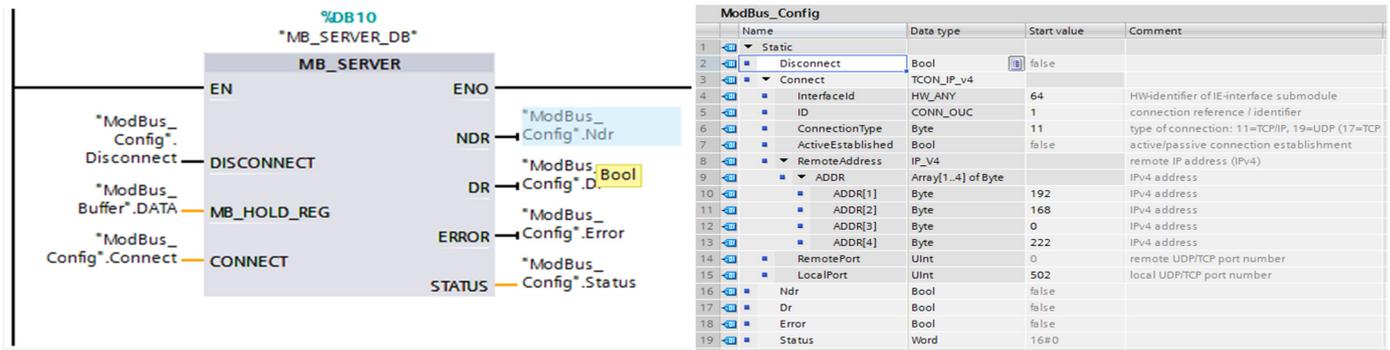


Figure 22. Siemens Modbus Server configuration in Main PLC.

All three control loops communicate through Remote PC, which also acts as a SCADA server and controls the ARS, eye-in-hand VSS and Cyton 1500 RM and manages the synchronization with the FC, ML and the coordination between them.

### 2.3.3. Communication and Synchronization between A/D/RML and ARS

As mentioned before, centralized architecture is used, where the Main PLC (Siemens S7 1200) acts as the master PLC and synchronizes the operation with the ARS, which handles the recovering process. The communication between master PLC (Flexible Cell S7-1200 PLC) and ARS is conducted via a Modbus TCP link (Figure 22).

The Modbus protocol was developed in 1979 by Modicon, Incorporated, for industrial automation systems, and it became an industry standard method for the transfer of discrete and analog I/O information and register data between industrial control and monitoring devices. Modbus TCP/IP shares the same physical and data link layers as the traditional IEEE 802.3 Ethernet and uses the same TCP/IP suite of protocols. Therefore, it remains fully compatible with the already installed Ethernet infrastructure of cables, connectors and network-related devices. Unlike traditional Ethernet, which was not considered a viable fieldbus for industrial control, Modbus itself is an a deterministic industrial application protocol, as it defines rules for organizing and interpreting data, but remains simply a messaging structure, independent of the underlying physical layer, and every message is sent or received in a finite and predictable amount of time. Modbus devices communicate using a master–slave (client–server) technique in which only one device (the master/client) can initiate transactions (called queries). The other devices (slaves/servers) respond by supplying the requested data to the master or by taking the action requested in the query. A master’s query will consist of a slave address (or broadcast address), a function code defining the requested action, any required data and an error checking field. A slave’s response consists of fields confirming the action taken, any data to be returned and an error checking field. Note that the query and response both include a device address, a function code, plus applicable data and an error checking field. A Modbus map is required to know how to interpret the data that is returned. Because TCP is a connection-oriented protocol, a TCP connection must first be established before a message can be sent via Modbus TCP/IP. Following the client–server principle, this connection is established by the client (master). This connection can be handled explicitly by the client user-application

software or automatically by the client TCP connection manager. More commonly, this is handled automatically by the client protocol software via the TCP socket interface, and this operation remains transparent to the application. All Modbus TCP/IP message connections are point-to-point communication paths between two devices, which require a source address, a destination address and a connection ID in each direction. Thus, Modbus TCP/IP communication is restricted to unicast messages only. The well-known port 502 has been specifically reserved for Modbus applications. A Modbus server will listen for communication on port 502. When a Modbus client wants to send a message to a remote Modbus server, it opens a connection with remote port 502. As soon as a connection is established, the same connection can be used to transfer user data in either direction between a client and server and may also establish several TCP/IP connections simultaneously [8].

Depending on the task performed by the A/D/RML, Repair process (one cylinder released) (Figure 11) or Disassembly process (all workparts released) (Figure 10), distinct command signals, as shown in Figure 23, will be needed for interfacing between master PLC S7 1200 and ARS:

- Start Job ARS: Recover Cylinder 1;
- Start Job ARS: Recover Cylinder 2;
- Start Job ARS: Recover Body Workpiece;
- Start Job ARS: Recover Top Workpiece;
- Stop Command: stop Job ARS.

Name	Send from PLC	Receive IO in S7 1200	Type	ModBus Code	Description
ARS_MRobot_Ready	Coil 9	Q 11.0	BOOL	05-Write bit ; Device Id 1	ARS In<-> Mobile Robot-Ready for Command
ARS_MRobot_Cylinder1_Busy	Coil 10	Q 11.1	BOOL	05-Write bit ; Device Id 1	ARS In<-> Mobile Robot Job Take 1st Cylinder-Busy
ARS_MRobot_Cylinder2_Busy	Coil 11	Q 11.2	BOOL	05-Write bit ; Device Id 1	ARS In<-> Mobile Robot Job Take 2nd Cylinder-Busy
ARS_MRobot_Body_Busy	Coil 12	Q 11.3	BOOL	05-Write bit ; Device Id 1	ARS In<-> Mobile Robot Job Take Body Part-Busy
ARS_MRobot_Cover_Busy	Coil 13	Q 11.4	BOOL	05-Write bit ; Device Id 1	ARS In<-> Mobile Robot Job Take Cover Part-Busy
ARS_MRobot_AckCmd	Coil 14	Q 11.5	BOOL	05-Write bit ; Device Id 1	ARS In<-> Mobile Robot Job Acknowledge Command
Spare	Coil 15	Q 11.6	BOOL	05-Write bit ; Device Id 1	
Spare	Coil 16	Q 11.7	BOOL	05-Write bit ; Device Id 1	

Name	Send IO from PLC	Receive in ARS	Type	ModBus Code	Description
ARS_MRobot_Cylinder1_TakeCmd	Q 10.0	Coil 1	BOOL	01-Read bit ; Device Id 1	ARS Out<-> Start Mobile Robot (Take 1st Cylinder)
ARS_MRobot_Cylinder2_TakeCmd	Q 10.1	Coil 2	BOOL	01-Read bit ; Device Id 1	ARS Out<-> Start Mobile Robot (Take 2nd Cylinder)
ARS_MRobot_Body_TakeCmd	Q 10.2	Coil 3	BOOL	01-Read bit ; Device Id 1	ARS Out<-> Start Mobile Robot (Take Body Part)
ARS_MRobot_Cover_TakeCmd	Q 10.3	Coil 4	BOOL	01-Read bit ; Device Id 1	ARS Out<-> Start Mobile Robot (Take Cover Part)
ARS_MRobot_StopCmd	Q 10.4	Coil 5	BOOL	01-Read bit ; Device Id 1	ARS Out<-> Stop Mobile Robot Command
Spare	Q 10.5	Coil 6	BOOL	01-Read bit ; Device Id 1	
Spare	Q 10.6	Coil 7	BOOL	01-Read bit ; Device Id 1	
Spare	Q 10.7	Coil 8	BOOL	01-Read bit ; Device Id 1	

Figure 23. Modbus message interface (Modbus Map).

In the same way, ARS must acknowledge that the received command/action from A/D/RML is handled (Figure 24); therefore, 3 synchronization signals will be used between ARS and master PLC S7 1200:

- ARS Ready for Command-Status;
- ARS Acknowledge Command-Status;
- ARS Job started: Busy Status.

Network topology as shown in Figures 1 and 19 is implemented in the A/D/RML assisted by ARS. OPC UA is the communication data structure between SCADA and main PLC, integrated into an industrial system to provide a standard way for setting a secure and reliable data exchange between industrial devices of multiple vendors and software systems [29], but the other main reason for using this technology for the proposed assisted manufacturing line is that it operates and communicates with other industrial protocols. The flexible manufacturing line also runs with a multitude of protocols such as Profibus, Profinet, Modbus and Ethernet/IP.

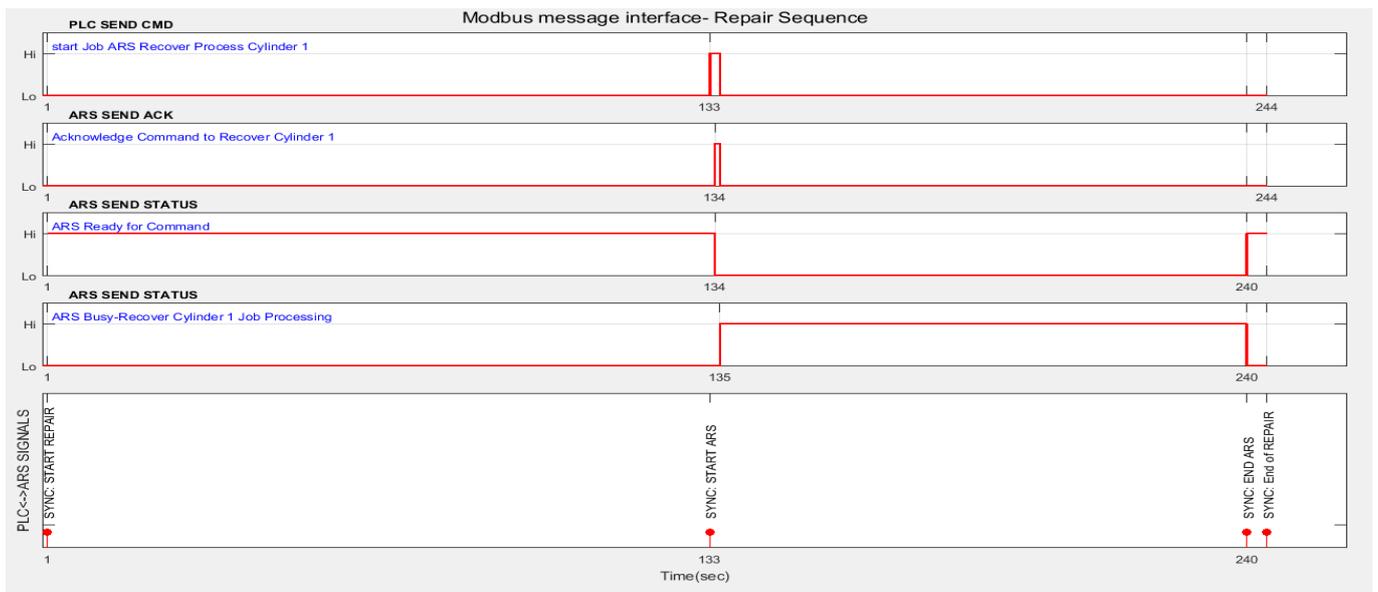


Figure 24. Handshake sequence interfacing master PLC S7 1200 and ARS.

### 3. Real-Time Results for A/D/RML Control Based on SHPN Model

The SHPN model is transposed via the SCADA platform from Siemens into a real-time application, obtained by interfacing the SHPN model with synchronized signals taken from the real process by means of PLC and sensors [28,30,31].

Following implementation, real-time results within the laboratory setup are shown in Figures 25–28, for continuous and discrete places associated with displacements of ARS and FC, for later comparing and validating data with the simulation framework results as presented in Section 2.2.

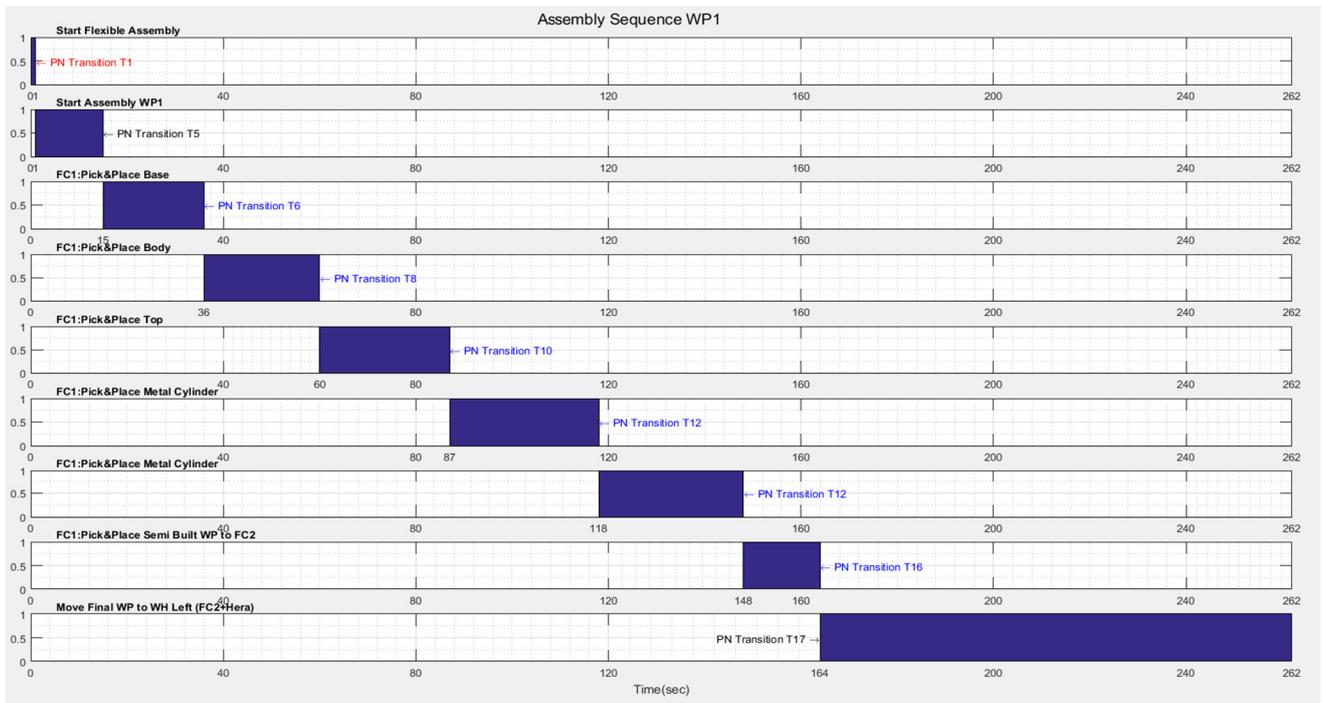


Figure 25. Results for continuous and discrete places associated with displacements of FC with IRM for Assembly WP1.

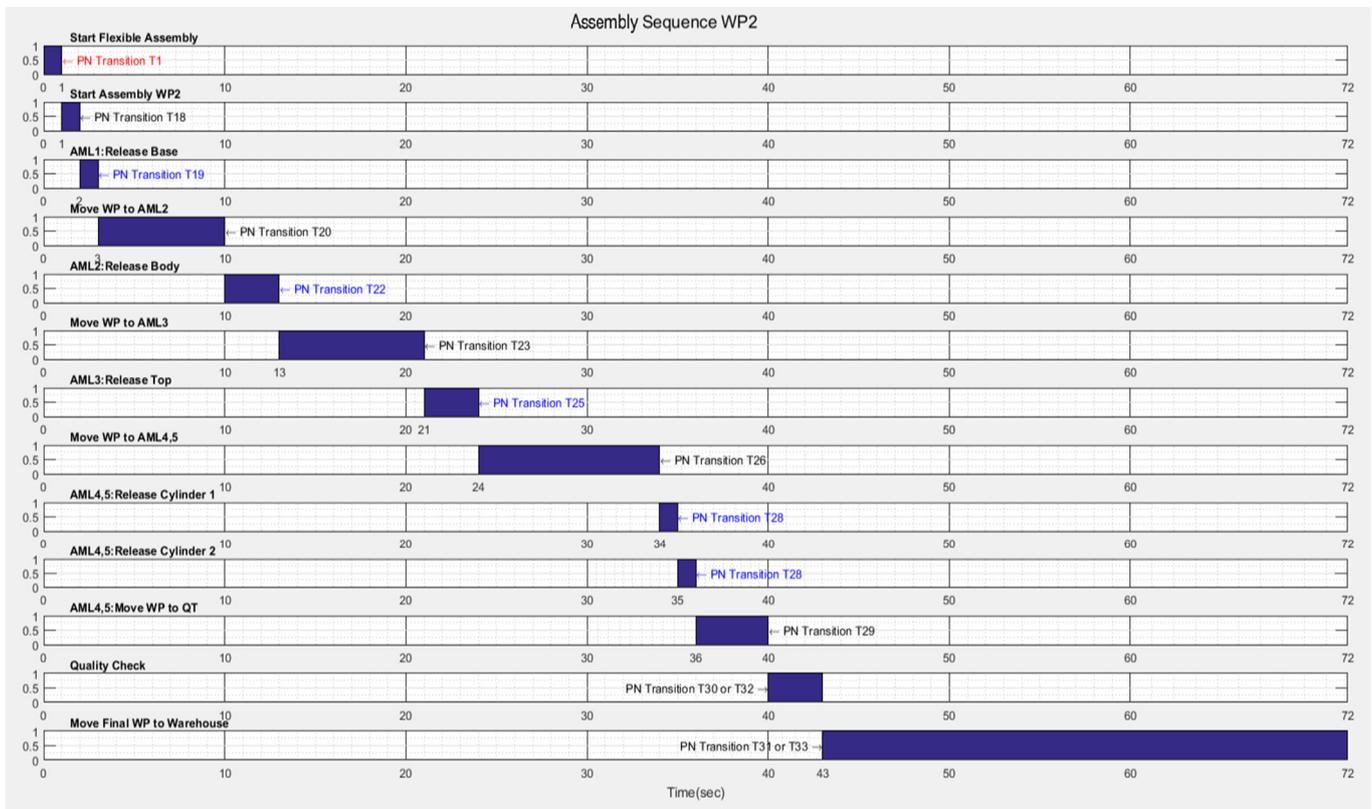


Figure 26. Results for discrete places and transitions on Assembly WP2.

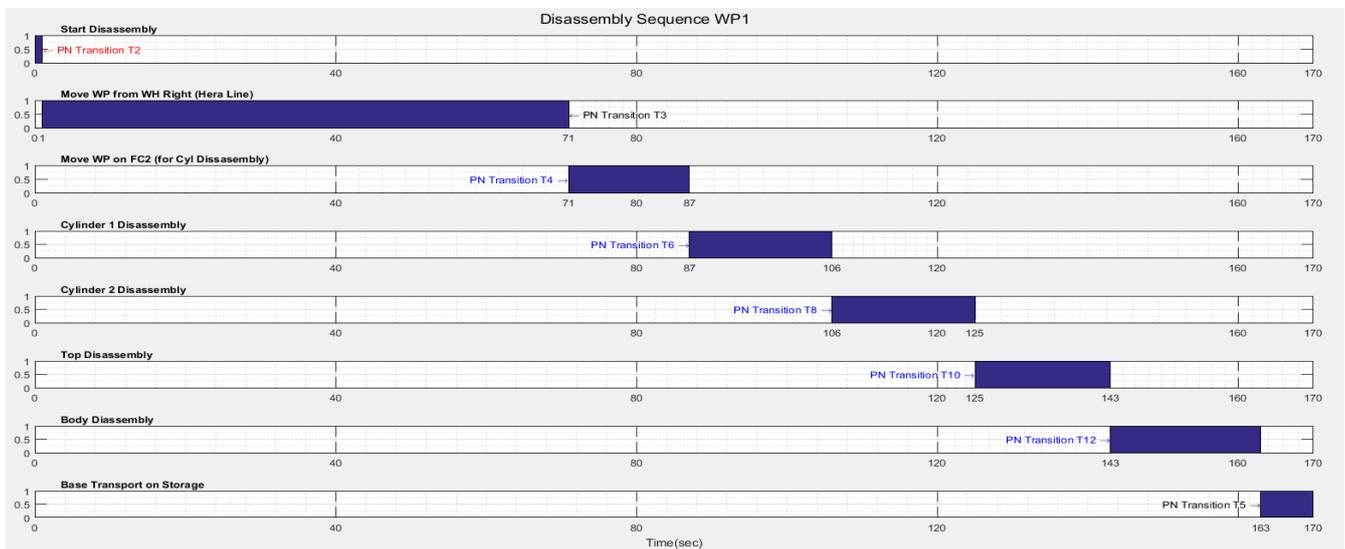
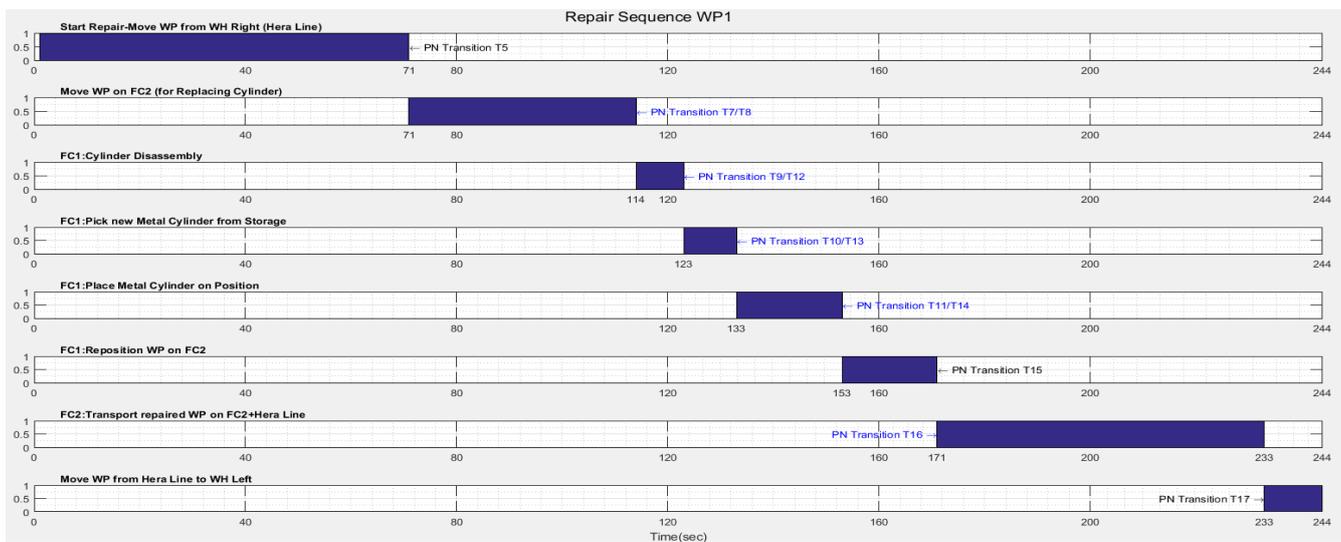


Figure 27. Results for continuous and discrete places associated with displacements of ARS and FC with IRM for Disassembly.

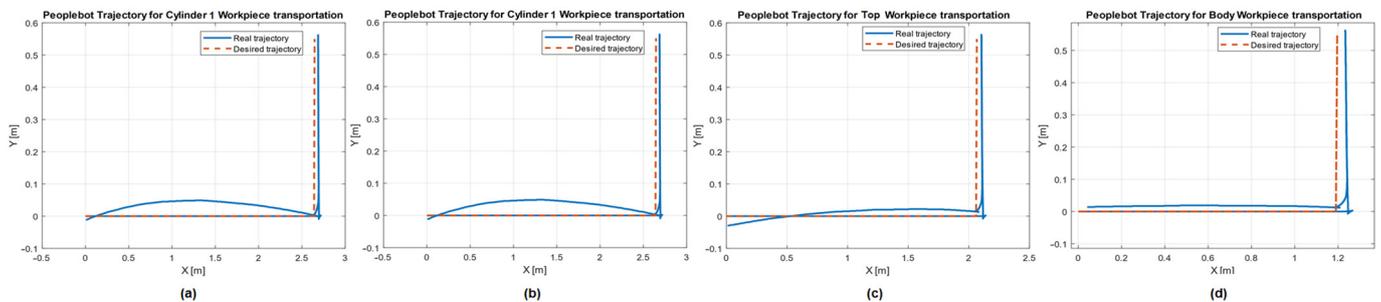
The synchronization signals, used in the real-time control application, validate certain transitions into the SHPN model [32]. These transitions are conditioned by the associated signals for releasing recovered workparts on FC trays or on the ML storage units by the ARS. Synchronization will lead to initializing the robot and to monitoring/controlling assembly/disassembly/repair operations with the ARS. Discrete time and sliding-mode control, in trajectory tracking, based on a kinematic and dynamic model, is used to control WMR. In this way, both ARS and the A/D/RML are controlled so as to achieve a minimum assembly and disassembly time cycle.



**Figure 28.** Results for continuous and discrete places associated with displacements of ARS and FC with IRM for Repair.

In order to grab the recovered workparts and place them on the dedicated storage positions, the ARS PeopleBot is equipped with 7-DOF Cyton RM with a gripper paddle and HD video camera on the end effector (Figure 8), connected both via USB with the Remote PC. The gripper is positioned by VSS so as to grab the disassembled component and transport and place it into the dedicated warehouse.

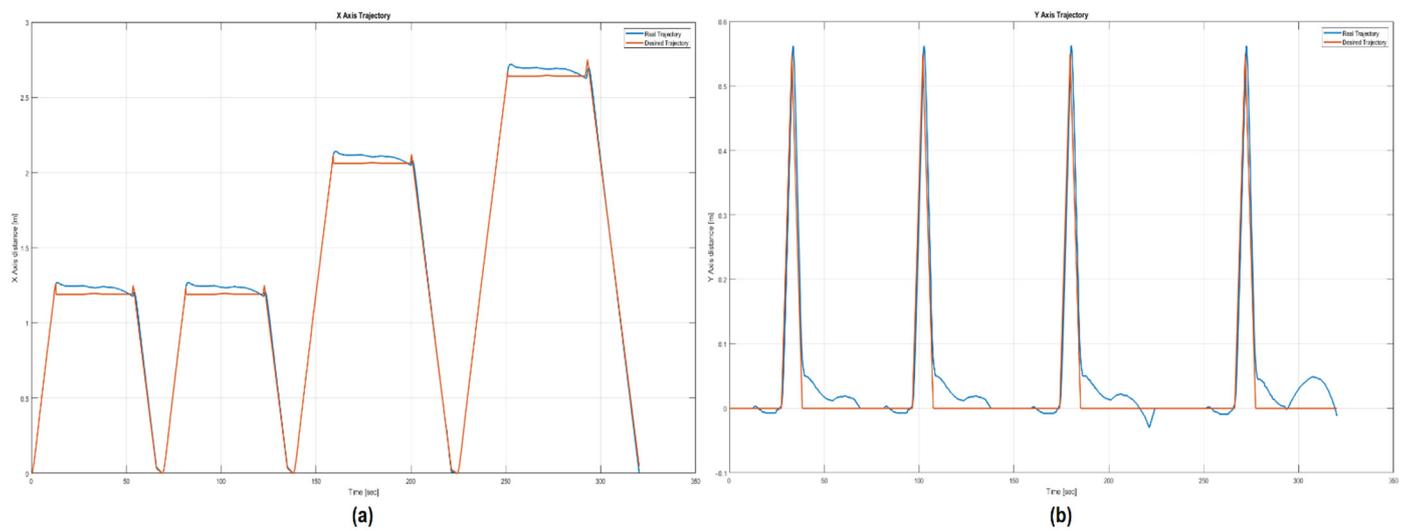
Figure 29 shows the desired and real trajectories of the ARS PeopleBot obtained with the TTSMC in a closed loop control to move from the FC to the storage unit from the mechatronics line and back to the FC in the desired time.



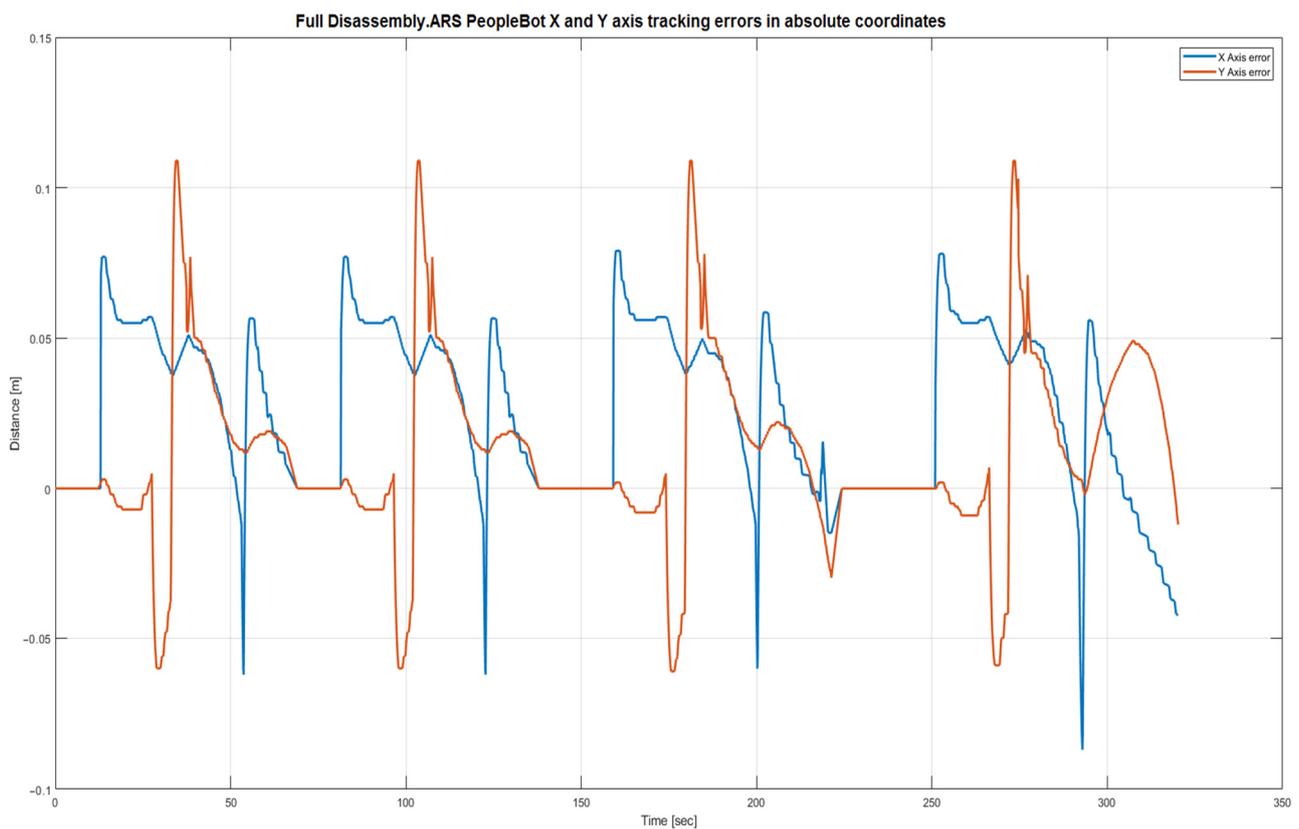
**Figure 29.** Full disassembly process. Desired and real trajectories of ARS PeopleBot based on TTSMC: (a) Cylinder 1, (b) Cylinder 2, (c) Top and (d) Body.

In Figure 30 presents X and Y axis trajectories for a complete disassembly process, both desired and the real one so that the differences between them can be easily distinguished.

Figure 31 illustrates X and Y axis tracking errors in absolute coordinates for the disassembly process as well, where ADRML is served/assisted by ARS for robotic pick-and-place operations for the recovered/dismantled components and transporting them back to the storage units.



**Figure 30.** Full disassembly process. Desired and real trajectories of ARS PeopleBot based on TTSMC: (a) X axis, (b) Y axis.



**Figure 31.** Full disassembly process. Trajectory tracking errors in absolute coordinates.

#### 4. Discussion

The paper proposes an extension both in hardware as well in software, which allows the implementation of a flexible and multifunctional technology able to manufacture different products (Figure 9) and to disassemble (Figure 10), recover components or to repair products that do not correspond to the desired quality (Figure 11). All these functionalities are made with high precision due to the integration of an industrial robotic manipulator (ABB 120 IRM), an autonomous robotic system equipped with a mobile visual servoing system and by using a multi-agent control strategy and communication structure between

the flexible cell and the mechatronics line that allows synchronizations of the requested operations. Therefore, the master PLC synchronizes with subsystems PLCs to automate their respective areas and for operating and controlling their local IO devices, after confirmation from the main control unit is applied (Figure 24).

Modeling of the system using hybrid Petri Nets, in which A/D/RML is a hybrid SHPN model having the Hera&Horstmann mechatronics line with discrete states and transitions and the ARS subsystem with continuous dynamics, is presented in the paper and represents only an intermediate stage (Figure 12). Due to the dynamic nature of the system, analytical methods can be used, but are limited; therefore, task scheduling and the simulation of the model, which tackle the compatibility between the two subsystems, is used for studying the evolution of the discrete states of A/D/RML with the physical constraints and continuous states of the ARS.

The real-time research and implementations is followed, comparing and validating data with the simulation framework results. SCADA environment is developed (Figure 20) so that the entire system works autonomously, fully automated to meet the actual industry requirements. The actual results also showed that the actual manufacturing line implementation satisfied the design target. By using the smart and autonomous technologies to operate in a seamless and secured way, this meets also the new requested requirements standards of Industry 4.0, increasing the degree of integration and compatibility with the actual industry needs

The control of the robotic arm Cyton 1500, for handling and precise positioning operations, when gripping or releasing the part, is based on the inverse kinematic model and is robust, having the desired behavior even in presence of uncertainties and external disturbances. Cyton 1500 manipulator is equipped with an anti-collision map tested on the simulation stage; the robotic arm moves until the object detected is in the center, and if the time needed to get to the object is higher than expected or a supplementary torque is detected, for example an obstacle has been placed in the trajectory, the robotic arm returns to the home position and notifies the user that the trajectory path following has been unsuccessful. The implementation of multifunctional flexible manufacturing technology in a laboratory system, to be as close as possible to the real industrial world, draws some limitations as well; we could not gather consistent data regarding the performance of robotic arm in the presence of noise for applying methods to overcome that. A more sophisticated approach has not been implemented, as the deviations that appear are just on the X or Y axis, due to the complex autonomous robot transportation errors.

## 5. Conclusions

The presented research is still in progress; it is a place for further improvements and fine tunings, and the important benefit and contribution of this research is the implementation of manufacturing technology assisted by autonomous robotic systems at the laboratory level, which works in real-time and which, if used industrially in the real world, would increase efficiency, reliability and precision. This research aimed for a dual purpose, one educational and another to implement, test and adapt this technology to be as close as possible to the real industry world requirements.

The educational goal aims to familiarize the system designer with everything that defines new industry architecture, including Industry 4.0 concepts, and to try to improve the actual technology design with the integration of all new, state of the art aspects of production and engineering, including smart manufacturing products and intelligent material handling systems and technologies.

Regarding the correspondence with the real industrial world, most manufacturing industrial technologies are served by robotic systems that have a fixed position (robotic manipulators). Through this study, we extended the degree of automation and efficiency of these production lines by using new technologies such as autonomous robotic systems equipped with manipulators and visual servoing systems. The goal is to adapt this technology to meet as much as possible the actual industry needs to confirm the feasibility of

the line and to keep up the rhythm with the technology development. Therefore, the final purpose is to develop a fully automated multifunctional flexible manufacturing technology without the intervention of the human operator for a predefined production volume with the recovery of components of bad assembled products that did not pass the quality tests and integrating new emerging technologies such as SCADA, IIOT and MQTT protocols for Cloud interface.

Although this is a technology that has been used at the level of a laboratory, it can be extended further to real industry, where high accuracy and positioning are needed. Multispectral video sensors, providing new imaging capabilities without adding size or weight, can be used in order to reduce errors in reflectance estimation for remote sensing on production line inspection or workparts validation and quality checking to more strongly demonstrate the reliability and to increase speed and efficiency by integrating with the ARS of the presented manufacturing line technology, especially for recovery and accurate positioning operations.

The implementation of robust control architectures to uncertainties will be further considered for all systems: ARS, FC and the mechatronics line. As a result, this increases the reliability, flexibility and robustness of the technology to the uncertainties that might come from the sensors from the ARS and VSS.

The presented control architecture is a hybrid structure, multi agent-based control. Unlike using this control strategy, the system can be enhanced with artificial intelligence (AI), which is a combination of situational awareness and creative problem solving, to identify and fix potential assembly problems much faster and can diagnose and prevent further issues by directly alerting through SCADA systems when anomalous units are identified.

Additionally, we will also focus on the time study system performance evaluation and optimization methods of the complete production process to improve the performance and support better product quality [33]. Efficiency requirements are one of the key factor nowadays; therefore, optimization in what concern costs, energy and time will be one of the further purposes of development for manufacturing lines using ARS equipped with robot manipulators and visual servoing systems.

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