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Modelling and control of an assembly/disassembly mechatronics line served by mobile robot with manipulator

Eugenia Minca [a], Adrian Filipescu [b,*], Alina Voda [c]

[a] Department of Automation, Computer Science and Electrical Engineering, "Valahia" University of Targoviste, Bulevardul Unirii 18-20, Targoviste, Romania
[b] Department of Automation and Electrical Engineering, "Dunarea de Jos" University of Galati, Street Domneasca, 47, Galati 800008, Romania
[c] Grenoble Image Parole Signal Automatique (GIPSA-lab), University Joseph Fourier Grenoble 1/CNRS, UMR 5216, B.P. 46, F-38402 St. Martin d'Heres, France

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ABSTRACT

The aim of this paper is to reverse an assembly line using a mobile platform equipped with a manipulator. By reversibility we mean that the line is able to perform disassembly. For this purpose, an assembly/disassembly line balancing (A/DLB) and a synchronised hybrid Petri nets (SHPN) model will be used to model and control an assembly/disassembly mechatronics line (A/DML), with a fixed number of workstations, served by a wheeled mobile robot (WMR) equipped with a robotic manipulator (RM). The SHPN model is a hybrid type, where A/DML is the discrete part, and WMR with RM is the continuous part. Moreover, the model operates in synchronised mode with signals from sensors. Disassembly starts after the assembly process and after the assembled piece fails the quality test, in order to recover the parts. The WMR with RM is used only during disassembly, to transport the parts from the disassembling locations to the storage locations. Using these models and a LabView platform, a real-time control structure has been designed and implemented, allowing automated assembly and disassembly, where the latter is assisted by a mobile platform equipped with a manipulator.

1. Introduction

The approach proposed in the paper responds to the concepts of planning and control of the processes of assembly/disassembly on mechatronics lines served by mobile platforms equipped with manipulators, with emphasis on the planning of operations.

An assembly line is a flow-oriented production system where the productive units perform operations on workstations, which may be configured as serial, parallel, circular, U-shaped, cellular or two-sided lines. The work pieces visit stations successively as they are moved along the line, usually by some kind of transport system, e.g., a conveyor belt (Choi, Zhang, Ng, & Lau, 1998). Disassembly operations involve separation of the reusable parts from the discarded products. These parts either undergo remanufacturing operations or are sold to suppliers (Kopacek & Kopacek, 1998; Seliger, Grudzien, & Zaidi, 1999). Assembly/disassembly manufacturing systems are real-time and complex control systems, which involve multiple operation conditions and tasks. Hybrid systems are currently the focus of considerable attention. The assembly/disassembly manufacturing lines served by mobile robots have hybrid characteristics, consisting of continuous dynamic behaviours and discrete event behaviours. Hybrid Petri Nets (HPNs) are tools used to model such systems (Ghomri & Alla, 2008; Minca, Filipescu, & Voda, 2012; Voda, Radaschin, Minca, & Filipescu, 2012). The assembly/disassembly plans are made up of parts or subassemblies that are fitted together (Albus & Meystel, 1996). Particularly relevant research topics include assembly/disassembly representations, work-cell planning, sequence planning, etc. Off-line task planning is a large area encompassing a diverse set of planning methodologies capable of producing a detailed operation plan, including planning sensory action, planning manipulator action, planning the trajectory of mobile robots (Gasparetto & Zanotto, 2007), rough motion planning, fine motion planning and other planning (Feng & Song, 2008). On-line planning addresses execution and reaction issues such as how to develop plans on-line, how to execute and monitor a plan developed off-line, and how to react to various situations that arise during plan execution (Ganget, Hattenberger, & Alami, 2005). These issues can be further classified into: plan monitoring, reactive scheduling, and behaviour-based action. The assembly/disassembly planning process involves more complex requirements such as geometric relationships, performance measurement and evaluation, resource scheduling, kinematics control, and system planning. This is a difficult task for complex assembly/disassembly lines in a concurrent and flexible manufacturing environment. These factors combined make real assembly/disassembly planning more difficult and require extensive experience

* Corresponding author. Tel.: +40 724537594; fax: +40 236460182.
E-mail addresses: eugenia.minca@valahia.ro (E. Minca), adrian.filipescu@ugal.ro (A. Filipescu), alina.voda@gipsa-lab.grenoble-inp.fr (A. Voda).

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and knowledge on the part of the designer and production engineer. Up to now, numerous techniques in task planning, such as use of binary matrices, directed graphs, establishment conditions, precedence relationships, AND/OR graphs (Cao & Sanderson, 1998), have been proposed for generation and representation, reasoning, and search of assembly plans in designing intelligent and efficient assembly/disassembly operations, where operators (robot or human) autonomously perform a given task based on certain designated, stored or sensed information. However, in a mobile robotic system with manipulator, a planning strategy oriented to the characteristics of the system is often more effective than techniques derived from domain-independent methods. Conventional representation of a system model without constraints may result in a huge search space for feasible plans. Using this model, the task planner can determine the sequence of components that must be removed to achieve a specific sequence of tasks. If the target consists of disassembling a specific component, the task planner can provide the best sequence for reaching the specific component (Moore, Gungor, & Gupta, 2001). If the fully assembled product fails the quality test, the task planner provides the best sequence for completely disassembling the product. A comprehensive knowledge-based approach to disassembly task planning is required, which considers all aspects of complex interaction and domain knowledge subjected to technical and economic constraints (David & Alla, 2010). Development of knowledge based on a HPN model integrated with a sequence generation algorithm was successfully applied to modelling and planning of a flexible disassembly process and system at a high level. However, the typology of the autonomous mobile robot with manipulator, disassembly planning method, and task level planning, greatly improves the efficiency of the entire process and reduces the cost of product disassembly. Task specification in low-level task planning consists in changing models or operation sequences (Hiraishi, 1999). This paper presents a Synchronised Hybrid Petri Nets (SHPN) model for an Assembly/Disassembly Mechatronics Line (A/DML) served by a Wheeled Mobile Robot (WMR) equipped with a Robotic Manipulator (RM), together with an Assembly/Disassembly Line Balancing (A/DLB) model. Disassembly line balancing is used to find the set of tasks assigned to each workstation for each product to be disassembled. The problem is critical for minimising the use of valuable resources (such as time and money) invested in disassembly, and maximising the level of automation of the disassembly process and the quality of the parts or materials recovered (McGovern & Gupta, 2007). In this thesis, we consider a Disassembly Line Balancing Problem (DLBP) with a fixed number of workstations so as to maximise the value of recovered parts. Lambert (2002) emphasises that a disassembly process does not imply a reverse assembly process. The A/DLB and SHPN models have been customised for an assembly mechatronics line, which assembles a 5-part product. Using the LabView platform, real-time control of A/DML served by WMR with RM is presented, based on A/DLB and SHPN models. These models provide a high-level description of the product to be disassembled. The aim is to assign the tasks to the disassembly line workstations so as to maximise the total value of the recovered parts. The disassembly operations are performed on the same assembly line, consisting of a number of linear configured workstations. The first workstation takes the product to be disassembled, and the parts are disconnected on different workstations. A cycle terminates, i.e. the product leaves the line, whenever all its required parts are disassembled. In this paper, the concepts of assembly/disassembly tasks are illustrated in a SHPN model, which complies with both aspects: the discrete approach for the elementary assembly/disassembly operations, and the continuous approach for displacement of WMR. Thus, the A/DML system becomes reversible and is served, during the disassembling process, by a robotic manipulator mounted on a mobile platform. The A/DML dynamics are determined by events, supplied by the control sequences of the automatic system, and by interaction with the WMR, which represents the continuous time part of the system. The considered system is a hybrid one and requires specialised tools for modelling. The hybrid model is elaborated using the dedicated modelling tool, HPN, described in David and Alla (2010). A SHPN model results from the combination of the SED model of the analysed system with the cyclic and continuous time of the WMR with RM.

The rest of the paper is organised as follows: in Section 2, useful preliminary assumptions are laid out for developing A/DLB and SHPN models; a model with an objective function, useful for optimising A/DBL, is presented in Section 3; the description of the A/DML served by WMR with RM is shown in Section 4; a SHPN model, in generalised and customised form, is elaborated in Section 5. Simulation results are also presented for the customised SHPN model associated with A/DML, served by WMMR equipped with RM; in Section 6, using the LabView platform, real-time control of A/DML is briefly presented, served by WMR equipped with RM, based on A/DLB and SHPN models; some final remarks can be found in Section 7.

2. Preliminary remarks concerning A/DLB and SHPN models

The assembly/disassembly line is served by a WMR equipped with RM during the disassembly phase, Fig. 1. The aim is to make the assembly/disassembly line balanced and reversible. Moreover, the mobile robot is used to carry the disassembled components to a proper storage warehouse.

2.1. Assembly assumptions

Assembly lines are special flow-line production systems, which are typical in industrial production of high quantity standardised commodities. According to Choi et al. (1998), there are several classification schemes for assembly lines, which take into account the nature of the products, operation modes and the nature of operation times. Corresponding to these classifications, the following assumptions hold concerning the assembly of mechatronics systems:

A.1. The A/DML is a single-model line, by the nature of the product, paced line (transfers between the workstations are

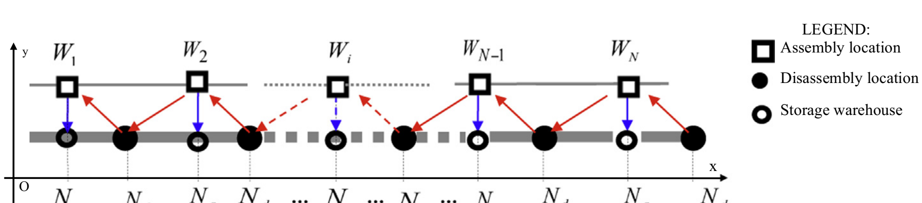

Fig. 1. Assembly/disassembly and storage warehouse locations.

synchronous), by the operation mode, and deterministic line, by the nature of operation times (times known certainly).
A.2. There is a fixed number of stations, while minimising cycle time with respect to assembly line balancing of the A/DML.

2.2. Disassembly assumptions

In Altekin, Kindlier, and Ozdemirel (2008) and Gungor and Gupta (2002), the DLB model is described for partial and complete disassembly, respectively.

The importance of disassembly lines in product recovery is discussed, as are also the various complications involved when creating an efficient disassembly line.

To elaborate the DLB model, the following assumptions must be made:

A.3. The disassembly line is paced.
A.4. One type of product is disassembled, and each product has an identical configuration.
A.5. The complete disassembly process is considered, and all parameters, i.e., task times, cycle times, part demands, costs, are known with certainty, i.e., deterministic.
A.6. There are N workstations, linear-configured with a first workstation taking the product to be disassembled. The number of workstations is the same as the number of parts released by disassembly.
A.7. Each period is specified by a single part disassembly hence there are N periods where each period is referred to as an elementary cycle. The same tasks run in each cycle, but with different durations.
A.8. Each task is specified by its cost and processing time. The part releasing tasks have additional parameters, i.e., revenues.
A.9. Disassembly process starts immediately after the assembly process and after the product fails the quality test.
A.10. Storage warehouse places are identical to positions where assembly occurs.
A.11. In an assembly/disassembly operation, only one part is assembled/disassembled.
A.12. By convention it is assumed that the end product fails the quality test if it contains cylinders of different materials.
A.13. Once the last remaining part in the disassembly process has been transported to the storage warehouse, a new assembly process will start.
A.14. Mobile platform displacement, in each elementary cycle, is linear, without obstacles and with the same constant speed.
Let N be the number of parts to be assembled and disassembled.
Let N_{a_i}, $i=\overline{1,N}$ be the assembly locations on the positive direction of the Ox axis.
Let N_{d_j}, $j=\overline{1,N}$ be the disassembly locations on the negative direction of the Ox axis.
Let W_i; $i=\overline{1,N}$ be the warehouse locations, which are identical to the assembly locations.
Let $D(N_{d_j},W_{N+1-j})$ be the distance between the disassembly location, N_{d_j}, and the corresponding storage warehouse, W_{N+1-j}.
Let $D(W_{N+1-j},N_{d_{j+1}})$ be the distance between the last storage warehouse W_{N+1-j} and the next disassembly location $N_{d_{j+1}}$.
Let $D_{r_j}=D(N_{d_j},W_{N+1-j})+D(W_{N+1-j},N_{d_{j+1}})$ be the distance travelled by the mobile robot in the $j$stage of disassembly.

Variable $r=1+3(j-1)$ indexes: a continuous place of the robot, *Pcr*, a continuous transition of the robot, *Tcr*, and a discrete transition of the disassembly process, *Tdd*. Variable $k=1+5(j-1)$ indexes a discrete place of the disassembly process, *Pdd*. Variable $l=1+4(j-1)$ indexes a discrete transition of the robot, *Tdr*.

3. A/DLB optimised model

This section presents a model based on the above assumptions, used to find an optimum solution for the A/DLB problem. Due to assumptions A.1, A. 2 and A.10, it may be considered that, in terms of the assembly process, the line is balanced. Consequently, the assembly line balancing (ALB) problem is solved implicitly.

3.1. Disassembly tasks

Let M be the total number of tasks required for the disassembly of a product, and M_c the number of tasks per cycle (period). The tasks associated with a cycle, TC_i, $i=\overline{1,M_c}$, are set out below:

TC_1 – stop line.
TC_2 – release disassembled part.
TC_3 – RM positioning at disassembly location.
TC_4 – grip disassembled part.
TC_5 – start line.
TC_6 – RM positioning for WMR displacement.
TC_7 – WMR displacement from disassembled location to storage warehouse.
TC_8 – RM positioning at storage warehouse location.
TC_9 – part storage in warehouse.
TC_{10} – RM positioning for WMR displacement.
TC_{11} – WMR displacement from storage warehouse to the next disassembled location.

Remark 1. According to assumption A.11, the last operation of disassembly does not take place and, therefore, task TC_5 is missing from the last cycle.

3.2. DLB optimisation problem criterion

Let CT be the maximum cycle time allowed for any cycle.
Let t_{ij}, $i=\overline{1,M}$, $j=\overline{1,M_c}$ be the processing time of task i from cycle j; hence t_{ij} is the processing time of task TC_{ij}.
Let d_{ij}, $i=\overline{1,M}$, $j=\overline{1,M_c}$ be the demand of the part released by task T_{ij}.

Let NR_{ij} be the net revenue of task TC_{ij}, i.e. the difference between the revenue obtained by releasing a part and the cost of the task

$$NR_{ij}=R_{ij}-C_{ij}, \tag{1}$$

where R_{ij} is the revenue due to task, TC_{ij}, and C_{ij} is the cost of task, TC_{ij}. If the task, TC_{ij}, does not release a part, then $R_{ij}=0$.

Let DV_{ijk}, $i=\overline{1,M}$, $j=\overline{1,N}$, $k=\overline{1,N}$ be the decision variables, which are assignments of tasks to workstations in each period. These assignments are explained by the following decision variables: if task i is assigned to workstation j in cycle k, then $DV_{ijk}=1$, otherwise, $DV_{ijk}=0$.

The following constraints hold:

C.1. The demand of the part releasing tasks should be satisfied

$$\sum_{j=1}^{N}\sum_{k=1}^{N} DV_{ijk} \geq d, \quad i=\overline{1,M}, \quad d=\sum_{i=1}^{M}\sum_{j=1}^{M_c} d_{ij}. \tag{2}$$

C.2. The cycle time limit should not be exceeded

$$\sum_{i=1}^{M} t_{ij} DV_{ijk} \le CT, \quad \forall j, \quad \forall k. \tag{3}$$

C.3. A task can be assigned to at most one station in each period

$$\sum_{j=1}^{N} DV_{ijk} \le 1, \quad i = \overline{1,M}, \quad k = \overline{1,N}. \tag{4}$$

C.4. The decision variables should be non-negative since they are binary, implying the assignment of each task to the workstations in each period

$$DV_{ijk} \ge 0, \quad i = \overline{1,M}, \quad j = \overline{1,N}, \quad k = \overline{1,N}. \tag{5}$$

The target function of the DLB optimum problem, subject of constraints C.1, C.2, C.3 and C.4, has to maximise the sum of net revenue obtained by each executed task

$$J_{DBL} = \text{Max} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{N} NR_{ij}\, DV_{ijk} \tag{6}$$

4. A/DML served by WMR with RM

4.1. Hardware description

The general approach will be customised for an A/DML mechatronics line, Hera&Horstmann, shown in Figs. 2, 3 and 4a and b, which assemblies a five-parts piece, shown in Fig. 4c and d. The WMR, Pioneer3-DX, has an odometric system, two driving wheels, and one rear free wheel. Also, an on-board embedded microcontroller is able to read position information and send it, via a WI–FI link, to a remote PC according to a specific protocol. The remote PC computes control input and sends it to WMR. Also, the remote PC sends the data to the assembly line PLC (Peng & Zhou, 2003). The WMR is equipped with a RM with three articulations and one gripper paddle. The assembly/disassembly manufacturing flexible line is equipped with a SIEMENS Simatic S7-300 Programmable Logic Controller (PLC), with 5 distributed modules connected by Profibus. The 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 a 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 enables workflow operations such as assemblies, testing, sorting, storage, and disassembling. The components to be assembled are (Fig. 4c and d): work part carrier (base platform) (1), body (2), cover (3), metal cylinder (4) and plastic cylinder (5).

4.2. Task planning

The assembly/disassembly operation can be broken down into a sequence of elementary assembly tasks coupled in parallel with work-piece positioning tasks along the conveyor, as in Choi et al., (1998), Ganget, Hattenberger, and Alami (2005), Radaschin, Filipescu, Minzu, Minca, and Filipescu (2011) and Radaschin, Voda, Minca, and Filipescu (2012). The hybrid disassembly strategy is based on the hierarchical model proposed in Kallrath (2003) and Radaschin et al. (2011), which uses a graph representation of the product in which component relationships are expressed by means of arrows. The hybrid disassembly strategy is based on the hierarchical model proposed in Minca, Dragomir, Dragomir, Enache, and Radaschin (2011), Minca et al. (2012), Radaschin et al. (2012), and Seliger et al. (1999), which uses the general representation in Fig. 1. Fig. 5 presents the distances between disassembly locations and storage warehouses of the A/DML served by WMR with RM. WMR carries the component from the place where disassembly occurs to the appropriate storage warehouse. Fig. 6 shows the task planning of 5 parts and their transport by WMR.

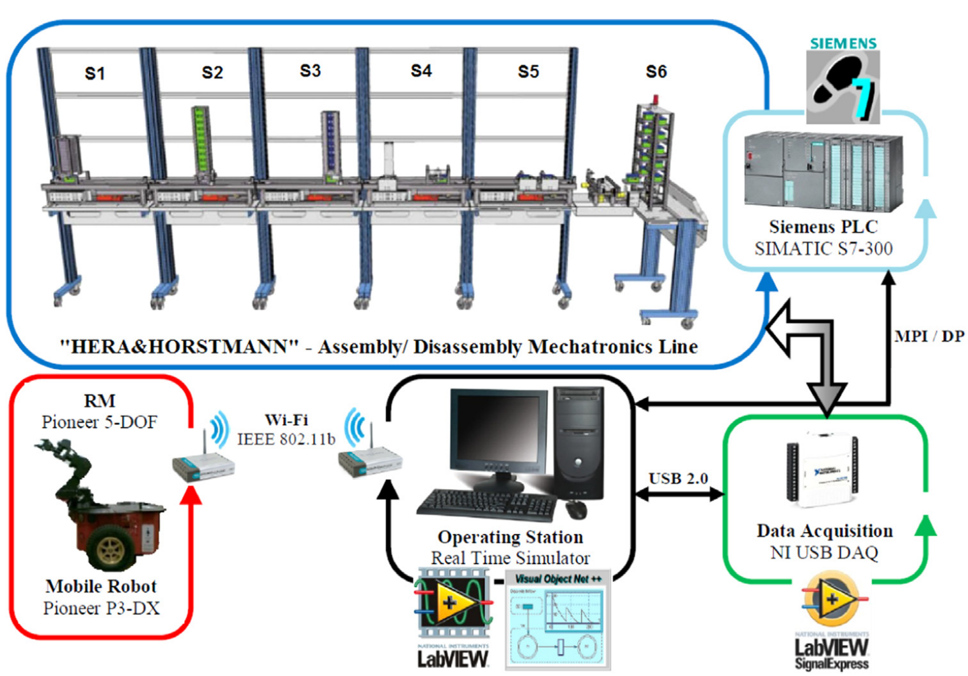

Fig. 2. Control structure of A/DML Hera&Horstmann served by WMR with RM.

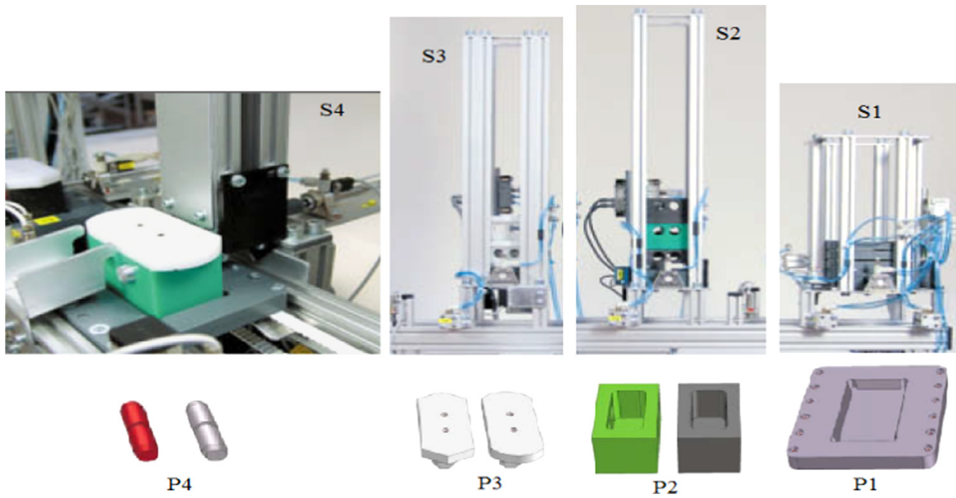

Fig. 3. Assembly workstation storage warehouses, assembly parts.

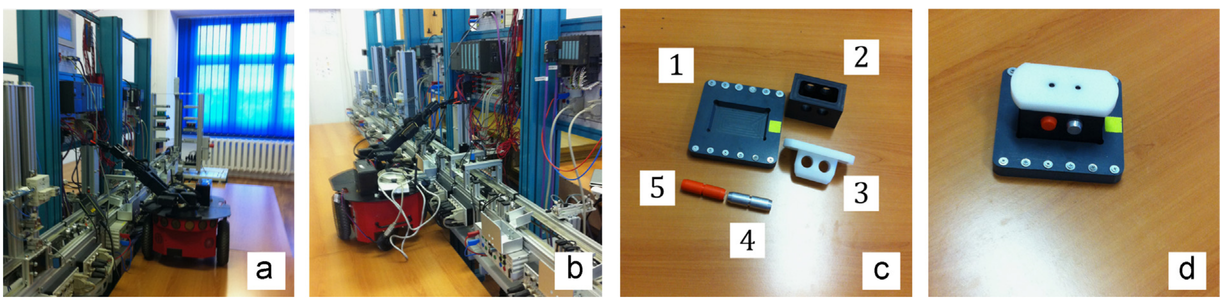

Fig. 4. (a) A/DML served by WMR, Pioneer 3-DX, equipped with RM; (b) Pioneer 5-DOF Arm; (c) parts; (d) assembled product.

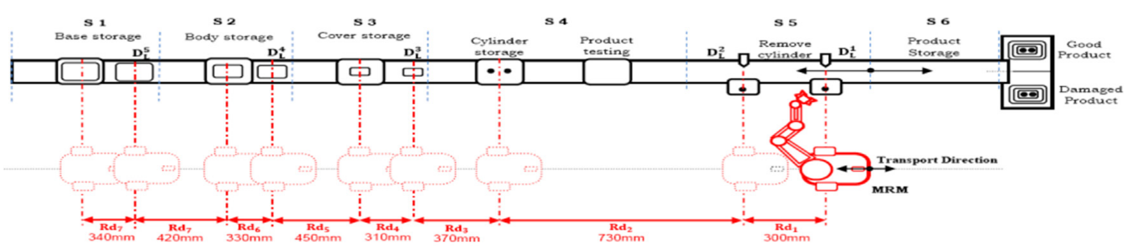

Fig. 5. Assembly/disassembly mechatronics line of a 5-part product, served by the WMR equipped with RM.

5. SHPN model of an A/DML served by WMR equipped with RM

5.1. Structure of the SHPN model

The hybrid aspect of the model is determined by variables related to distances travelled by the robot. 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 mobile platform speed between A/DML locations.

To develop a global assembly and/or disassembly model, we shall consider the hybrid aspect of the assembly/disassembly process served by the platform. For modelling we shall use Timed Hybrid Petri Nets (THPN) (David & Alla, 2010), which integrate the discrete appearance of the assembly/disassembly process with the continuous appearance of moving of the WMR and handling of components by the RM.

The entire model is of the SHPN type as it is interfaced with external events for synchronisation in a modelling/simulation approach useful in real-time control.

The SHPN structure, in Fig. 7, and the SHPN representation by blocks in Fig. 8 are obtained by modelling assembly/disassembly and continuous service assistance, for disassembly operations, performed by a mobile platform equipped with a manipulator. SHPN morphology results in integration of three PN models, each of which has a specific typology: Timed PN (TPN), Synchronised PN (SPN), and Timed Hybrid PN (THPN). These models describe the following automatic operations:

- Assembly/storage in warehouses (TPN typology).
- Disassembly of damaged products (SPN and TPN typologies).
- Service assistance, during the disassembly process, performed by the mobile robot equipped with a manipulator (THPN typology).

5.2. Assembly/disassembly repetitive sequences

Fig. 9 shows an elementary TPN model corresponding to an assembly operation. Fig. 10 shows the generalised TPN model

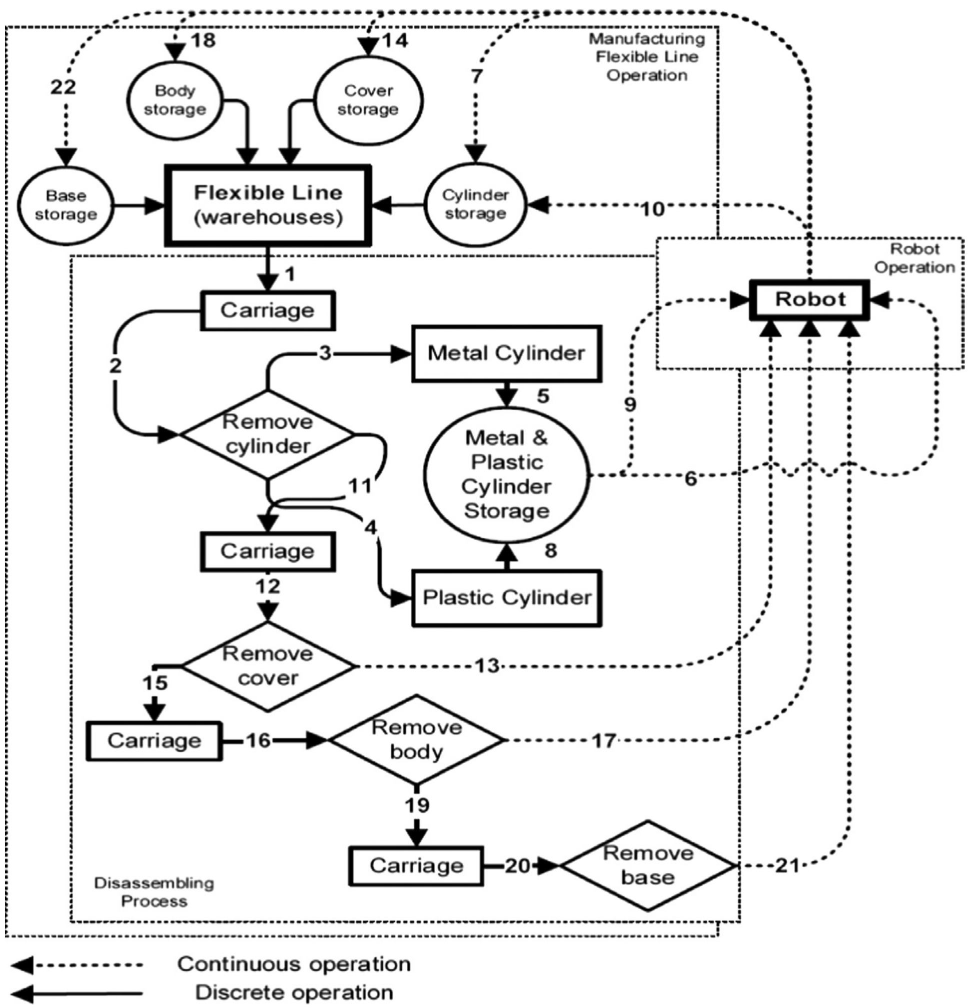

Fig. 6. Disassembly task scheduling.

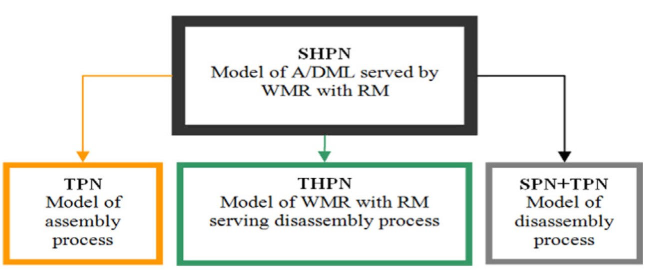

Fig. 7. Structure of the SHPN model.

corresponding to the assembly process, which includes a sequence associated with the quality test for the end product. During the disassembly process, a repetitive sequence can be identified, associated with a single disassembly operation and service assistance of WMR equipped with RM. These can all be modelled using a SHPN, known as an elementary SHPN, as shown in Fig. 11.

$E^1_{dd(j)}$ and $E^2_{dd(j+2)}$ are sensor external events used for line synchronisation with the WMR equipped with RM. $E^1_{dd(j)}$ is an external synchronisation signal, corresponding to STOPPING the line and STARTING disassembly. $E^2_{dd(j+2)}$ is an external synchronisation signal, corresponding to PICKING UP the disassembled component and STARTING the line.

Simulation of SHPN model autonomously (simulation of HPN model) is useful to join the discrete dynamics of the mechatronics

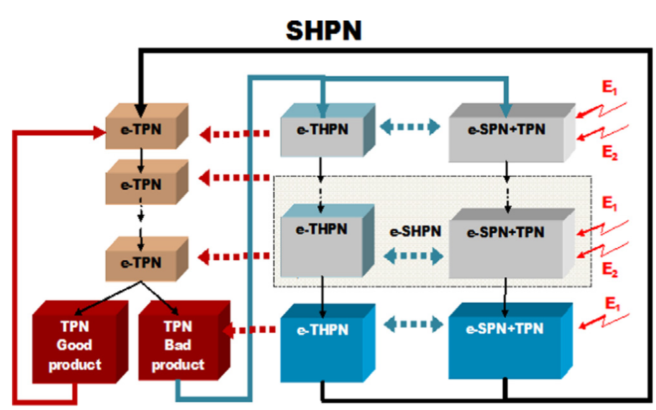

Fig. 8. SHPN representation by blocks with elementary modules: e-TPN for assembly, e-THPN for WMR with RM, e-SPN+TPN for disassembly, and e-SHPN for disassembly served by WMR with RM.

line with the continuous dynamics of the robotic system. Since, after the last disassembly operation, a line is no longer required to start a new disassembly, the SHPN model is different from the rest and is shown in Fig. 12. SHPN model (non-autonomous HPN model), allows, in case of uncertainty (faulty sensors/actuators, poor signal reception, other faults in A/DML and robotic system), the system to stop and continue working after the fault has been removed.

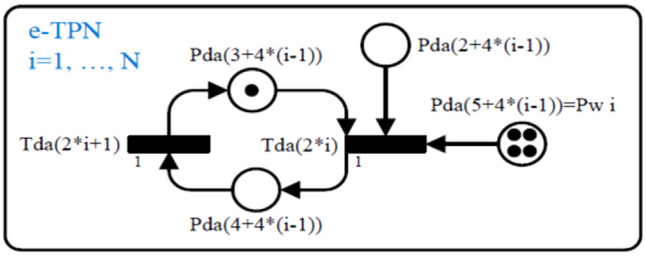

Fig. 9. e-TPN model for an elementary assembly operation.

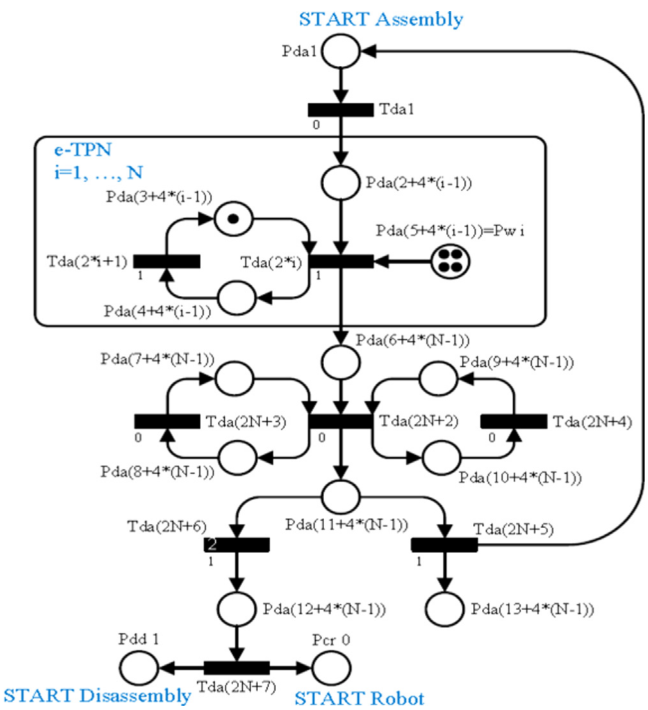

Fig. 10. Generalised TPN model for the assembly process of N components.

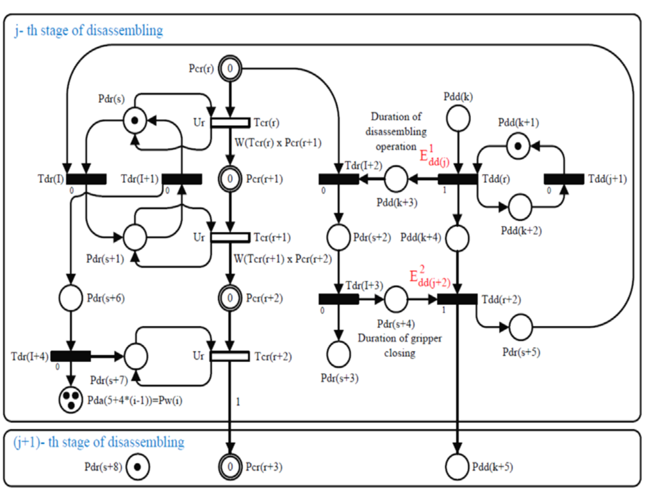

Fig. 11. e-SHPN model for the jth elementary disassembly operation.

5.3. Generalised and customised SHPN model

The SHPN model, associated with the assembly/disassembly is a triplet

$$SHPN = \langle THPN,\quad E,\quad Sync\,\rangle, \tag{7}$$

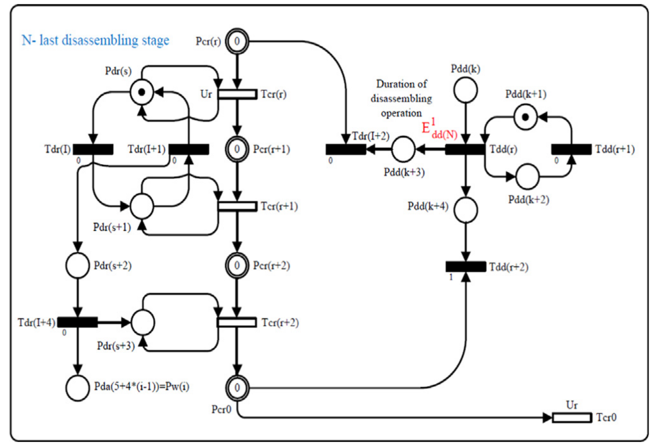

Fig. 12. SHPN model for the last disassembly operation, $j=N$.

where $THPN$ is a septuplet

$$THPN = \langle P, T, Pre, Post, m_0, h, tempo\rangle, \tag{8}$$

E is a set of external events

$$E = \{Edd_i^1, Edd_j^2\} \cup \{e\},\quad i = 1+3(k-1),\ j = 3(k-1),\ k = \overline{1,N} \tag{9}$$

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

$$Sync : T \rightarrow \{E^1, E^2\} \cup \{e\}, \tag{10}$$

where e is the continuously occurring event (it is the neutral element of the monoid E^*) and

$$Sync : \{Tdd_r\}_{r = 1+3(k-1), k=\overline{1,N}} \rightarrow \{E^1, E^2\},$$

$$Sync : \{Tdd_i\}_{i = 3(k-1), k=\overline{1,N}} \rightarrow \{Edd_i^2\}_{i=3(k-1), k=1,N},$$

$$Sync : T \setminus \{Tdd_r\}_{r=\overline{1,3+3(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5(N-1)}} \cup \{Tcr_r\}_{r=\overline{1,3+3(N-1)}} \rightarrow e$$

$$P = \{P_1, P_2, \ldots, P_n\} = P^D \cup P^C \tag{11}$$

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

$$P^D = \{Pda_i\}_{i=\overline{1,13+4(N-1)}} \cup \{Pdd_r\}_{r=\overline{1,5+5(N-1)}} \cup \{Pdr_s\}_{s=\overline{1,4+8(N-1)}}, \tag{12}$$

and P^C the set of continuous places

$$P^C = \{Pcr_k\}_{k=\overline{0,3+3(N-1)}}. \tag{13}$$

For $N=5$ (A/DML Hera&Horstmann), (12) and (13) become

$$P^D = \{Pda_i\}_{i=\overline{1,29}} \cup \{Pdd_j\}_{j=\overline{1,25}} \cup \{Pdr_k\}_{k=\overline{1,41}}, P^C = \{Pcr_k\}_{k=\overline{0,15}},$$

where $\{Pda_i\}_{i=\overline{1,29}}$ is the set of discrete places for the assembly process; $\{Pdd_j\}_{j=\overline{1,25}}$ is the set of discrete places for the disassembly process; $\{Pdr_k\}_{k=\overline{1,41}}$ is the set of discrete places for the mobile robot states while serving the disassembly process; $\{Pcr_k\}_{k=\overline{1,15}}$ is the set of continuous places associated with the distances travelled by the mobile robot for each disassembly operation in order to transport the disassembled component from the disassembled location to the storage location

$$T = \{T_1, T_2, \ldots, T_m\} = T^D \cup T^C \tag{14}$$

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

$$T^D = \{Tda_i\}_{i=\overline{1,7+2N}} \cup \{Tdd_r\}_{r=\overline{1,3+3(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5(N-1)}} \tag{15}$$

and T^C the set of continuous transitions

$$T^C = \{Tcr_r\}_{r=\overline{1,3+3(N-1)}}$$

For $N=5$, (14) and (15) become

$$T^D = \{Tda_i\}_{i=\overline{1,17}} \cup \{Tdd_j\}_{j=\overline{1,15}} \cup \{Tdr_k\}_{k=\overline{1,24}},$$

$$T^C = \{Tcr_k\}_{k=\overline{1,15}},$$

where $\{Tda_i\}_{i=\overline{1,17}}$ is the set of discrete transitions for the assembly operation model; $\{Tdd_j\}_{j=\overline{1,15}}$ is the set of discrete transitions for the disassembly operation model; $\{Tdr_k\}_{k=\overline{1,24}}$ is the set of discrete transitions for the mobile robot states while serving the disassembly operations; $\{Tcr_k\}_{k=\overline{1,15}}$ is the set of continuous transitions associated with the distances travelled by the mobile robot for each disassembly operation. The maximum linear speed of the WMR is associated with these transitions.

Remark 2. 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 3. 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

$$h : P \cup T \to \{D, C\}, \tag{16}$$

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

$$h : P^D \cup T^D \to \{D\}; h : P^C \cup T^C \to \{C\}, \tag{17}$$

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

$$tempo : T \to Q_+ \cup \{0\}. \tag{18}$$

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

For each discrete assembly transition of the set

$$T_a^D = \{Tda_i\}_{i=2k, k=\overline{1,N}} \cup \{Tda_{2(N+1)}\}, \tag{19}$$

$$tempo(Tda_i) = d_{da_i}, \tag{20}$$

where d_{da_i} represents the duration (in seconds) associated with the corresponding assembly operation.

For each discrete disassembly transition of the set

$$T_d^D = \{Tdd_r\}_{r=1+3(k-1), k=\overline{1,N}}, \tag{21}$$

d_{dd_r} is the duration of the corresponding disassembly.

For each discrete WMR transition of the set

$$T_r^D = \{Tdr_l\}_{l=4+5(k-2), k=\overline{2,N}}, \tag{22}$$

d_{dr_l} is the duration of RM positioning for picking up and setting down a disassembled component.

For $N=5$, (19)–(22) become

$$T_a^D = \{Tda_i\}_{i=\{2,4,6,8,10\}} \cup \{Tda_{12}\},$$
$$tempo(Tda_i)_{i=\{2,4,6,8,10,12\}} = \{9.5, 9.3, 8.5, 0.5, 4.75, 27.2\}$$

where d_{da_i} represents the duration of the current assembly operation together with the transport time to the next assembly location, for $i \in \{2,4,6,8,10\}$, and the duration of the quality test together with the transport time to the end product warehouse elevator, for $i \in \{12\}$

$$T_d^D = \{Tdd_r\}_{r=\{1,4,7,10,13\}}, d_{dd_r, r=\{1,4,7,10,13\}} = 1,$$

where d_{ddr} is the duration of the current disassembly operation

$$T_r^D = \{Tdr_l\}_{l=\{4,9,14,19\}}, d_{dr_l} \in \{5.1, 21.2, 8.9, 7.8\},$$

where d_{drl} is the duration of RM positioning for picking up and setting down a disassembled part.

If $T_{cr} \in T^C$ then

$$U_r = \frac{1}{tempo(T_{cr})} \tag{23}$$

is the flow rate associated with T_{cr}.

For

$$T^C = \{Tcr_r\}_{r=3+3(k-1), k=\overline{1,N}}, U_{cr_r} = U_r; U_{r\max} = V_r,$$

where U_{cr} is the variable flow of the mobile robot displacement between disassembly stations. Consider the average speed of motion of 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

$$ED(T_j, m) = \min_{P_i \in {}^0T_j \cap P^D} \left\lfloor \frac{m_i}{Pre(P_i, T_j)} \right\rfloor. \tag{24}$$

Definition 2. The maximum firing speed of transition T_{cr_r} is the product of its flow rate U_r by its ED-enabling degree.

Suitable Definitions 1 and 2, for the general case, can be expressed as

$$ED(T_{cr_j}, m_{cr(j+1)}) = \{0, 1\}, \tag{25}$$

$$m_{cr(j+1)} = V_j \cdot w(Tcr_j \times Pcr_{(j+1)}), \tag{26}$$

$$w(Tcr_r \times Pcr_{r+1}) = D(W_{N+1-j}, N_{d_{j+1}})/D(N_{d_j}, W_{N+1-j}), \tag{27}$$

where $m_{cr(j+1)}$ is the mark associated with a continuous place, and $w(Tcr_{(r)} \times Pcr_{(r+1)})$ is the weight of the arc from a continuous transition to a continuous place of the WMR.

For $N=5$ the arches $(P_i \times T_j)$, have a weight equal to one, where

$$P_i = (ROBOT\ state1, ROBOT\ state2) \in {}^0\{Tcr_k\}_{k=\overline{1,10}} \cap P^D.$$

Remark 4. For a synchronised 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 associated event.

Sync is a function from (10), becomes in customised form as follows:

$$Sync : \{Tdd_j\}_{j=\{1,3,4,6,7,9,12,13\}} \to \{Edd^1, Edd^2\}; \tag{28}$$

$$Sync : \{Tdd_i\}_{i=\{1,4,7,13\}} \to \{Edd_i^1\}_{i=\{1,4,7,13\}}; \tag{29}$$

$$Sync : \{Tdd_i\}_{i=\{3,6,9,12\}} \to \{Edd_i^2\}_{i=\{3,6,9,12\}}; \tag{30}$$

$$Sync : \{Tdd_j\}_{j=\overline{1,16}} \cup \{Tdr_k\}_{k=\overline{1,21}} \cup \{Tcr_k\}_{k=\overline{1,10}} \to e. \tag{31}$$

5.4. Simulation of the SHPN model

The proposed model, HPN, has been tested, analysed and verified through simulation package Sirphyco. HPN model was useful to find maximum speed of the mobile platform that provides minimum cycle time of disassembly. This speed should

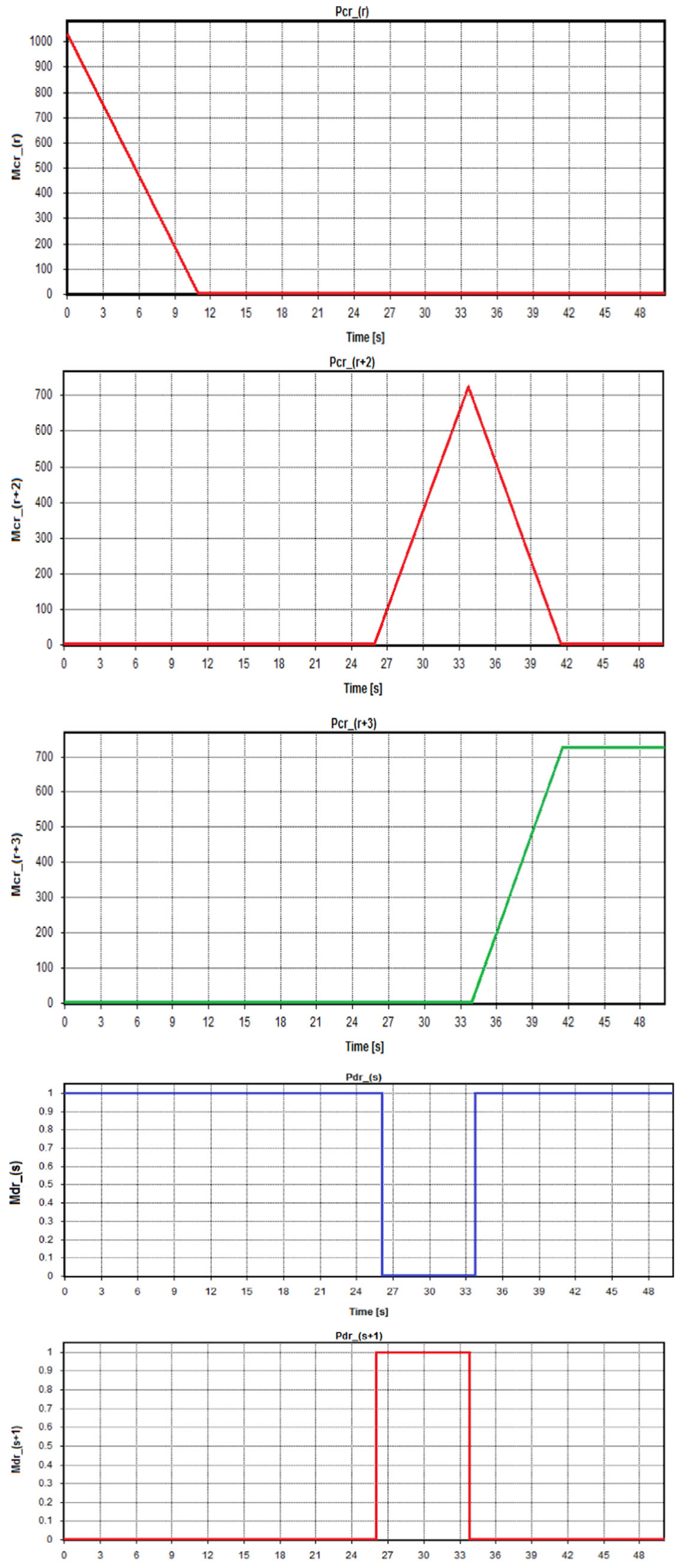

Fig. 13. Variation of the continuous and discrete places associated with displacements of WMR with RM for the first disassembly period.

be set respecting the physical limitations of the mobile platform, which ultimately is the optimum displacement speed. Analysis of the SHPN model is relevant at basic level according to an elementary THPN module, denoted e-THPN. The SHPN model is obtained by recurrent assembling of these elementary e-THPN modules (corresponding to each basic disassembly served by WMR with RM). The

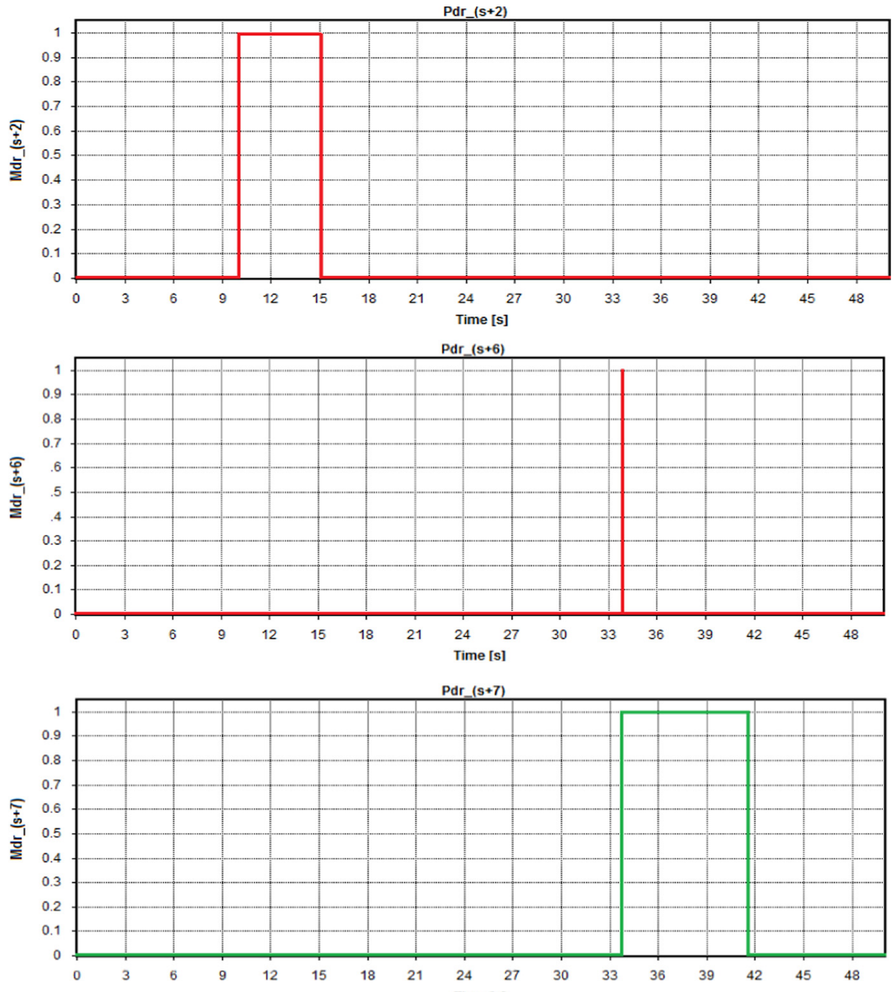

Fig. 13. (*continued*)

SHPN global model is an exclusive relationship between TPNs associated with the assembly process, elementary THPN modules associated with WMR service assistance, and SPN with TPNs associated with the disassembly process. Fig. 13 shows the simulated response of the continuous and discrete places of WMR and RM for the hybrid model in Fig. 11. The WMR markings of the continuous places, before and after simulation, match the distances shown in Fig. 5. In Fig. 13, the evolution of the WMR, continuous and discrete place markings, corresponding to $j=1$, is shown as following: $Mcr(r)$ – the temporal variation of the travelled distance by the robot between stage 1 of disassembly and warehouse 5 (1031 mm according to Fig. 5); $Mcr(r+1), Mcr(r+2)$, $Mcr(r+3)$ – the variation of the distance to be travelled by the robot in the following stage (730 mm according to Fig. 5) correlated to the synchronization of the events Edd_1^1 and Edd_3^2. $Mdr(s)$, $Mdr(s+1)$, $Mdr(s+2)$, $Mdr(s+6)$, $Mdr\ (s+7)$ – represent the temporizations associated with the discrete actions of the WMR (piece gripping and dropping, gripper closure, repositioning to the next disassembly work-station) correlated with the travelling of the disassembled piece in-between work-stations along the conveyor belt.

For the final stage of disassembly (Fig. 14), the maximum value of the marking $Mcr(r+3)|_{j=5} = Mcr(0)|_{j=5}$ is equal to the distance travelled by the WMR during stage 1 of disassembly $Mcr(r)=1031$ and corresponds to the initialisation of the new disassembly cycle. Similarly, the graphic representations $Mdr(s)$, $Mdr(s+1)$, $Mdr(s+2)$, $Mdr(s+6)$, $Mdr(s+7)$ do not quantify the temporisation induced by the reception of the event Edd^2 (STARTING next stage of disassembly) as the disassembly is finalised.

6. A/DML real-time control based on A/DLB and SHPN models

The SHPN model is transposed via the LabView platform into a real-time application, obtained by interfacing the HPN model with synchronised signals taken by acquisition from the real process. The real-time application is synchronised with the controlled process by the positioning signals of the work piece along the conveyor taken by acquisition card NIUSB-6008. The synchronisation signals, used in the LabView real-time control application, validate certain transitions into the SHPN model. These transitions are conditioned by the associated signals of the position work piece on the conveyor track. Synchronisation will lead to initialising the robot and to monitoring/controlling assembly/disassembly operations of the WMR with RM. Discrete time and sliding-mode control, in trajectory tracking, based on a kinematic model, is used to control WMR (Dumitrascu, Filipescu, Radaschin, Minca, & Filipescu, 2011). In this way, both the robot and the flexible line are controlled, so as to achieve a minimum assembly and disassembly time cycle. The robot is initialised by a signal transmitted via a wireless access point mounted on the robot, received by the LabView application. Via the acquisition board, the state signals are transmitted to the flexible line to control the position of the work piece along the conveyor and to synchronise the robot with the flexible line. The LabView I/O module transmits the signals to the A/DML PLC (SIMATIC S7-300) via the acquisition board. The gripper is positioned by a visual system so as to grab the disassembled component and store it in the warehouse. Linear velocity of the complete WMR disassembly cycle in trajectory

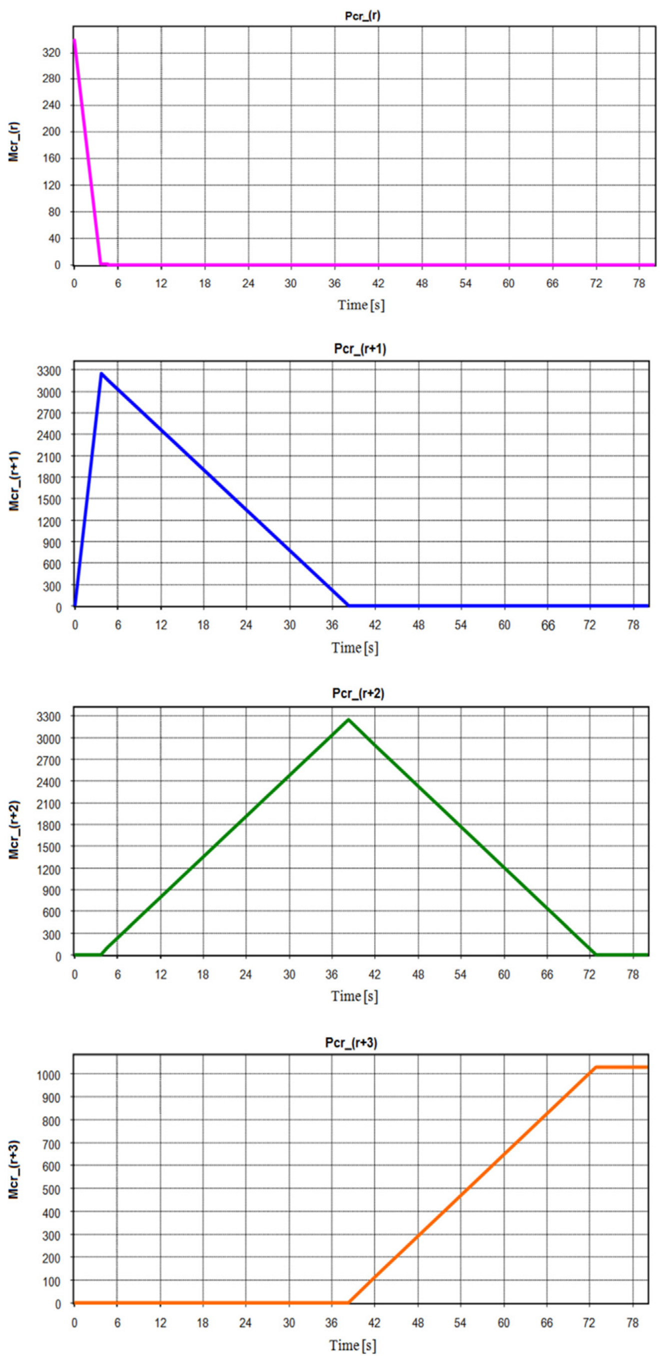

Fig. 14. Variation of the continuous and discrete places associated with displacements of WMR with RM for the last disassembly period.

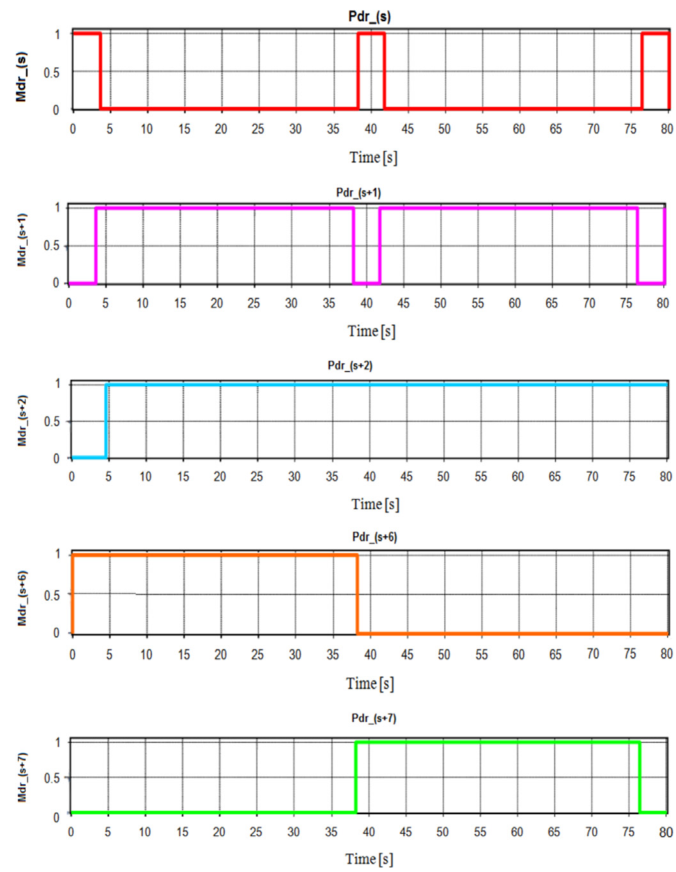

Fig. 14. (*continued*)

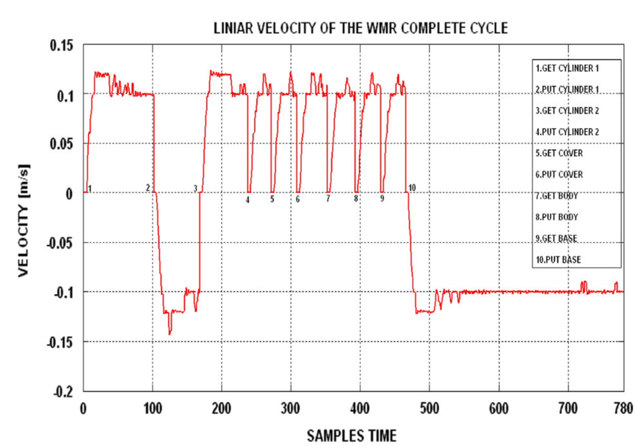

Fig. 15. WMR's linear speed during disassembly process.

tracking, real-time, sliding-mode control, is presented in Fig. 15. Sliding-mode control of the mobile platform servicing A/DML does not address issues related to the possibility of uncertainty of type: false information, faulty sensors/actuators and possible route/storage space blockage. The state transition of the disassembled components and the WMR for transport of these components to the storage location is shown in Fig. 16. The complete structure of the A/DML real-time control served by WMR is shown in Fig. 2.

7. Conclusions

This paper is mainly focused on operations planning and control of an A/DML served by a mobile platform equipped with manipulator. Real-time control of a fully reversible A/DML served by WMR equipped with RM is based on operations planning and SHPN model, via a LabView platform. The A/DLB and the generalised SHPN models are customised for an A/DML assembling a five-part product. The SHPN model is conditioned on certain state transitions by external events representing signals supplied by sensors. The WMR equipped with RM is used only during disassembly for transporting the disassembled parts to the storage warehouses. 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 the assembly process. The SHPN model has been tested via simulation, and used in real-time control.

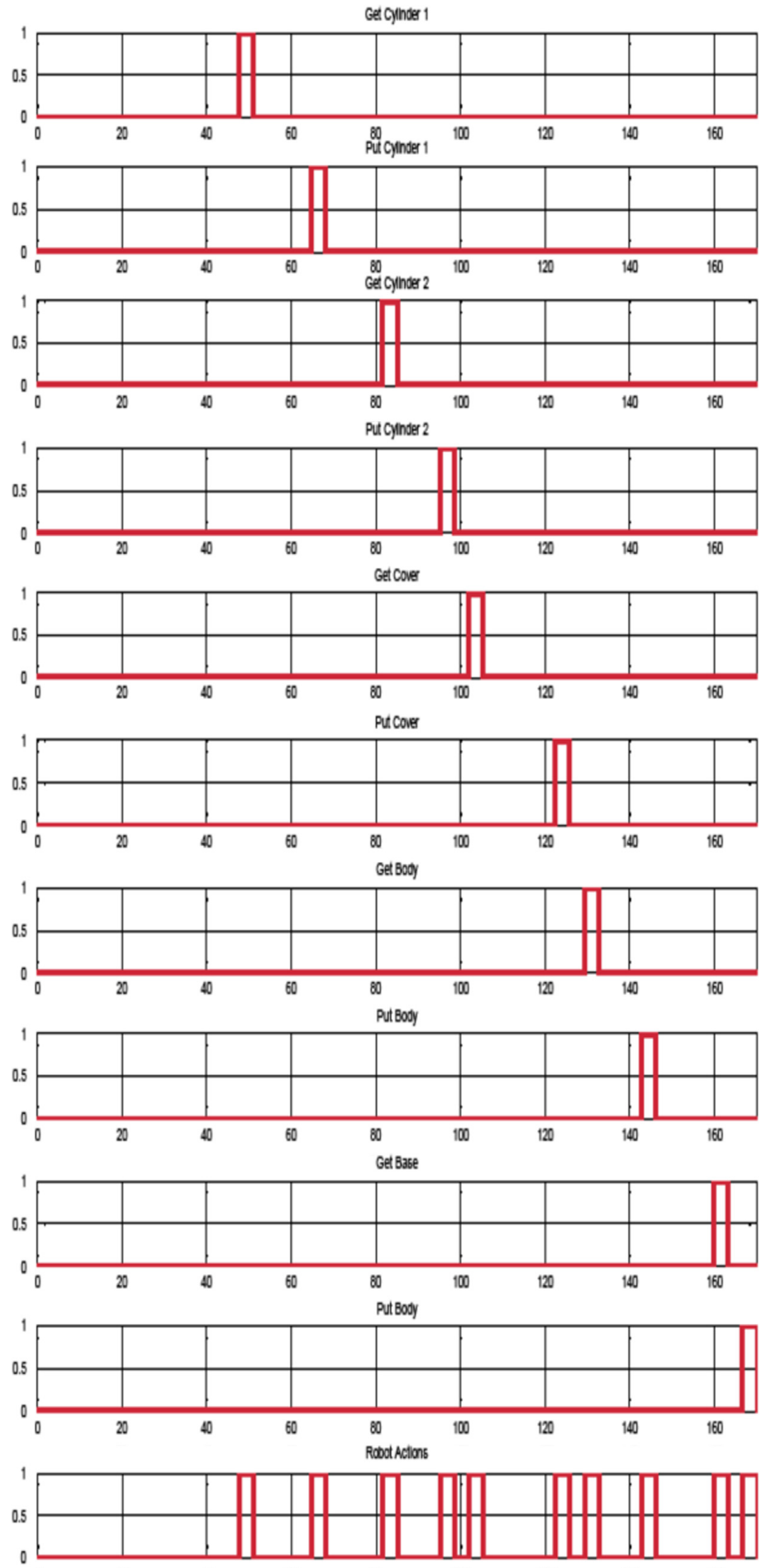

Fig. 16. State transition of disassembly parts and their transport from disassembly locations to the storage locations.

The problem needs to be solved in the future is robustness to uncertainties of the mechatronics line and robotic platform. Have to be considered as uncertainties: faulty sensors/actuators, route/storage space blockage and payload variation. Also, need to be used collaborative systems of mobile platforms equipped with manipulators to transport and handle weights in a wide range of variation.

The most eloquent correspondents in the real world are assembly processes in the automotive industry, car body, gearbox and engine block assembly. In most cases, robotic manipulators that have a fixed location serve these assembly lines. Through this study, we extended the degree of automation and efficiency of these production lines using mobile robotic systems equipped with manipulators. Thus, the assembly lines become reverse, being able to recover and reuse of components and subassemblies, in the event that the final product does not meet quality requirements.

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