Hybrid Modelling and Simulation of a P/RML with Integrated Complex Autonomous Systems

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***Abstract*—The main objective of this research is to obtain a good model for the tasks performed by a flexible manufacturing mechatronics line (FMML) with integrated complex autonomous systems (CASs). The FMML has four collaborative workstations, line shaped, and being serviced by two CASs, wheeled mobile robots (WMRs) with robotic manipulators (RMs), for caching, transporting and releasing work piece. The decision of a good or bad work piece is being taken after a quality test that is performed by last stations in the line. Following this hypothesis, the processing/reprocessing mechatronics line (P/RML) serviced by two complex autonomous systems, and visual servoing systems, was modelled as synchronized hybrid Petri nets (SHPN). The complex autonomous system are controlled in trajectory tracking using sliding mode control (SMC) method, while RMs are positioned by visual servoing systems for caching and releasing work piece.**

Keywords—FMML, P/RML, CAS, WMR, RM, SM, visual servoing.

I. Introduction

The expansion in the processing and assembly market forces the important industrial companies to develop new techniques for facing the evolution, in order to improve their relationships with customers and to ensure higher productivity. One of the methods for facing these new requirements implies using flexible manufacturing systems because of their capabilities of adapting. For increasing the reliability of the system and also for optimizing the process different robotic structures had been used and integrated within the production lines. Robotic structures integration may also reduce or eliminate uncertainties and safety risks because of the intervention of the human operator in the process.

In processing/reprocessing systems, due to the large amount of tasks, conditions and operations, the modelling structure involves very complex aspects. That is why the use of hybrid modelling has an important contribution for system developing. In this case, the P/RML components by their discreet or continuous behaviour will give the hybrid aspect of the line. Hybrid Petri Nets (HPNs) had been used for modelling different kinds of systems, like shown in [2], [5], [6], [11], [12]. Another important aspect for modelling a production line is the quality test. In real time flexible processing lines also ensure the needed quality tests, step that could be made at the end of the line, or in a specific phase of the process, depending on the complexity of the activity. The aim of the quality test is to detect different kinds of defects that can appear during the process. In the case of a flexible processing line the scrap pieces resulted after such a quality test should be sent, using a transporting operation, to reprocessing, which can be done on the same line, or in a specific station dedicated for this scope.

The main objective for this research paper is to model a flexible processing line. One of the best and efficient modelling tool is Petri Nets, due to the capacity to formally check the obtained model. The modelling with Petri Nets will take care of the discreet operations of the line, on one hand, and the continuous modelling of the mobile robot's movement for piece recovery and transport. Another objective consists in customizing the obtained model in order to improve the P/RML's performance. After the real time implementation the structure will be able to control the P/RML in full automated mode and this will allow the developing of operations like processing, transport and manipulation without the human operator's intervention. From the timeline point of view, there are two kind of general operations in the system. First, the processing operation in the P/RML will be a periodic job while the transporting and reprocessing tasks will be externally triggered and will be started after a quality test result of rejected piece.

This paper is divided in 7 sections: Section 2 describes the P/RML, the two WMR's used for recovery and transport and the RM, Section 3 presents the constraints that have been imposed for the system analysis and for determining the model of the line; Next, in Section 4 is presented the SHPN

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model obtained after the analysis and in Section 5 some simulation results after simulating the model in the modelling and simulation tools Sirphyco and Visual Object Net++. Section 6 presents the real time control of the processing line while using autonomous systems with visual servoing for control of the RM's and finally in Section 7 are presented some final remarks.

II. P/RML SERVICED BY CAS

A. *Hardware structure of the P/RML, WMR's and RM*

In this paper is used a didactic mechatronics line FESTO MPS-200 for developing a P/RML. The line has 4 workstations in order to ensure the necessary operations for work piece processing. These stations are controlled by a separate Siemens S7 300 PLC and each of them ensures the operations in different stages: buffer, handling, processing and sorting. For the recovery operation is used the Pioneer P3-DX WMR, which has 2 driving wheels and 1 free wheel. For the transport operation is used the PeopleBot WMR which is built on the same Mobile Robots platform as Pioneer. The control of the WMR's is done by a specialized application developed and executed on a remote PC that transmits commands via Wi-Fi Link, [5]. On the Pioneer WMR is also fixed a RM with 5 degrees of freedom and a gripper, also controlled via Wi-Fi. In order to return the piece to the line is used a fixed manipulator Cyton Gamma 1500 with 7 degrees of freedom which is connected via USB with the process PC. Synchronization of the line with the WMR and RM and guidance for piece recovery and return are ensured with 2 HD video cameras of the visual servoing system. The line, the WMRs, RMs and the main operations are shown in Fig. 1 and Fig. 2.

B. *Task planning of P/RML*

With the given hardware structure, the main operations of the P/RML can be separated into a few essential tasks, [7]. For flexibility reasons these tasks will be parallel related with those tasks that ensure positioning for piece recovery. The hierarchical graph model used for hybrid modelling is shown in [9] and [10]. The main structure of the P/RML along with main field distances regarding P/RML and WMR are shown in Fig. 3. The main task of the WMR is to recover work pieces that are rejected at the quality test and transport them at the beginning of the line for reprocessing. This task of recovering will be a random event. An oriented graph that defines the processing cycle is shown in Fig.4.

III. ASSUMPTIONS MADE FOR MODELLING THE P/RML SERVICED BY CAS

Specialized processing line represents the base of an flexible industrial production line that gives a high range of standard products. The types of processing lines lately developed depend on aspects like operation modes, operation lengths and types of finished products [8]. In the case of this processing line some assumptions have been made in order to clarify constraints that have to be imposed for operation:

Fig. 1. P/RML serviced by Pioneer and PeopleBot

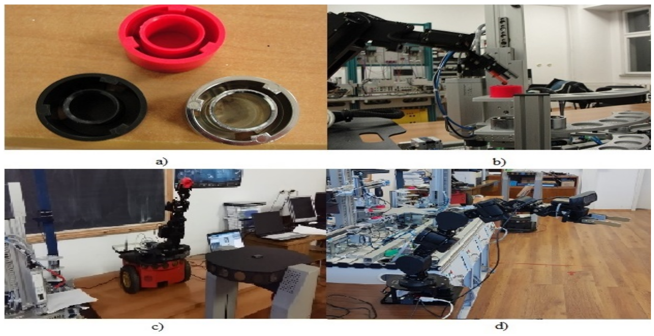

Fig. 2. a) types of work pieces used; b) WMR Pioneer with RM while servicing P/RML; c) Pioneer sending piece to PeopleBot for transporting d) Cyton Arm used for returning piece

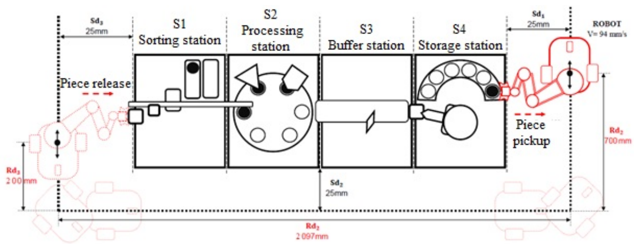

Fig. 3. Main structure of flexible line Festo MPS-200

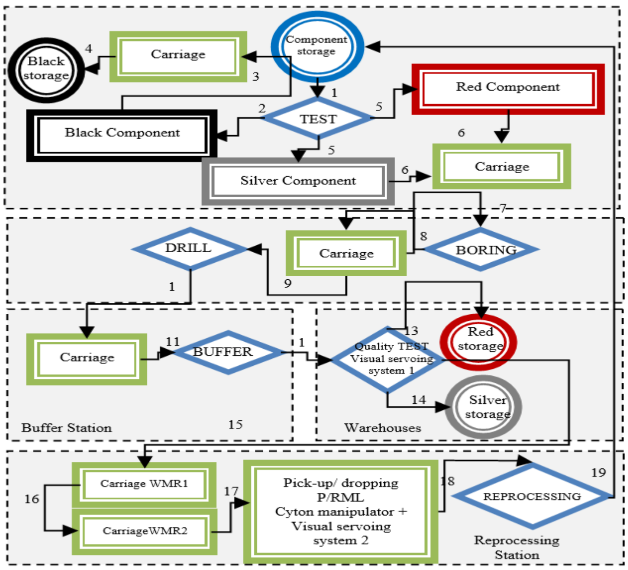

Fig. 4. Oriented graph for defining the processing/reprocessing cycle

A.1.–The mechatronics line will be declared deterministic and with a single model;

A.2.–The number of the stations involved in processing is previously known and will remain the same during the whole process;

A.3.–Only one type of work piece is to be reprocessed;

A.4.–All conditions and parameters of the process are initially known. This includes task durations, costs and quantity of work pieces that will take part in the process;

A.5.–The workstations of the mechatronics line have a linear distribution;

A.6.–The operations for processing and reprocessing are executed on the same line and only to one piece at a time.

A.7.–A red work piece will mean that the quality test is not passed and reprocessing is needed;

A.8.–In the deposit, the first level from the top is for rejected work pieces.

WMR's use is justified for collaborating with the P/RML in order to recover the rejected work pieces and transport them for reprocessing at the beginning of the line. The path and distances that the WMR's should pass are shown in Fig. 3, with some notations: R_L^1 shows the WMR position for work piece recovering; R_L^2 shows the WMR position for work piece depositing; T_L^1 shows the place where the work piece to be reprocessed is put, so that the recovering WMR could grab it; T_L^2 shows the position where WMR should go in order to return the work piece that will be reprocessed.

IV. SHPN Model of the P/RML while Serviced by CAS

A. *SHPN model representation*

The hybrid aspect of the P/RML with CAS model will be determined knowing the defining variables for transporting distances that the WMR's go through in order to recover and transport the piece.

The global model of the P/RML serviced by CAS is obtained considering the hybrid aspect of the operations. Thus, like shown in [2], if it is considered as the discrete part the operations of the flexible processing line and as continuous part the CAS displacement while serving the P/RML, the Petri Net model will be THPN (Timed Hybrid Petri Nets), [1].

Adding the apparition of external events used for synchronization of the P/RML and the CAS, the final model will have a SHPN structure that is shown in Fig. 5. The structure presented is obtained after having complete models for all the components of the process which is done with the help of three PN structures with a specific functionality: Timed PN (TPN), Synchronized PN (SPN) and THPN. Depending on the need, each of the models represent a sequence in the real time control operation, as it follows: TPN type for processing/ reprocessing operations and SPN+TPN type for work piece retrieving, transport and manipulation.

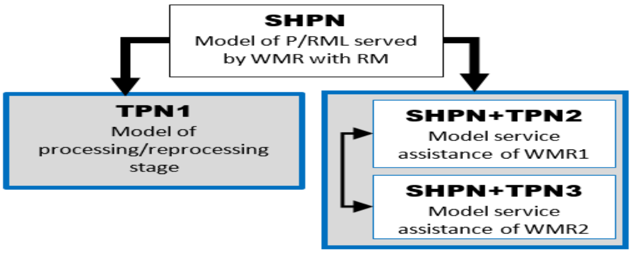

Fig. 5. Structure of the SHPN model

B. *SHPN model developing*

The SHPN model theory defines it as a triplet:

$$SHPN = \langle THPN,\ \ E_d,\ \ Sync \rangle \tag{1}$$

in which $THPN$ is a septuplet as it follows:

$$THPN = \langle P,\ T,\ Pre,\ Post,\ m_0,\ h,\ tempo \rangle \tag{2}$$

and E_d represents a set of external events;

$Sync$ is a function that will relate the set of discrete transitions to the external events set for synchronization;

$$Sync : T \rightarrow E_d \tag{3}$$

$$P = P_d \cup P_c \tag{4}$$

is a set of finite places, where:

$$P_d = \{P_{d_i}\}_{i=\overline{1,13}} \cup \{P_{r_j}\}_{j=\overline{1,5}} \tag{5}$$

with $\{P_{d_i}\}_{i=\overline{1,13}}$ representing the discrete places that are to be related to the operations of the P/RML (handling, drilling, boring, sorting etc.) and $\{P_{r_j}\}_{j=\overline{1,5}}$ the discrete places that define the CAS movement;

$$P_c = \{P_{c_k}\}_{k=\overline{1,2}}. \tag{6}$$

with $\{P_{c_k}\}_{k=\overline{1,2}}$ defines the continuous places of the CAS displacement.

$$T = T_d \cup T_c \tag{7}$$

is the set of finite transitions, where:

$$T_d = \{T_{d_i}\}_{i=\overline{1,10}} \cup \{T_{r_j}\}_{j=\overline{1,8}} \tag{8}$$

with $\{T_{d_i}\}_{i=\overline{1,10}}$ the discrete transitions set triggered for executing processing for a work piece and $\{T_{r_j}\}_{j=\overline{1,8}}$ defining the CAS discrete transitions set triggered for robots displacement while returning the work-piece for reprocessing;

$$T_c = \{T_{c_k}\}_{k=\overline{1,2}} \quad (9)$$

$\{T_{c_k}\}_{k=\overline{1,2}}$ the continuous transitions set triggered for the CAS transporting the work-piece at the beginning of the line;

Remark 1: The above shown sets P and T will be disjointed, $P \cap T = \varnothing$;

$Pre : P \times T \to Q_+$ is the input incidence function;

$Post : P \times T \to Q_+$ is the output incidence function;

Remark 2: While defining Pre, $Post$ and m_0, in the case where $P_i \in P_d$, the functions will be defined in N, and in the case where $P_i \in P_c$, the functions will be defined in Q_+

$m_0 : P \to R_+$ is the initial marking;

$$h : P \cup T \to \{D, C\} \quad (10)$$

known as the "hybrid function", applied for both discrete or continuous places and transitions

$$h : P_d \cup T_d \to \{D\};\ h : P_c \cup T_c \to \{C\}, \quad (11)$$

tempo is the function that defines the timings associated to the transitions in the network.

$$tempo : T \to Q_+ \cup \{0\} \quad (12)$$

If $T_j \in T_d$, then $d_j = tempo(T_j)$ is known as the timing associated with T_j. If $T_{cr} \in T_c$ then

$$U_r = \frac{1}{tempo(T_c)} \quad (13)$$

is the flow rate associated with T_c. For $T_c = \{T_{c_k}\}_{k=\overline{1,2}}$, $U_{c_k} = U_r; U_{r\max} = V_r$, where U_c is the variable flow of CAS displacement between continuous places. It will be considered the average speed of the WMR, $V_r = 94 mm/s$.

Definition 1: The ED-enabling degree of a C-transition T_j for a marking m, denoted by $ED(T_j, m)$, is the enabling degree of T_j after all the arcs, from a $C-$place to a $C-$transition, have been deleted.

$$ED(T_j, m) = \min_{P_i \in {}^0T_j \cap P^D} \left\lfloor \frac{m_i}{Pre(P_i, T_j)} \right\rfloor \quad (14)$$

Definition 2: The maximum firing speed of transition T_c is the product of its flow rate U_r by its ED-enabling degree.

Definitions 1 and 2, will have a general description as

$$ED(T_{c_j}, m_{c(j+1)}) = \{0, 1\} \quad (15)$$

where: $m_{c(j+1)} = V_j \cdot w(T_{cj} \times P_{c(j+1)})$ is the mark associated to a continuous place;

$w(T_{cr} \times P_{cr+1}) = D(W_{N+1-j}, N_{d_{j+1}}) / D(N_{d_j}, W_{N+1-j})$ is the weight of the arc connecting a continuous transition to a continuous place of the WMR.

For $N = 2$ the arches $(P_i \times T_j)$, have a weight equal to one, where: $P_i = \{\text{WMR } state1, WMR\ state2\} \in^o \{Tc_k\}_{k=\overline{1,10}} \cap P_d$.

Remark 3: For a synchronized Petri Net, a transition is enabled if each of its input places has enough tokens.

V. Final SHPN Model Simulation and Results

After testing and simulation using Sirphyco simulation package a final SHPN model has been obtained, shown in Fig. 6. The advantage of common simulation of both discrete and continuous actions in the model is that the interaction between the two parts can be obtained and analyzed. Also using the hybrid model simulation the maximum speed of the two CAS collaborating with the P/RML has been obtained.

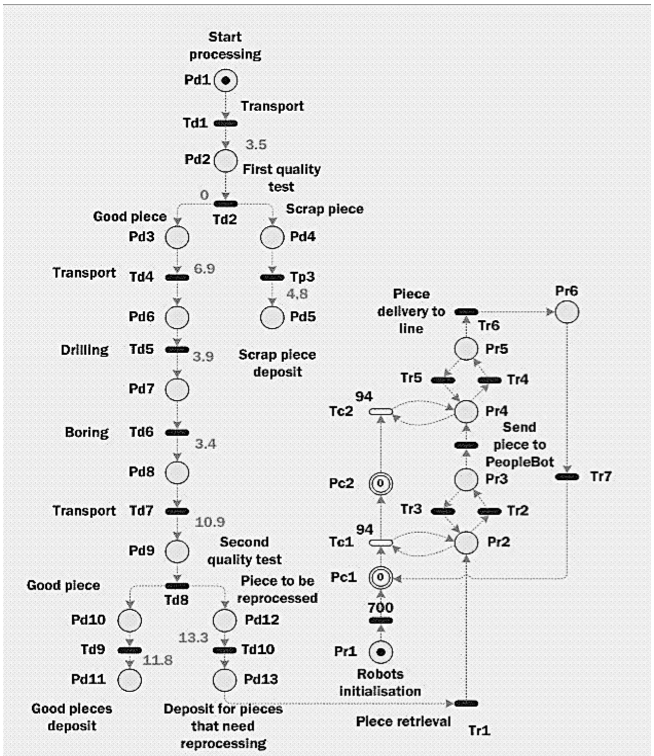

Fig. 6. The Petri Nets Graph for hybrid modelling of the P/RML

The speed was computed so that the cycle time for work piece recovery and transporting is minimum. Also are taken into account the hardware constraints of the CAS for obtaining the best speed. By using the SHPN model it is obtained a unique and precise connetionc between the TPN which model the P/RML tasks and the THPN which model the operations of CAS while retrieving and transporting work pieces. In the complete graph, represented in Fig. 6, each task performed by the P/RML like buffering, handling drilling, boring etc is very clear time determined, along with the durations of WMR's movement. Fig. 7 and Fig. 8 present simulation results of the obtained model and it can be seen that the time ranges correspond to the given reality.

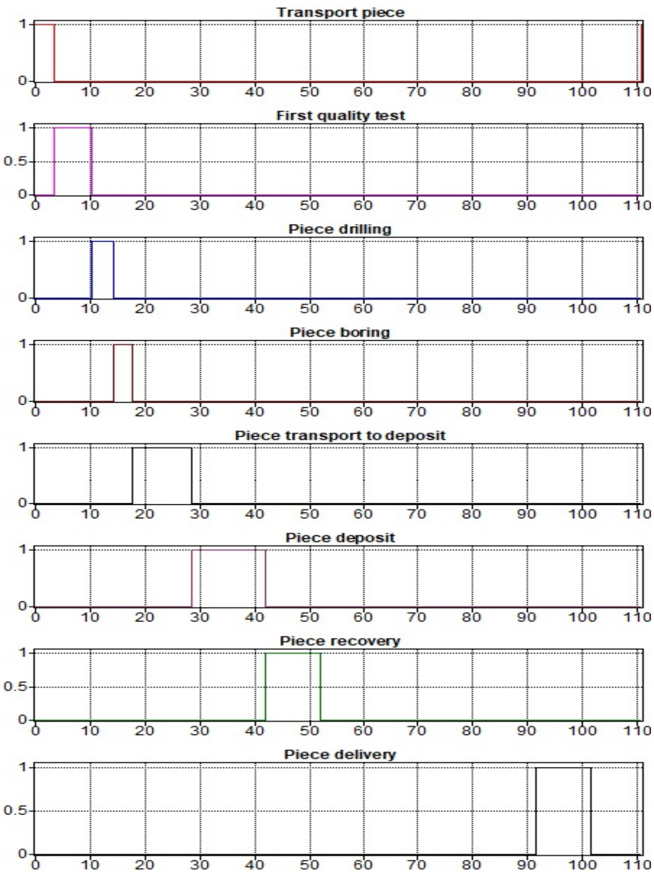

Fig. 7. Evolution of discrete transitions of the P/RML

The CAS are initializing and then the Pioneer WMR waits for an external event that is described by the existence of a work piece that could be reprocessed. The video system used for synchronization detects the appearance of the work piece and creates this external event which will trigger the robot for retrieving. Next, the Pioneer robot will put the recovered work piece on the PeopleBot for transporting. Two synchronization signals will be needed:

- Edd_1: WMR synchronization with START PROCESSING/REPROCESSING;

- Edd_2: WMR synchronization with P/RML for reprocessing of the work-piece.

VI. Implementation of the Real Time Control Structure

Combining the results of the obtained SHPN model and a MATLAB platform for video processing and synchronization a real time control structure was developed. The synchronization signals are used from the 2 cameras mounted on the first workstation and on the fixed Cyton manipulator [2]. The movements of the CAS are controlled via sliding-mode with the kinematic model of the mobile platform [3],[5].

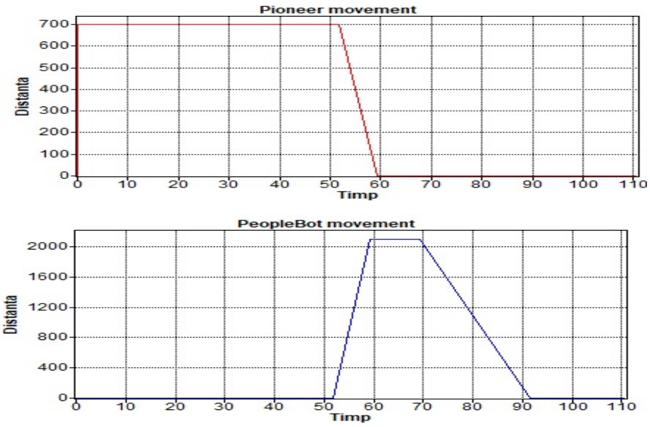

Fig. 8. Evolution of continuous transitions of the P/RML

Using this approach for real time control of the processing line will give the minimum cycle time achievement for a work piece processing. SMC of the CAS while collaborating with the P/RML could not handle issues related to the probability of uncertainty like: damaged sensors or actuators, false information or space blockage, [4]. Using the MATLAB program for mobile video processing, the Cyton RM is guided for work piece recovery (Fig. 9). The MaATLAB application, detects the piece, marks it, computes image moments features to achieve the position needed for recovery and finally retrieves it from the transporting robot. The integrated communication block used for real time control and monitoring of the processing line served by CAS is shown in the diagram in Fig. 10.

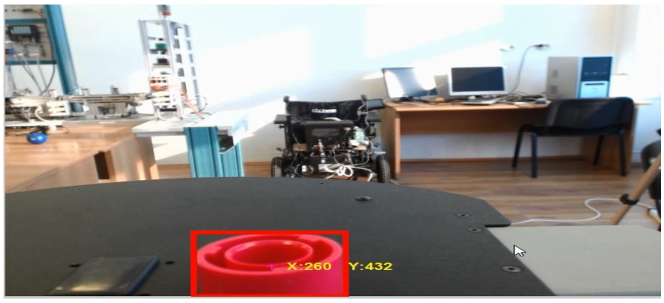

Fig. 9. Work piece recovery using Matlab application

VII. Conclusions

The main contributions in this paper are: organizational chart of tasks for the flexible processing line, the hybrid model of the processing line served by CAS, the model simulation and real time control of a P/RML. The two CAS integrated into the P/RML give SHPN model. SHPN model respects the 2 approaches necessary for complete modelling of the system: the discrete part for processing/reprocessing tasks and the continuous part for displacement of the CAS. Real-time control of a P/RML serviced by CAS is a combination of task planning, hybrid modelling, visual-servoing systems and SMC. The SHPN model will be dependent on certain state transitions generated by external events representing signals supplied by the video cameras. These external events trigger the CAS which are used for recovering and transporting a work piece that fails the quality test, to the first workstation of the P/RML in order to be reprocessed. Simulation of SHPN autonomously (simulation of HPN) model is useful to join the discrete dynamics of the P/RML with continuous dynamics of the WMR with RM.

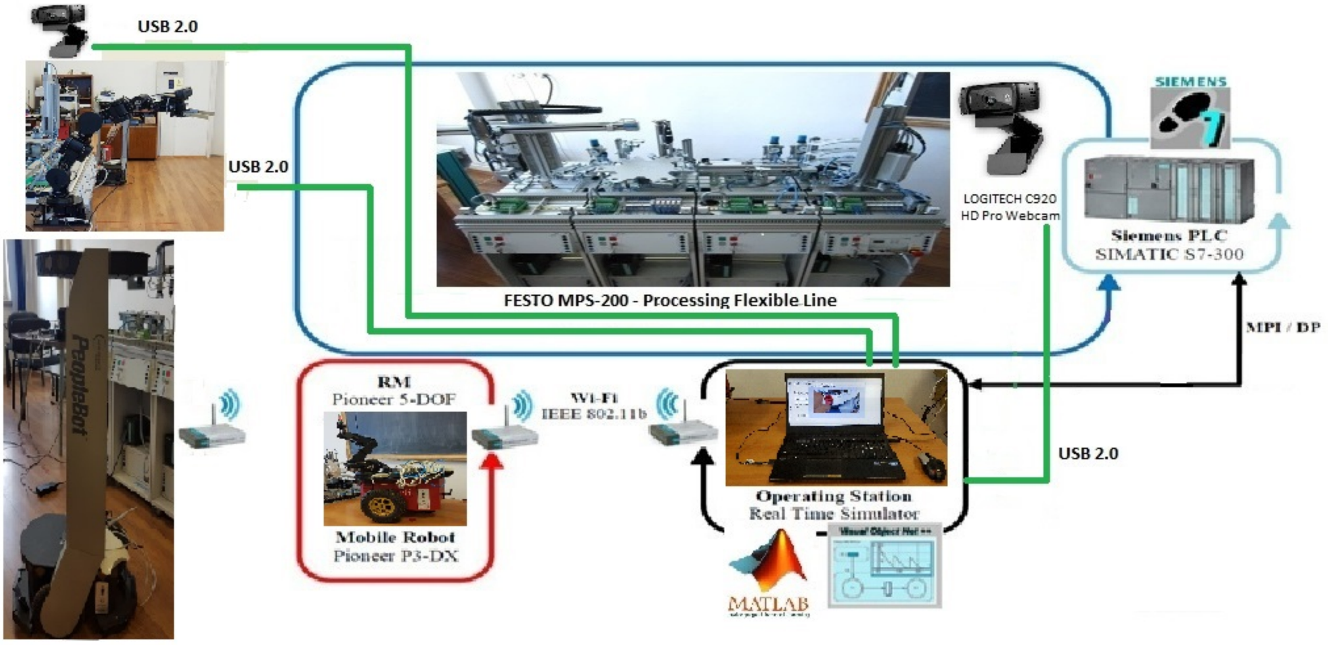

Fig. 10. Integrated communications for P/RML real time control

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