Hybrid Model Based Control of a Mechatronics Line Served by Mobile Robot with Manipulator

Eugenia Minca
Department of Automation, Computer Science and Electrical Engineering
"Valahia" University of Targoviste, Romania
eugenia.minca@gmail.com

Alina Voda
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
alina.voda@gipsa-lab.grenoble-inp.fr

Adrian Filipescu
Department of Automation and Electrical Engineering
"Dunarea de Jos" University of Galati, Romania,
adrian.filipescu@ugal.ro

Adriana Filipescu Jr.
Department of Automation and Electrical Engineering
"Dunarea de Jos" University of Galati, Romania
adriana.filipescu@ugal.ro

Abstract—**This paper presents the model and control structure of an assembly/disassembly mechatronics line (A/DML) served by a wheeled mobile robot (WMR) equipped with robotic manipulator (RM). The model is a hybrid type, where A/DML is the discrete part and WMR with RM is the continuous part. Moreover, the model operates as a synchronized with signals from sensors. Thus, using Petri Nets (PN) in modeling, get a Synchronized Hybrid Petri Nets (SHPN). The disassembly process starts after the assembly process and final piece fails the quality test, in order to recover the components. The WMR equipped with RM is used only in disassembling process, in order to transport the components from the disassembling locations to the storage locations. Thus, the A/DML becomes reversible. Using a LabView platform and SHPN model, a real-time control structure is implemented.**

Keywords—assembly/disassembl; manufacturing line; wheeled mobile robo;, robotic manipulator; Petri nets.

I. WHY A/DML SERVED BY WMR WITH RM?

This paper presents a Synchronized Hybrid Petri Nets model for an assembly/disassembly mechatronics line served by wheeled mobile robot equipped with robotic manipulator. Generalized model will customize for an assembly mechatronics line (HERA&Horstmann) of a piece in five components. Also, SHPN model based real-time control of A/DML served by WMR with RM is presented. 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 assembly/disassembly operations and the continuous approach for displacement of WMR. The system of reversible A/DML 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. That one represents the continuous time part of the system. 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] and [10]. Combining the SED model of the analyzed system with the cyclic and continuous time of the WMR with RM results a SHPN model. This paper is organized as follows: the description of A/DML served by WMR with RM and SHPN model, in generalized and customized forms, are presented in Section 2; generalized and customized SHPN formalism is presented in Section 3. Also, are presented simulation results of customized SHPN model; Section 4 is reserved to real-time control of A/DML served by WMR with RM based on SHPN model; some conclusion remarks can be found in Section 5.

II. DESCRIPTION OF A/DML, WMR EQUIPPED WITH RM AND SHPN MODEL

The assembly/disassembly line is served by a WMR equipped with RM during of disassembly phase. The objective is to make the assembly line reversible, i.e. to allow disassembly. Moreover, the mobile robot is used to carry the disassembled component to proper storage warehouse.

General approach will customize to an A/DML, mechatronics line, HERA&Horstmann, shown in Fig.1a and 1b, which makes assembling a piece of five components, shown in Fig.1c and Fig. 1d The WMR, Pioneer 3-DX, is with two driving wheels and one rear wheel, has its own odometric system and an on-board embedded microcontroller is able to read the position information and to send it, over a WI-FI link, to a remote PC where runs the according to a specific protocol and send the data to PLC of the assembly 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. 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.

This work was supported by UEFISCDI, project number PN-II-ID-PCE-2011-3-0641

978-1-4673-6322-8/13/$31.00

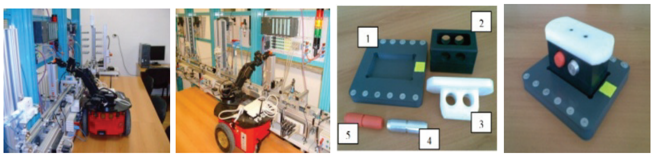

Figure 1. a) and b) assembly line, Hera, served by WMR, Pioneer 3-DX, equipped with RM, Pioneer 5-DOF Arm; c) parts; d) assembled product

The work part carrier is equipped with 6-Bit identification which provides a large number of possible codes, read out byinductive sensors. The four-piece work part enable workflow model such as assemblies, testing, sorting, storage and disassemblies.

The components to be assembled are (Fig. 1c and 1d): work part carrier (base platform) (1), body (2), cover (3), metal cylinder (4) and plastic cylinder (5). The assembly/disassembly operation can by decomposed 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 the general representation from Fig. 2. In Fig. 3 is presented the particular case of an assembly/disassembly of a product consists of 5 parts, served by WMR with RM. WMR carries the component from the place where disassembly occurs to the appropriate storage warehouse.

The following assumption hold:

A.1. The disassembly process starts immediately after the assembly process and final piece fails the quality test;

A.2. Storage warehouses places are identical to positions where assembly occurs;

A.3. In an assembly/disassembly operation is assembled/disassembled only one piece;

A.4. By convention it is assumed that the end product fails the quality test if it contains cylinders of different materials;

A.5. After the last remaining piece of disassembly process is transported to the storage warehouse starts a new assembly process.

Let N be the number of components which to be assembled. For $N = 5$ gets the customized case.

Let $N_{a_i}, i = \overline{1, N}$ be the assembly locations on the positive sense of Ox axis.

Let $N_{d_j}, j = \overline{1, N}$ be the disassembly locations on the negative sense of Ox axis. Obviously, $i = N - j + 1$.

Let $W_i; i = \overline{1, N}$ be the warehouse locations, which are identically with the assembly locations. Obviously, $W_{N+1-j} \equiv W_i, j = \overline{1, N}$.

Let $D(N_{d_j}, W_{N+1-j})$ be the distance between 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 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.

$r = 1 + (j-1)\cdot 3$ indexes: a continuous place of the robot, Pcr; a continuous transition of the robot, Tcr and a discrete transition of disassembly process Tdd.

$k = 1 + (j-1)\cdot 5$ indexes a discrete place of disassembly process, Pdd.

$l = 1 + (j-1)\cdot 4$ indexes a discrete place of the robot, Tdr.

The hybrid aspect of the model is determined by variables related to distances travelled by the robot. These distances are between places where disassembly occurs and places of storage warehouses. The variation of these variables is with constant or variable speed. This variation is performed by the mobile platform speed between locations of A/DML. SHPN structure from Fig. 4 is obtained by modelling 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). During disassembly process can identify a repetitive sequence associated to a single disassembly operation and service assistance of WMR equipped with RM. All of these can be modelled with a SHPN, called elementary SHPN, as is represented in Fig.5 (e-SHPN model of j-th elementary disassembly operation) and Fig.6 (e-TPN model for an elementary assembly operation).

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

III. Formalism of the SHPN Model

SHPN model associated to A/DML is a triplet,

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

such that: $THPN$ is a septuplet

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

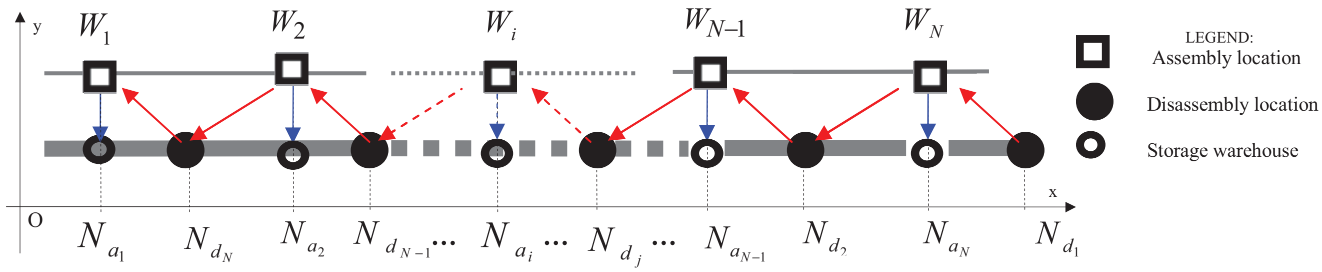

Figure 2. Assembly/Disassembly and storage warehouse locations

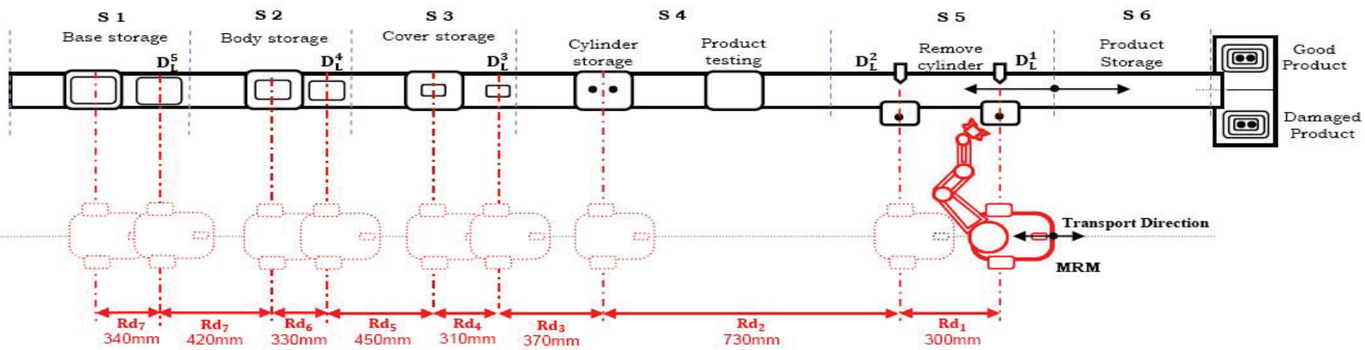

Figure 3. Assembly/disassembly line of a product consists of 5 components, served by the WMR equipped with RM

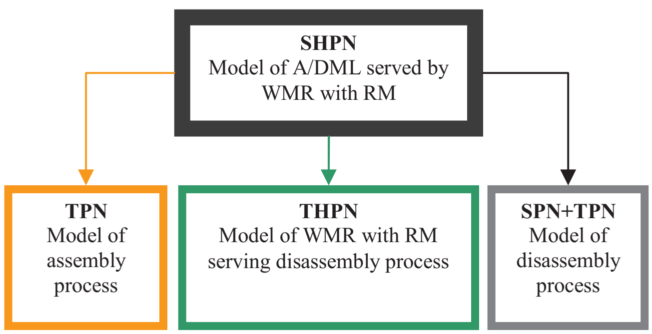

Figure 4. Structure of SHPN model.

E is a set of external events

$$E = \left\{Edd_i^1, Edd_j^2\right\}_{\substack{i=1+3\cdot(k-1)\\ j=3\cdot(k-1)}}\Bigg|_{k=\overline{1,N}} \cup \{e\}, \quad (3)$$

Sync is a function from the set of the discrete disassembly 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^*) and

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

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

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

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

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

$$P^D = \{Pda_i\}_{i=\overline{1,13+4\cdot(N-1)}} \cup \{Pdd_r\}_{r=\overline{1,5+5\cdot(N-1)}} \cup \{Pdr_s\}_{s=\overline{1,4+8(N-1)}} \quad (6)$$

and P^C the set of continuous places

$$P^C = \{Pcr_k\}_{k=\overline{0,3+3(N-1)}}, \quad (7)$$

For $N = 5$ (A/DML Hera&Horstmann), (6) and (7) become:

$$P^D = \{Pda_i\}_{i=\overline{1,29}} \cup \left\{Pdd_j\right\}_{j=\overline{1,25}} \cup \{Pdr_k\}_{k=\overline{1,41}}$$

$$P^C = \{Pcr_k\}_{k=\overline{0,15}},$$

where:

$\{Pda_i\}_{i=\overline{1,29}}$ is the set of discrete places for assembly process;

$\left\{Pdd_j\right\}_{j=\overline{1,25}}$ is the set of discrete places for disassembly process;

$\{Pdr_k\}_{k=\overline{1,41}}$ is the set of discrete places for the states of mobile robot while serving disassembly process;

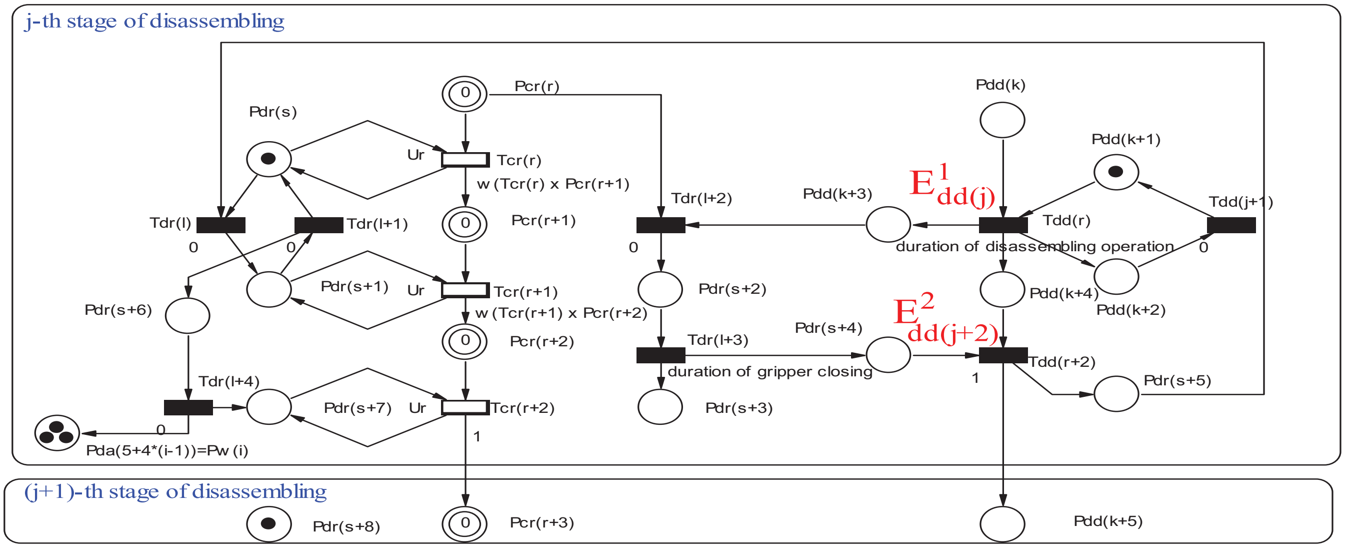

Figure 5. e-SHPN model of j-th elementary disassembly operation

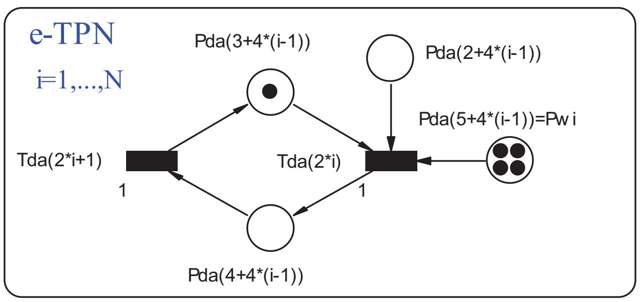

Figure 6. e-TPN model for an elementary assembly operation

$\{Pcr_k\}_{k=\overline{1,15}}$ 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;

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

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

$$T^D = \{Tda_i\}_{i=\overline{1,7+2\cdot N}} \cup \{Tdd_r\}_{r=\overline{1,3+3\cdot(N-1)}} \cup \{Tdr_l\}_{l=\overline{1,4+5\cdot(N-1)}} \tag{9}$$

and T^C the set of continuous transitions

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

For $N = 5$, (8) and (9) 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 assembly operations model;

$\{Tdd_j\}_{j=\overline{1,15}}$ is the set of discrete transitions for disassembly operations model;

$\{Tdr_k\}_{k=\overline{1,24}}$ is the set of discrete transitions for states of mobile robot while serving disassembly operations;

$\{Tcr_k\}_{k=\overline{1,15}}$ is the set of continuous transitions associated to distances performing by the mobile robot for each disassembly operation. To these transitions is associated the maximum linear speed of the WMR.

Remark 1: 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 2: In the definitions of Pre, $Post$ and m_0, N corresponds to the case when $P_i \in P^D$, and Q_+ or R_+ corresponds to the case when $P_i \in P^C$.

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

$$h: P \cup T \to \{D, C\}, \tag{10}$$

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),

$$h: P^D \cup T^D \to \{D\}; \tag{11}$$

$$h: P^C \cup T^C \to \{C\} \tag{12}$$

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

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

If $T_j \in T^D$, then $d_j = tempo(T_j)$ is timing associated with T_j. For each discrete assembly transition of the set

$$T_a^D = \{Tda_i\}_{i=2\cdot k_{k=\overline{1,N}}} \cup \{Tda_{2\cdot(N+1)}\}, \quad (14)$$

the timing is

$$tempo(Tda_i) = d_{da_i} \quad (15)$$

where d_{da_i} represents the duration (in seconds) associated to the corresponding assembly operation. For each discrete disassembly transition of the set

$$T_d^D = \{Tdd_r\}_{r=1+3\cdot(k-1)_{k=\overline{1,N}}}, \quad (16)$$

d_{dd_r} is *the duration of the corresponding disassembly operation*. For each discrete WMR transition of the set

$$T_r^D = \{Tdr_l\}_{l=4+5\cdot(k-2)_{k=\overline{2,N}}}, \quad (17)$$

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

For $N = 5$ (14), (15), (16) and (17) 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 elevator of end products warehouse, for $i \in \{12\}$;

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

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_{dd_l} is the duration of RM positioning in picking up and dropping down of a disassembled component.

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

$$U_r = \frac{1}{tempo(T_{cr})} \quad (18)$$

is flow rate associated to T_{cr}.

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

where U_{cr} is the variable flow of 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 removed:

$$ED(T_j, m) = \min_{P_i \in {}^0T_j \cap P^D} \left\lfloor \frac{m_i}{Pre(P_i, T_j)} \right\rfloor \quad (19)$$

Definition 2: The *maximal 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, it can write:

$$ED(T_{cr_j}, m_{cr(j+1)}) = \{0,1\} \quad (20)$$

$$m_{cr(j+1)} = V_j \cdot w(Tcr_j \times Pcr_{(j+1)}) \quad (21)$$

$$w(Tcr_r \times Pcr_{r+1}) = D(W_{N+1-j}, N_{d_{j+1}}) / D(N_{d_j}, W_{N+1-j}) \quad (22)$$

where $m_{cr(j+1)}$ is the mark associated to 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.

Remark 3: 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.

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

$$Sync : T \rightarrow \{E^1, E^2\} \cup \{e\} \quad (23)$$

and can be expressed as follow:

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

where:

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

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

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

SHPN model is obtained by recurrent assembling of these elementary e-THPN modules (corresponding to each basic disassembly served by WMR with RM). The SHPN global model is an exclusive relationship between TPN associated to the assembly process, elementary THPN modules associated to WMR service assistance and SPN with TPN associated to disassembly process. In Fig.7 is shown the simulated response of the continuous places of WMR with RM of the hybrid model.

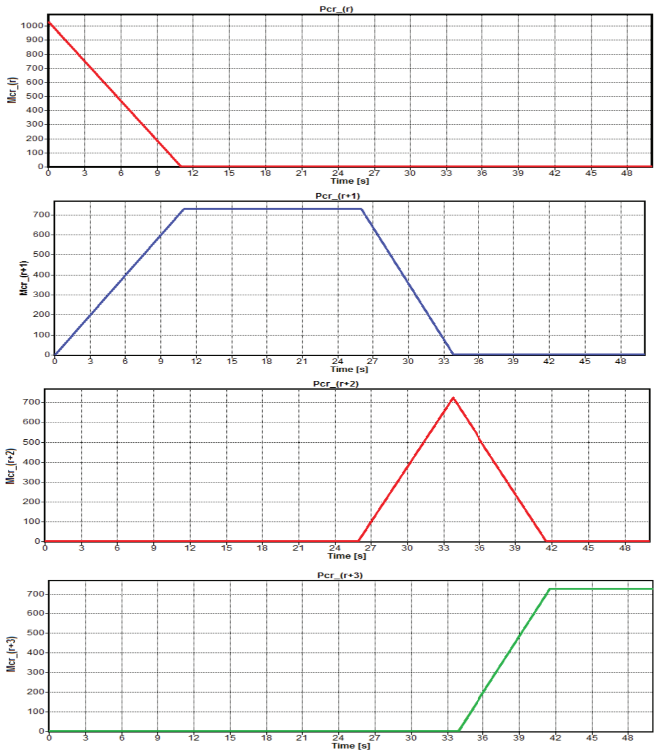

Figure 7. Variation of the continuous places asociated to displacements of WMR and RM corresponding to the first stage of disassembling

IV. SHPN Model Based Real-Time Control of A/DML

The SHPN model is transposed under LabView platform in a real-time application, obtained by interfacing HPN model with synchronized signals taken by acquisition from the real process.. 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. The synchronization will lead to initialize robot and to monitoring/control operations of assembly/disassembly of WMR with RM. Discrete time, sliding-mode control, in trajectory-tracking, based on kinematic model is used in order to control WMR. In this way both the robot and flexible line are controlled, in order to achieve a minimal time cycle of assembly/disassembly. 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. Linear velocity of the WMR disassembly complete cycle in trajectory tracking, real-time, sliding-mode control is presented in Fig.8.

Conclusions

A THPN model, in synchronized form, based real-time control of fully reversible assembly/disassembly mechatronics line is presented in this paper. The SHPN model is conditioned on certain state transitions by external events representing signals supplied by sensors. e A/DML is served by a WMR equipped with RM which is used only in disassembling in order to transport the disassembled components to the storage

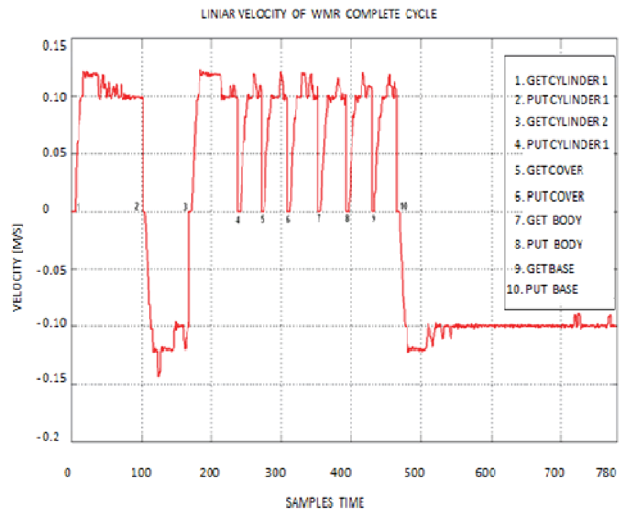

Figure 8. Displacement speed of WMR during disassembly operations

warehouses. Therefore, the assembly line becomes reversible, i.e. executes automated disassembly. The disassembly process is started when the final product, obtained by assembly, fails quality test. The disassembled components are recovered and transported to storage locations, in order to be used again in assembly process. The THPN model has been tested via simulation and used in real-time control.

References

[1] D. F. Baldwin, T. E. Abell, C. M. Lui, T. L. De Fazio, D. E . Whitney, „An integrated computer aid for generation and evaluation assembly sequences for mechanical products”, IEEE Transactions on Robotics until Automation, 1991, pp. 78-94.

[2] C. K. Choi, X. F. Zhang., T. L. Ng, W. S. Lau, “On the generation of product assembly sequences”, International Journal of Production Research, 1998, pp. 617-633.

[3] J. Rosell, “Assembly and task planning using Petri nets: A survey and a roadmap towards autonomous robotic assembly systems", Technical report IOC-DT-P-2002-13, Univ. Politecnica de Catalunya, 2002.

[4] J. Ganget, G. Hattenberger and R. Alami, “*Task planning and control for multi-UAV system:architecture and algotithms”,* IEEE Intl. Conf. On Intelligent Robot and System, Vol.18, 758-768, 2005.

[5] G. Seliger, W. Grudzien, H. Zaidi, „New methods of product data provision for a simplified disassembly”, Proceedings of the 6th International Seminar on Life Cycle Engineering, Kingston, Canada, June 21–23, 1999. p. 250–9.

[6] A. Radaschin, A. Filipescu, V. Minzu, E. Minca and A. Filipescu Jr., ”Adaptive disassembly sequence control by using mobile robots and system information”, Proceeding of 15th IEEE International Conference in System Theory, Control and Computing, pp: 499-505, 14-16 Oct., 2011, Sinaia, Romania, ISBN: 978-973-621-323-6.

[7] A. Radaschin, A. Voda, E. Minca, A. Filipescu, “Task Planning Algorithm in Hybrid Assembly/Disassembly Process”, 14th IFAC Symposium on Information Control Problems in Manufacturing, May 23-25, 2012, Bucharest, ISSN: 1474-6670; ISBN: 978-3-902661-98-2, pp. 571-576.

[8] B. Kopacek, P. Kopacek (1999), “Robots for disassembly”, Proceedings of the 30th International Symposium on Robotics, Tokyo, pp 207–212.

[9] R. David and H. Alla, Discrete, Continuous and Hybrid Petri Nets, ISBN 978-3-642-10668-2, Springer-Verlag Berlin Heidelberg, 2010.

[10] A. Filipescu, S. Filipescu, E. Minca, “Hybrid System Control of an Assembly/Disassembly Mechatronic Line Using Robotic Manipulator Mounted on Mobile Platform”, The 7th IEEE Conference on Industrial Electronics and Applications (ICIEA2012), 18-20 July,2012, Singapore, pp. 433-438, IEEE Catalog Number CFP 1220A-CDR, ISBN: 978-1-4577-2117-5.