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# New Approach in Control of Assembly/Disassembly Line Served by Robotic Manipulator Mounted on Mobile Platform

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*Abstract*—**The new idea of this paper is to make reversible an assembly line, i.e. to allow complete disassembly, by using a mobile platform equipped with robotic manipulator. The approach is a hybrid one in which the assembly/disassembly line is the discrete system whilst the wheeled mobile robot (WMR) together with the robotic manipulator (RM) is considered the continuous one. The mobile platform is used only in disassembling operations, in order to transport the components from the disassembling locations to the storage locations. Therefore, Synchronized Hybrid Petri Nets (SHPN) approach is used in modeling and control. This hybrid system takes into consideration the distribution of the necessary tasks to perform the hybrid disassembly of the components, using robot synchronization with flexible line process. The ultimate goal is to make completely reversible the assembly line. The SHPN model is transposed into LabView platform, thus getting a control structure of the mechatronic line and of WMR.**

## I. Introduction

THIS approach presents a real-time control of an assembly/disassembly line served by RM based on a SHPN model. This model gives a high-level description of product to be disassembled. In this paper, the concepts of assembly/disassembly tasks are illustrated in SHPN model which respect both aspects: the discrete approach for the elementary tasks and the continuous approach for continuous movement of the robot serving the disassembly tasks. The system of reversible assembly/disassembly line served by robotic manipulators mounted on mobile platforms has a dynamics determined both, by events (events supplied by the control sequences of the automatic system) and by the interaction with the WMR, which represent the continuous time part of the system. The considered system is a hybrid one and requires specialized tools for modeling.

This paper is organized as follows: system description is presented in Section 2; in Section 3, the disassembly task scheduling is presented; the description of SHPN model together with external events are presented in Section 4; in Section 5, the closed loop control of WMR equipped with RM control is presented; Section 6 is reserved to monitoring and control of assembly and disassembly process by LabView interface; some conclusions and future research direction are presented in Section 7.

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## II. System Description

Since the assembly line HERA, Fig. 1, does not implement fully automatic disassembly, it proposes an extension of control system in order to perform complete disassembly. Therefore, the system designed initially to perform automatic assembling becomes a reversible one by the implementation of a hybrid control system for automatic disassembling, served by a mobile platform equipped with manipulator. The robot has its own odometric system and an on-board embedded microcontroller is able to read the position information and to send it over a radio communication link, according to a specific protocol and send the data to PLC on manufacturing flexible line. The WMR is equipped with RM having three articulations and one gripper paddles. The assembly/disassembly manufacturing flexible line is equipped with SIEMENS Simatic S7-300 PLC (Programmable Logic Controller), with 5 distributed modules connected by Profibus DP network for every station. Flexible line includes five individual workstations with different tasks, carrying and transporting, pneumatic workstations, conveyor belt, sorting unit, test station and warehouse. The work part carrier is used for carrying and transporting the four-piece work part on conveyor belt system. The work part carrier is equipped with 6-Bit identification which provides a large number of possible codes, read out by inductive sensors. The four-piece work part enable workflow model such as assemblies, testing, sorting, storage and disassemblies.

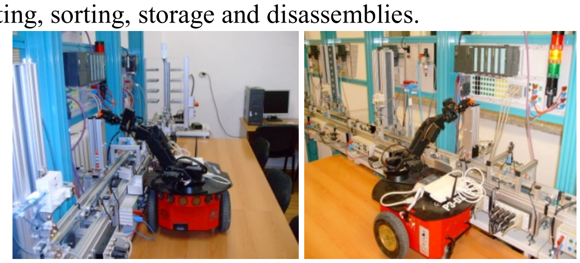

Fig. 1. Assembly line, Hera, served by WMR, Pioneer 3-DX, equipped with RM, Pioneer 5-DOF Arm.

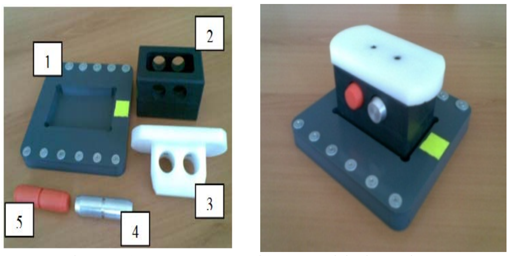


Fig. 2. a) components; b) assembled product.

The components to be assembled are (Figure 2): work part carrier (base platform) (1), body (2), cover (3), metal cylinder (4) and plastic cylinder (5).For disassembly operation, the configuration of the product's components is needed. This includes position and orientation of components and the material it is made, plastic or metal, elements that are relevant for activation the hybrid disassembly operation.

## III. DISASSEMBLY TASK PLANNING

A robotic disassembly system consists of many different kinds of components such as mobile robot, flexible line, sensors, handling mechanism, and parts. Different task may be assigned to and implemented by the system. The disassembly operation can be decomposed into a sequence of elementary tasks coupled in parallel with movements of pick-up/dropping /positioning of the robot. The assembly operation can by decompose into a sequence of elementary assembly tasks coupled in parallel with positioning tasks of work-piece along conveyor, as in [1], [2], and [4]. The hybrid disassembly strategy is based on the hierarchical model proposed in [5], [6], [7] and [8] which uses a graph representation of the product in which the relations among components are expressed by means of arrows. If the fully assembled product does not pass the quality test, the task planner provides the best sequence completely to disassemble the product, shown in Fig. 3 and 10.

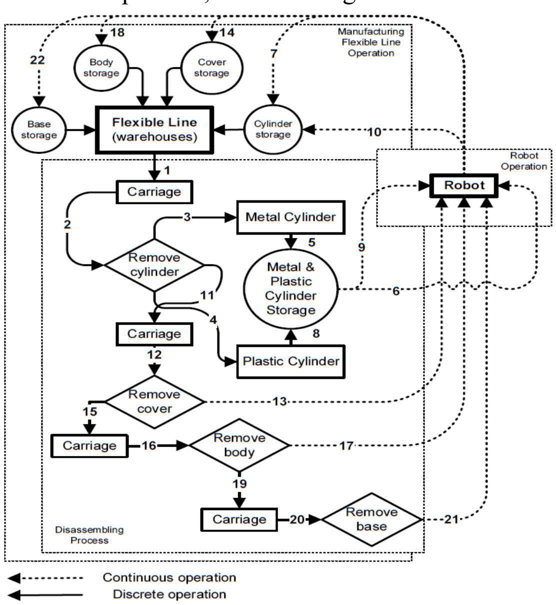


Fig. 3, Disassembly task planning.

## IV. SYNCHRONIZED HYBRID PETRI NET MODEL

The system of reversible assembly/disassembly line served, during disassembling process, by robotic manipulator mounted on mobile platform has a dynamics determined by events (events supplied by the control sequences of the automatic system) and by the interaction with the WMR, which represents the continuous time component of the system (Fig. 4). The considered system is a hybrid one and requires specialized tools for modeling as in [3]. The hybrid model is elaborated using the dedicated modeling tool, HPN, described in [9]. Combining the SED model of the analyzed system with the cyclic and continuous time of the robotic manipulator mounted on mobile platform, results a synchronized hybrid model, SHPN. SHPN structure from Fig. 4 and SHPN model from Fig. 5 is obtained by modeling of assembly/disassembly and continuous service assistance, for disassembly operations, performed by mobile platform equipped with manipulator. SHPN morphology results by integration three PN models. Each of these models has a specific typology: TPN (Timed PN), SPN (Synchronized PN) and THPN (Timed Hybrid PN). These models describe the following automatic operations:

- Assembling/storage in warehouses (TPN typology);
- Disassembling of damaged product (SPN and TPN typologies);
- Service assistance, during disassembling process, performed by the mobile robot equipped with manipulator (THPN typology).

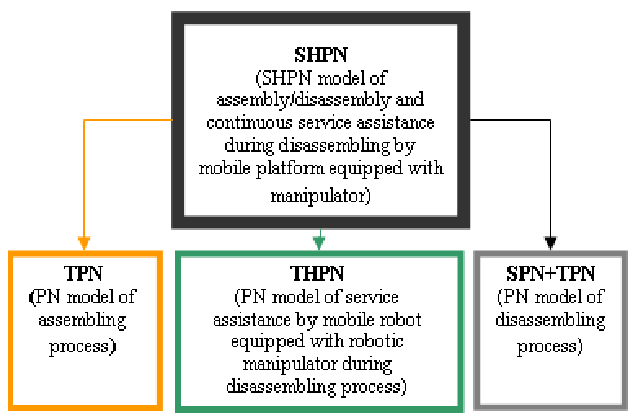


Fig. 4. SHPN decomposition in subsystems: assembling, WMR equipped with RM and disassembling

The SHPN model associated to the assembly/disassembly is a triple

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

such that: $THPN$ is a seventhly

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

$E$ is a set of external events

$$E = \left\{ E_i^1, E_j^2 \right\}_{\substack{i \in \{1,4,7,10,13\} \\ j \in \{3,6,9,12,15\}}} \cup \{e\}, \quad (3)$$

and $Sync$ is a function from the set of the transitions to the set of external events

$$Sync : T \to \left\{ E^1, E^2 \right\} \cup \{e\} \quad (4)$$

where $e$ is the always occurring event (it is the neutral element of the monoid $E^*$).

It follows detailed explanation for each component of SHPN model from (1):

$$P = \{P_1, P_2, ... P_n\} = P^D \cup P^C \quad (5)$$

is a finite, not empty, set of places with $P^D$ the set of discrete places

$$P^D = \{Pda_i\}_{i=\overline{1,22}} \cup \left\{ Pdd_j \right\}_{j=\overline{1,26}} \cup \{Pdr_k\}_{k=\overline{1,16}} \quad (6)$$

and $P^C$ the set of continuous places

$$P^C = \{Pcr_k\}_{k=\overline{1,15}}, \quad (7)$$

$\{Pda_i\}_{i=\overline{1,22}}$ is the set of discrete places for assembly process;
$\left\{ Pdd_j \right\}_{j=\overline{1,26}}$ is the set of discrete places for disassembly process;
$\{Pdr_k\}_{k=\overline{1,16}}$ is the set of discrete places for the states of mobile robot while serving disassembly process;
$\{Pcr_k\}_{k=\overline{1,15}}$ is the set of continuous places associated to the distances performing by the mobile robot for each disassembly operation in order to transport the disassembled component from the disassembled location to the storage location;

$$T = \{T_1, T_2, ..., T_m\} = T^D \cup T^C \quad (8)$$

is a finite, not empty, set of transitions with $T^D$ the set of discrete transitions

$$T^D = \{Tda_i\}_{i=\overline{1,14}} \cup \left\{ Tdd_j \right\}_{j=\overline{1,16}} \cup \{Tdr_k\}_{k=\overline{1,21}} \quad (9)$$

and $T^C$ the set of continuous transitions

$$T^C = \{Tcr_k\}_{k=1,10}, \quad (10)$$

$\{Tda_i\}_{i=\overline{1,14}}$ is the discrete transitions for assembly operations;

$\left\{ Tdd_j \right\}_{j=\overline{1,16}}$ is the set of discrete transitions for disassembly operations model;
$\{Tdr_k\}_{k=\overline{1,21}}$ is the set of discrete transitions for states of mobile robot while serving disassembly operations;
$\{Tcr_k\}_{k=1,10}$ is the set of continuous transitions associated of distances performing by the mobile robot for each disassembly operation. To these transitions is associated the maximum linear speed of the WMR.
The sets $P$ and $T$ are disjointed $P \cap T = \varnothing$;

$Pre : P \times T \to Q_+$ or $N$ is the input incidence application;
$Post : P \times T \to Q_+$ or $N$ is the output incidence application;

Remark 1: In the definitions of $Pre$, $Post$ and $m_0$, $N$ corresponds to the case where $P_i \in P^D$, and $Q_+$ or $R_+$ corresponds to the case where $P_i \in P^C$.

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

$$h : P \cup T \to \{D, C\}, \quad (11)$$

called "hybrid function", indicates for every node whether it is a discrete node (sets $P^D$ and $T^D$) or a continuous one (sets $P^C$ and $T^C$),

$$h : P^D \cup T^D \to \{D\};\ h : P^C \cup T^C \to \{C\}; \quad (12)$$

$tempo$ is a function from the set $T$ of transitions to the set of positive or zero rational numbers,

$$tempo : T \to Q_+ \cup \{0\} \quad (13)$$

If $T_j \in T^D$, then $d_j = tempo(T_j)$ is timing associated with $T_j$.

For $T^D = \{Tda_i\}_{i=\overline{1,14}}$, then $d_{da_i} = 1$ where $d_{da_i}$ represents the delay associated to the corresponding assembling operation.

For $T^D = \left\{ Tdd_j \right\}_{j=\overline{1,16}}$, then $d_{dd_j} = 1$, where $d_{dd_j}$ represents the transportation delay between disassembling location.

$T^D = \{Tdr_k\}_{k=\overline{1,21}}$, then $d_{dr_k} = \{0,1\}$ where $d_{dr_k}$ represents picking up and dropping down delays of WMR equipped with RM in front of disassembling or storage locations.

If $T_j \in T^C$, then $U_j = \dfrac{1}{tempo(T_j)}$ is the flow rate associated to $T_j$.

For $T^C = \{Tcr_k\}_{k=\overline{1,10}}$, then

$U_{cr_k} = \{\{v_k\}_{k=i+4} \cup \{v_k\}_{k=i}\}_{i=\overline{1,6}}$, where $U_{cr}$ represents the variable flow of mobile robot displacement between disassembly stations.

*Definition 1:* The maximal firing speed of transition $T_j$ is the product of its flow rate $U_j$ by its D-enabling degree

$$V_j = U_j \cdot D(T_j, m) \tag{14}$$

*Definition 2:* The D-enabling degree of a C-transition $T_j$ for a marking $m$, denoted by $D(T_j, m)$, is the enabling degree of $T_j$ after all the arches from a C-place to a C-transition have been deleted:

$$D(T_j, m) = \min_{P_i \in {}^0T_j \cap P^D} \left\lfloor \frac{m_i}{Pre(P_i, T_j)} \right\rfloor \tag{15}$$

Particularly, to the present SHPN, the arches $(P_i \times T_j)$, where $P_i = \{ROBOT\ state1, ROBOT\ state2\} \in {}^o\{Tcr_k\}_{k=\overline{1,10}} \cap P^D$, have the weight equal to one. Therefore, $Vcr_k = Ucr_k = 2|_{k=\overline{1,10}}$ (Fig. 6).

$\{E_i^1\}$, $i \in \{1,4,7,10,13\}$ is the set of external synchronization signals, supplied by the sensors, corresponding to STOP line and START disassembling;

$\{E_j^2\}$, $j \in \{3,6,9,12,15\}$ is the set of external synchronization signals, supplied by the sensors, corresponding to PICKING UP of disassembled component and START line;

*Remark 2*: for a synchronized PN a transition is enabled when each of its input places contains enough tokens. If it is enabled, it is firable on occurrence of the event associated with it.

*Sync* is a function from the set $T$ of the transitions to the set of external events

$$Sync: T \rightarrow \{E^1, E^2\} \cup \{e\} \tag{16}$$

and can be expressed as follow:

$$Sync: \{Tdd_j\}_{j=\overline{1,16}} \rightarrow \{E^1, E^2\}; \tag{17}$$

where:

$$Sync: \{Tdd_i\}_{i=\{1,4,7,13\}} \rightarrow \{E_i^1\}_{i=\{1,4,7,13\}}; \tag{18}$$

$$Sync: \{Tdd_i\}_{i=\{3,6,9,12,15\}} \rightarrow \{E_i^2\}_{i=\{3,6,9,12,15\}}; \tag{19}$$

$$Sync: \{Tdd_j\}_{j=\overline{1,16}} \cup \{Tdr_k\}_{k=\overline{1,21}} \cup \{Tcr_k\}_{k=\overline{1,10}} \rightarrow e. \tag{20}$$

The hybrid aspect of SHPN model is determined by the variables associated of distances. These distances are performed by mobile platform between disassembling locations.

$\{D_L^i\}_{i=\overline{1,5}}$ represent disassembling locations, $\{D_L^1, D_L^2\}$ for cylinders and $\{D_L^3, D_L^4, D_L^5\}$ for cover, body and base, respectively (Fig. 2). The variation of these variables is with constant or variable speed. These variations represent the mobile platform speed between $\{D_L^i\}_{i=\overline{1,5}}$ points of mecathronic line.

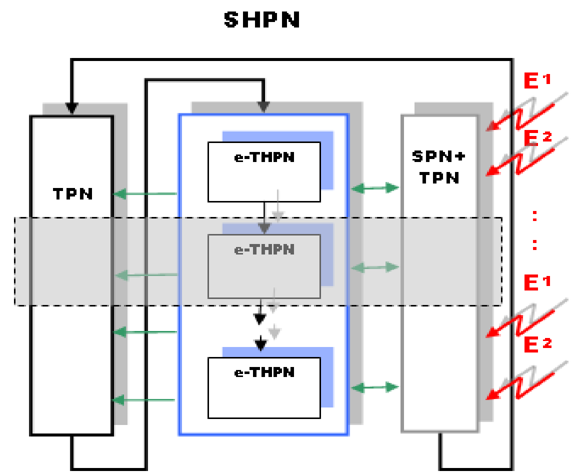


Fig.5. The SHPN representation by blocks with elementary THPN modules, e-THPN.

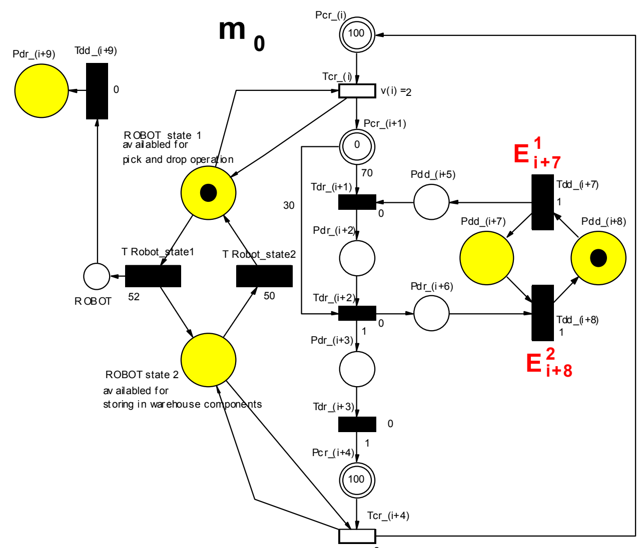


Fig.6. Elementary THPN module, e-THPN

The analysis of SHPN model is relevant at the basic level accordingly with an elementary THPN module, denoted e-THPN. SHPN model is obtained by recurrent assembling of these elementary e-THPN modules (corresponding to each basic disassembling and WMR equipped with RM service assistance). The SHPN global model is an exclusive relationship between TPN associated to the assembling process, elementary THPN modules associated to WMR service assistance and SPN with TPN associated to disassembling process.

## V. WMR Discrete-time Sliding-Mode Control

Discrete-time, sliding-mode control, in trajectory-tracking, based on kinematic model is used in order to control WMR Pioneer 3-DX. The structure of the closed-loop is shown in Fig. 7. Pioneer 3-DX is a mobile platform with two driving wheels and one rear wheel. The robotic manipulator, Pioneer 5-DOF Arm, mounted on mobile platform, is controlled in open loop by step by step motors located in each joint.

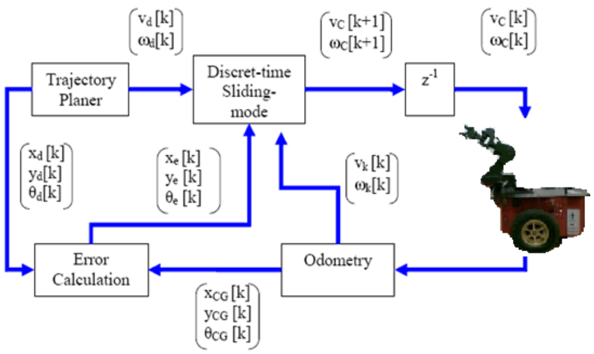


Fig.7. Closed loop WMR control

Linear velocity of the WMR disassembly complete cycle in trajectory tracking, real-time, sliding-mode control is presented in Fig.8. The positioning of the gripper in order to grab the disassembled component and its storage in the warehouse has been made by a visual servoing system.

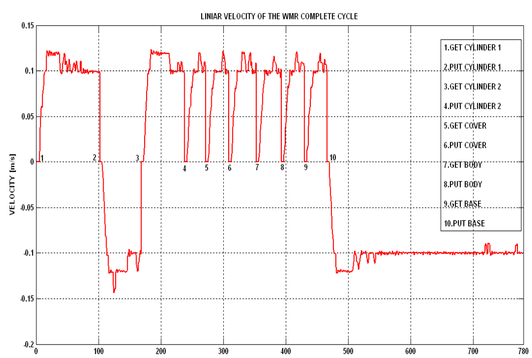


Fig.8. WMR linear velocity during disassembling operations

## VI. Real-Time Control of Reversible Assembly/Disassembly Line

The HPN model is transposed under LabView platform in a real-time application (Fig.11). The real-time application is obtained by interfacing HPN model with synchronized signals taken by acquisition of the real process. At the conceptual level, the control platform corresponds to a synchronized HPN model (SHPN). The synchronization of real-time application with the controlled process is achieved by the positioning signals of the work piece along the conveyor taken by acquisition board NI USB-6008. The synchronization signals, used in the LabView application of real-time control, validate certain transitions into SHPN model. These transitions are conditioned by the associated signals of position work piece on the conveyor track. The synchronization will lead to initialize robot and to monitoring/control operations of assembly/disassembly of WMR served with RM. In this way both the robot and flexible line are controlled, in order to achieve a minimal time cycle of assembly/disassembly. The initialization of the robot is performed by a signal transmitted through a wireless access point mounted on the robot, received by the LabView application. Through the acquisition board, the state signals are transmitted to the flexible line in order to control position of the work piece along with the conveyor and for synchronize robot with the flexible line. The signal transmitted by the acquisition board to SIMATIC S7-300 PLC of flexible line is done by the I/O module of LabView. The positioning of the gripper in order to grab the disassembled component and its storage in the warehouse has been made by a visual servoing system. The state transition of disassembled components and of the WMR for transporting those to the storage location are shown in Fig.9.

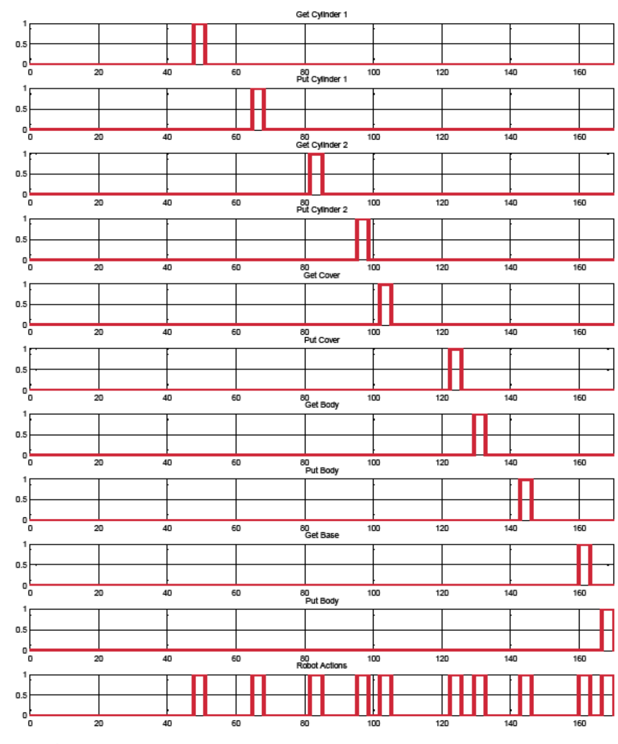


Fig.9. State transition of disassembly components and their transportation to the storage location

## VII. Conclusion

A SHPN model for control of fully reversible assembly/disassembly manufacturing line is presented in this paper. The SHPN model is conditioned on certain state transitions by external signals supplied by the sensors. In order to perform disassembly, a robotic manipulator mounted on a mobile platform is used. Therefore, the assembly line becomes reversible, i.e. executes automated disassembly. A disassembly process is started when the final product, obtained by assembly, is damaged. The disassembled components are recovered and transported to storage locations, in order to be used again in assembly process. As a future research direction, different mobile robots equipped with robotic manipulator should be used in order to transport small, medium and heavy weights disassembled components.

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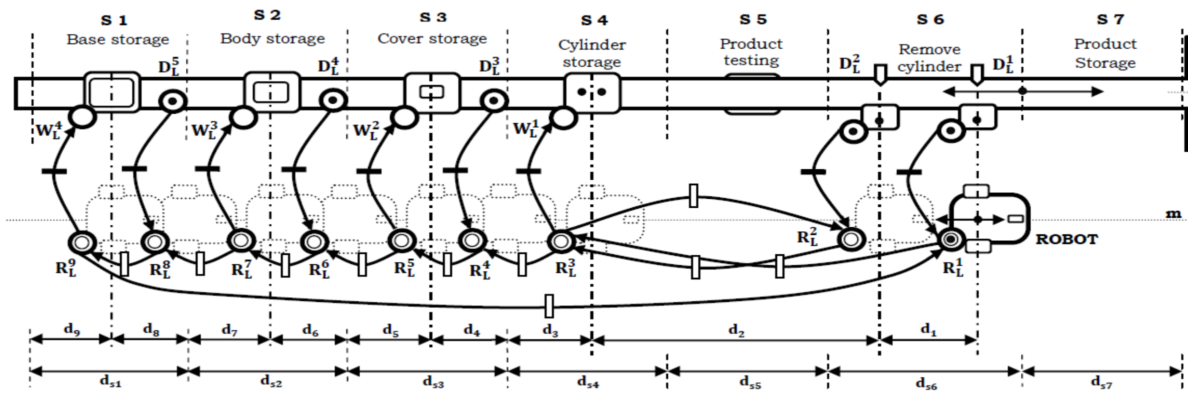


Fig.10. Disassembly operations and components transportation to storage warehouses by WMR equipped with RM

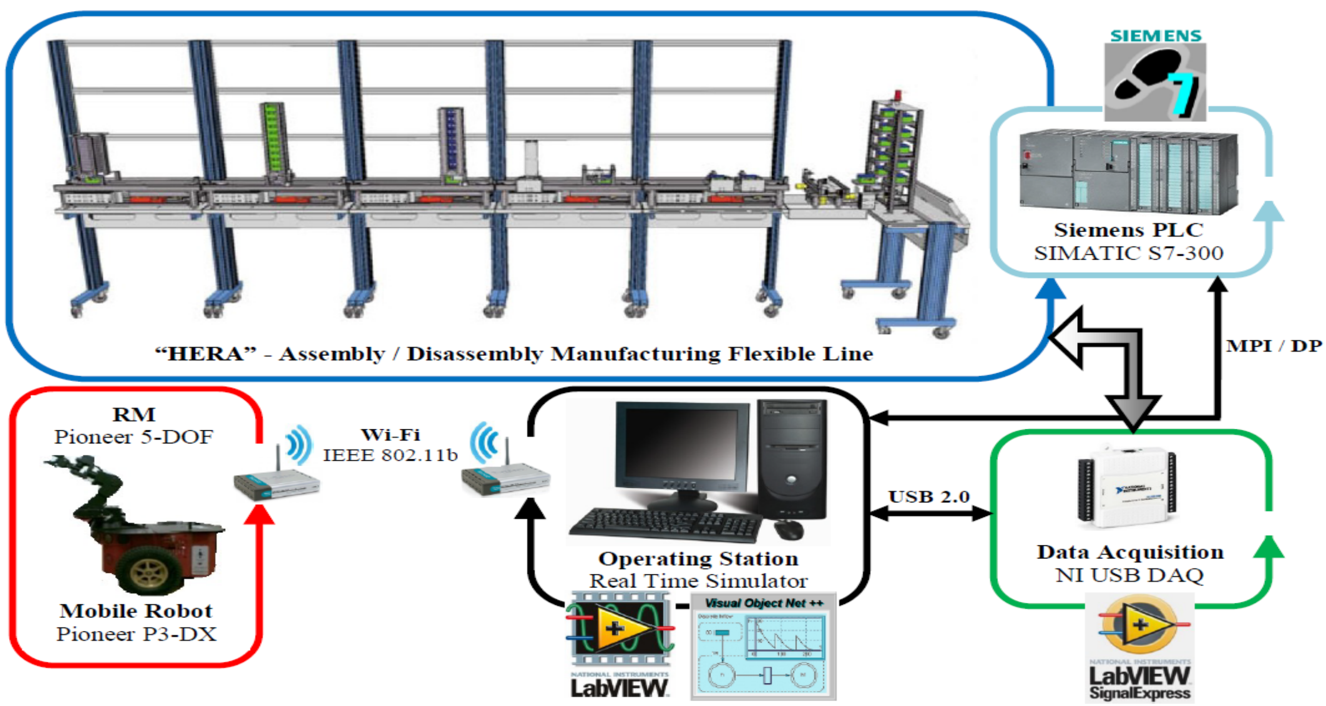


Fig. 11. Control structure of assembly/disassembly line served by WMR equipped with RM