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Two Mobile Robotic Systems Synchronous Servicing an Assembly/Disassembly Production Line

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Abstract— **This paper proposes a model for a reversible assembly line useful in order to analyze its structural properties. Wheeled mobile robots (WMRs) equipped with robotic manipulator are used in the disassembly operation. The developed model can be used in the stages of designing, configuring and sizing of an Assembly/Disassembly Mechatronic Line (A/DML). For the control and monitoring of an A/DML a Hybrid Petri Net (HPN) model is proposed. In order to facilitate the transformation of the developed HPN model into models useful for supporting the design of control algorithms, a methodology to transform arcs in synchronization events is outlined. The decomposition of Hybrid Petri Net in Synchronized Hybrid Petri Nets (SHPN) suitable for specific programming language is discussed. Finally, results from the simulation of HPN are compared with that recorded from the real A/DML.**

Keywords— Assembly/disassembly manufacturing systems, wheeled mobile robot, robotic manipulator, Hybrid Petri Net

I. Introduction

The assembly line and disassembly line are flow-oriented production systems where the productive units perform operations on work stations. Such systems may be configured as serial, parallel, circular, U-shaped, cellular, two-sided lines or a combination of these. The products visit workstation successively as they are moved along the line, by some kind of transport system, usually a conveyor belt [1]. Disassembly operations involve the separation of the reusable components from the discarded products. These components either undergo remanufacturing operations or are sold to suppliers [2, 3]. Assembly/disassembly manufacturing systems imply 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 behaviors and discrete event behaviors. Hybrid Petri Nets (HPNs) are useful tools in modelling such systems [4-6].

This paper presents a Hybrid Petri Nets (HPN) model for an Assembly Disassembly Mechatronic Line (A/DML) served by two cooperative Wheeled Mobile Robots (WMRs). The first WMR can execute just transportation tasks. The second WMR is equipped with a robotic manipulator and its duties are to assist the workstations during disassembly by handling extracted components and to load them on WMRT. Also, an Assembly/Disassembly Line Balancing (A/DLB) model for considered configuration is formulated. Disassembly line balancing is used to find the set of tasks assigned to each workstation and to the two mobile robots. The planer algorithm would determine the optimum moment for starting disassembly. The problem is critical for to not block the assembly operation, in the event there is no empty slots for faulty product and they remain on the line, and also for minimizing the use of valuable resources (such as energy and time) implied in disassembly, and maximizing the level of automation of the disassembly process and the quality of the components or materials recovered [7]. In what is following, we consider a Disassembly Line Balancing Problem (DLBP) with a fixed number of work stations so as to maximize the value of recovered components. In literature is stated that "a disassembly process does not imply a reverse assembly process" [8].

In the model we developed, the concepts of assembly/disassembly tasks are illustrated using HPN and SHPN models, which cover both aspects: the discrete approach, drive by events, for the elementary assembly/disassembly operations, and the continuous approach for displacement of WMRs. The AML system becomes reversible and is served, during the disassembling process, by a robotic manipulator mounted on a mobile platform. The A/DML evolution is determined by events, supplied by the control sequences of the automatic system, and by synchronization messages received from the two WMRs. The two WMRs represent the continuous parts of the system. The considered system is a hybrid one and requires specialized tools for modelling, as in [9]. We develop the hybrid model using the formalism of HPN and tools as described in [9]. A SHPN model for WMRT and RM results from the combination of the PN model of synchronization protocol of the three implied entities and continuous model of the two WMR.

The ADLB and HPN models have been customized for a laboratory assembly mechatronic line, which assembles a 5-components product. We developed an application in VisualC++ able to plan the disassembly operations, and to control in real-time the laboratory system represented by A/DML served by cooperative WMR. The evolution of the system during disassembly process is supervised based on

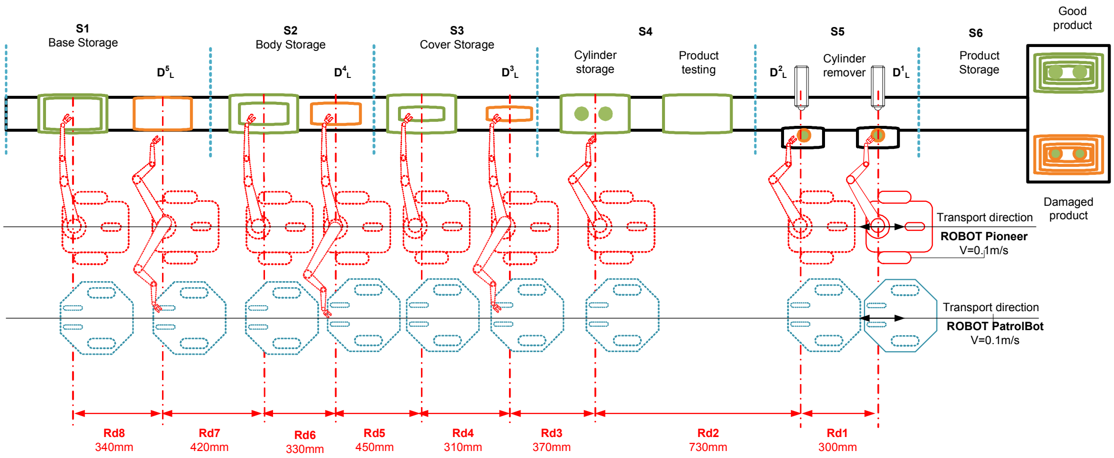

Figure 1. Two mobile robots servicing the disassembly operation on an ADML with five workstation

SHPN models. These developed models provide a high-level description of the product to be disassembled.

The details about sub-operation performed during disassembly process on each workstation are masked in order to keep the generality of the model. Also details about synchronization protocol are omitted being platform dependent. The disassembly operations are performed on the same assembly line eventually implying some other tools. The assembly line consists of a number of linear configured work stations. The first disassembling workstation takes the product to be disassembled, and the last added component is disconnected. And so on, on different planed workstations. A disassembly cycle is finished, when the product leaves the line, i.e. whenever all its required components are disassembled.

The rest of the paper is organized as follows. In Section 2, the A/DBL problem is outlined and useful preliminary assumptions are laid out for developing A/DBL and SHPN models. A model with an objective function, useful for optimizing A/DML is presented in Section 3. The description of the A/DML served by the two WMR is presented in Section 4. The HPN model and a SHPN, for an elementary disassembling operation are elaborated in Section 5.

II. PROBLEM FORMULATION

Assembling of many products is typically made in production lines organized in form of flow – line. This type of assembly line is usually characterized by high quantity of products per unit of time. The policy of waste treatment imposed by regulations and the economic reasons like cost of stocking final defect products that not pass the functional or quality test and the revenue obtained by reusing components from such a product, make feasible considering the disassembling process immediately after the fail of quality test. In this paper we consider an assembly line which can be reversed in order to remanufacture the product, reuse the components or recycle the material of non-reusable components. It is also assumed that each workstation from assembly line is able to perform the reverse operation eventually assisted by a mobile robotic manipulator (RM).

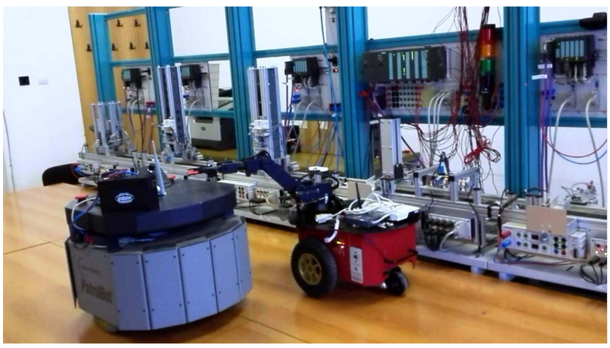

Figure 2. The two mobile robots loading reusable components in corresponding warehouse.

Because of the flow characteristics of the considered process, i.e. that in each workstation, previous to the final testing workstation, is a partially assembled product, the defected products need to be stored at the end of A/DML until the conveyer is emptied and can be reversed. In the design stage of A/DML, the warehouse for defect products need to be sized according to the number of installed workstation and the estimated costs of reversing the flow of products.

In each workstation the disassembled components are loaded by RM on a wheeled mobile robot transporter (WMRT) to be transferred back into corresponding storage warehouse in the case of reusable components, to recyclable waste station or to a test stand in the other cases. The WMRT and mobile robotic manipulator (MRM) can also be used for usual supplying of warehouses with components and as a consequence not all time available for disassembling process.

In such a complex system it is clear that an online planning algorithm must decide the optimum moment for reversing the line. The algorithm should take into account information like the number of free slots for defect products, the estimated rate of occurrence of defect product, the type of unit), the actual components stock of each warehouse (there aren't free slots for reusable components or there is a need for components), the availability of MRM and WMRT and other costs and time constrains. In order to generate an optimal sequencing of operations the planer algorithm must be able to compute accurate cycle time for each disassembly operation and also the feasible trajectories for the MRM and WMRT.

In order to compute accurate cycle time for one disassembly operation a model of this activity is needed. We develop a HPN model for an elementary disassembly operation in which the MRM load reusable components on WMRT and transfer them back into warehouses.

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

A. *Assembly assumptions*

In industries are developed several configuration for assembly line. In literature [2], are present 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 mechatronic lines:

A.1: The A/DML is a single-model line, by the nature of the product, paced line (transfers between the work stations are 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 minimizing cycle time with respect to assembly line balancing of the A/DML.

B. *Disassembly assumptions*

In [8] and [10], the DLB model is described for partial and complete disassembly, respectively. The importance of disassembly lines in product recovery is discussed, as are 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 work stations, linear-configured with a first work station taking the product to be disassembled. The number of work stations 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 a 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: The disassembly process starts immediately after the assembly process and after the end product fails the quality test;

A.10: Storage warehouse places are identical to positions where the assembly occurs;

A.11: In a disassembly operation, only one piece is 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 piece in the disassembly process has been transported to the storage warehouse, a new assembly process will start.

Remark 1: The assumption *A.11* that products are loaded for disassembling one by one, is forced by the fact that just one pair of MRM and WMRT are considered and the MRM can handle just the separated components from on workstation at a time. When a product is completely disassembled, the next one will be loaded from the defected products warehouse until it becomes empty.

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. Obviously, $i = N - j + 1$. Let $W_i, i=\overline{1,N}$ be the warehouse locations, which are identical to the assembly locations. Obviously, $W_{N+1-j} \equiv W_i, j=\overline{1,N}$. Let $D\left(N_{d_j}, W_{N+1-j}\right)$ be the distance between the disassembly location, N_{d_j}, and the corresponding storage warehouse, W_{N+1-j}.

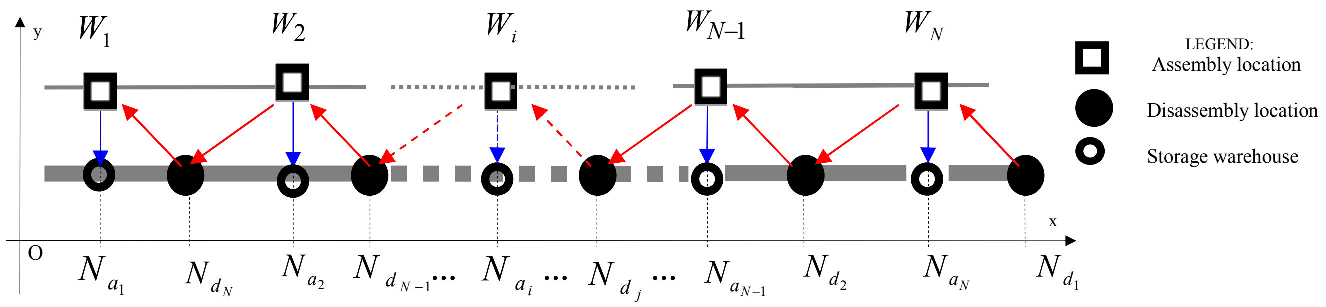

Figure 3. Assembly/Disassembly and storage warehouse locations

Let $D\left(W_{N+1-j}, N_{d_{j+1}}\right)$ be the distance between the last storage warehouse W_{N+1-j} and the next disassembly location $N_{d_{j+1}}$.

Let $D_{r_j} = D\left(N_{d_j}, W_{N+1-j}\right) + D\left(W_{N+1-j}, N_{d_{j+1}}\right)$ be the distance travelled by the mobile robot in the j stage of disassembly.

III. A/DLB MODEL

This section presents a model used to find an optimum solution for the A/DLB problem. Due to assumptions A.1 and A. 2, 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. Because the disassembly process implies the use of the two WMR, the disassembly line balancing (DLB) problem must be solved.

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:

TC_1 – Transport product on the line (using conveyor); TC_2 – Release disassembled component; TC_3 – MRM positioning at disassembly location; TC_4 – Grip disassembled component; TC_5 – Start line; TC_6 – MRM load component on WMRT displacement; TC_7 – MRM positioning for displacement; TC_8 – MRM displacement from disassembled location to storage warehouse; TC_9 – WMRT displacement from disassembled location to storage warehouse; TC_{10} – MRM unload component from WMRT displacement; TC_{11} – MRM positioning at storage warehouse location; TC_{12} – Store the component in warehouse; TC_{13} – RM positioning for WMR displacement TC_{14} – MRM displacement from storage warehouse to the next disassembled location; TC_{15} – WMRT displacement from storage warehouse to the next disassembled location;

Remark 2: It must be take into account that part of the task are executing in parallel.

	TC2	TC5	TC1…					
TC3	TC4	TC6	TC7	TC8	TC10	TC11	TC12	TC14
				TC9				TC15

3.2. DLB optimization 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_j be the demand of the component released by task T_{ij} in cycle j;

Let NR_j be the net revenue of task TC_{ij}, i.e. the difference between the revenue obtained by releasing a component and the cost of the tasks associated with its releasing

$$NR_{ij} = R_j - \sum_{i=1}^{M} C_{ij}, \tag{1}$$

where R_j is the revenue corresponding to component j and C_{ij} is the cost of task TC_{ij}. If task TC_{ij} does not release a reusable component then $R_j = 0$.

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 work stations in each period. These assignments are explained by the following decision variables: if task i is assigned to work station j in cycle k, then $DV_{ijk} = 1$. Otherwise, $DV_{ijk} = 0$.

The following constraints hold:

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

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

C. 2: The cycle time limit should not be exceeded considering also observation from *Remark 2.*

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

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

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

C. 4: The decision variable should be non-negative since /it is binary, implying the assignment of each task to the work stations in each period

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

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

$$J_{DLB} = Max \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{N} NR_{ij} DV_{ijk}.$$

This kind of problem is usually solved using integer programming or methaeuristics.

IV. A/DML SERVED BY COOPERATIVE ROBOTS

A. Hardware description

The general approach is exemplified on a laboratory mechatronic A/DML with five workstation produced by Hera&Horstmann (see Fig. 2). This laboratory line is controlled with a Siemens PLC and is assembling products using 5 components shown in Fig 7. During disassembly process the line is served by two WMR: a mobile robotic manipulator (MR) fixed on a Pionee3-DX and a wheeled mobile robot transporter (WMRT) represented by a PatrolBot, both produced by MobileRobots. The two robots have odometric systems, and their moving is based on two driving wheels and one respectively two free rear wheels. Each robot has an on-board embedded system able to rapport current position, to move to a target position and to fallow a trajectory transmitted by a supervisor. The Pionee3-DX is equipped with a RM with three articulations and one gripper paddle.

B. *Software description*

The supervisor application is implemented on a desktop computer and is responsible to plan the disassembling operation at optimum moment. In our laboratory application, the supervisor communicates with mobile robots through TCP/IP protocol and with A/DML through a data acquisition board connected to desktop paired with few digital IO on PLC. On an industrial application the communication with A/DML should take place also over TCP/IP and using an OPC server. In the case that more WMRs are available the supervisor application should select a pair. The supervisor application will allocate tasks to them with position to be achieved and operation to be completed. After that, the supervisor will mediate the synchronization signals and will monitories the disassembly evolution. The communication between software entities is presented in Fig. 4. A capture of the graphical interface is shown in Fig.5.

V. HPN MODEL OF A/DML SERVED BY COOPERATIVE ROBOTS

The HPN model described in [5,9] is used to model the evolution of the considered hybrid system. This model permits the design and the analysis of the synchronization protocol that should be implemented for real-time control of the A/DML and of the two WMRs. The HPN model corresponding to an elementary disassembly cycle is presented in Fig. 6. In this HPN, the WMRT is modeled by place and transition grouped in the left. The WMR equipped with RM is modeled by the place grouped in center and the A/DML by the discrete place and transition grouped in the right. There are arcs which pass from one group to other. These arcs model synchronization messages that are transmitted between A/DML and WMRs. In order to develop control algorithms from presented HPN, this must be converted in a model in form of an automata. For PN, TPN and SPN there are algorithms that can support this conversion. For special cases of HPN[8], there are also developed methodologies to transform HPN in hybrid automata. One assumption required in [8] is not met by HPNs corresponding to the WMRs such that we must base on the particular simple structure of our HPN to transform it in an automata model to support the real-time control.

VI. CONCLUSION

This paper is dedicated to model A/DL. In order to facilitate the transformation of the developed HPN model into models useful for supporting the design of control algorithms, a methodology to transform arcs in synchronization events is outlined.

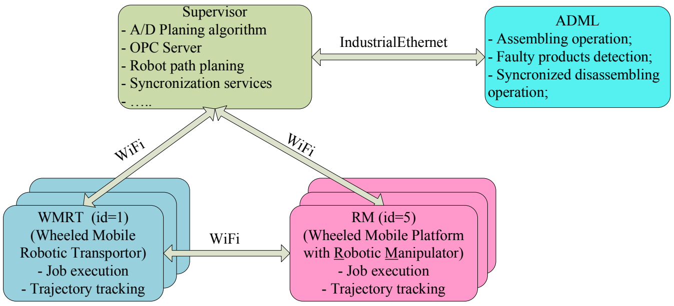

Figure 4. Software configuration of the real time controller for Hera A/DML

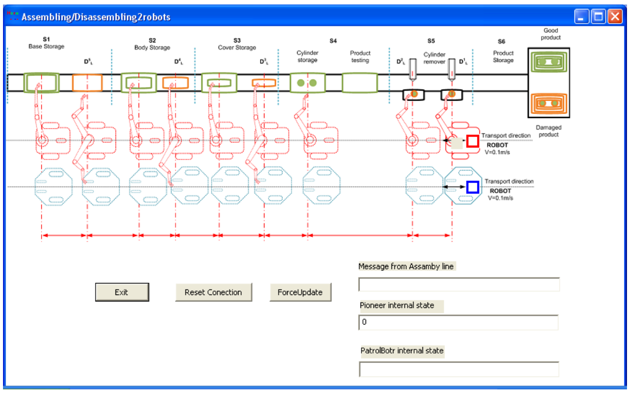

Figure 5. Graphical user interface of Visual C++ application.

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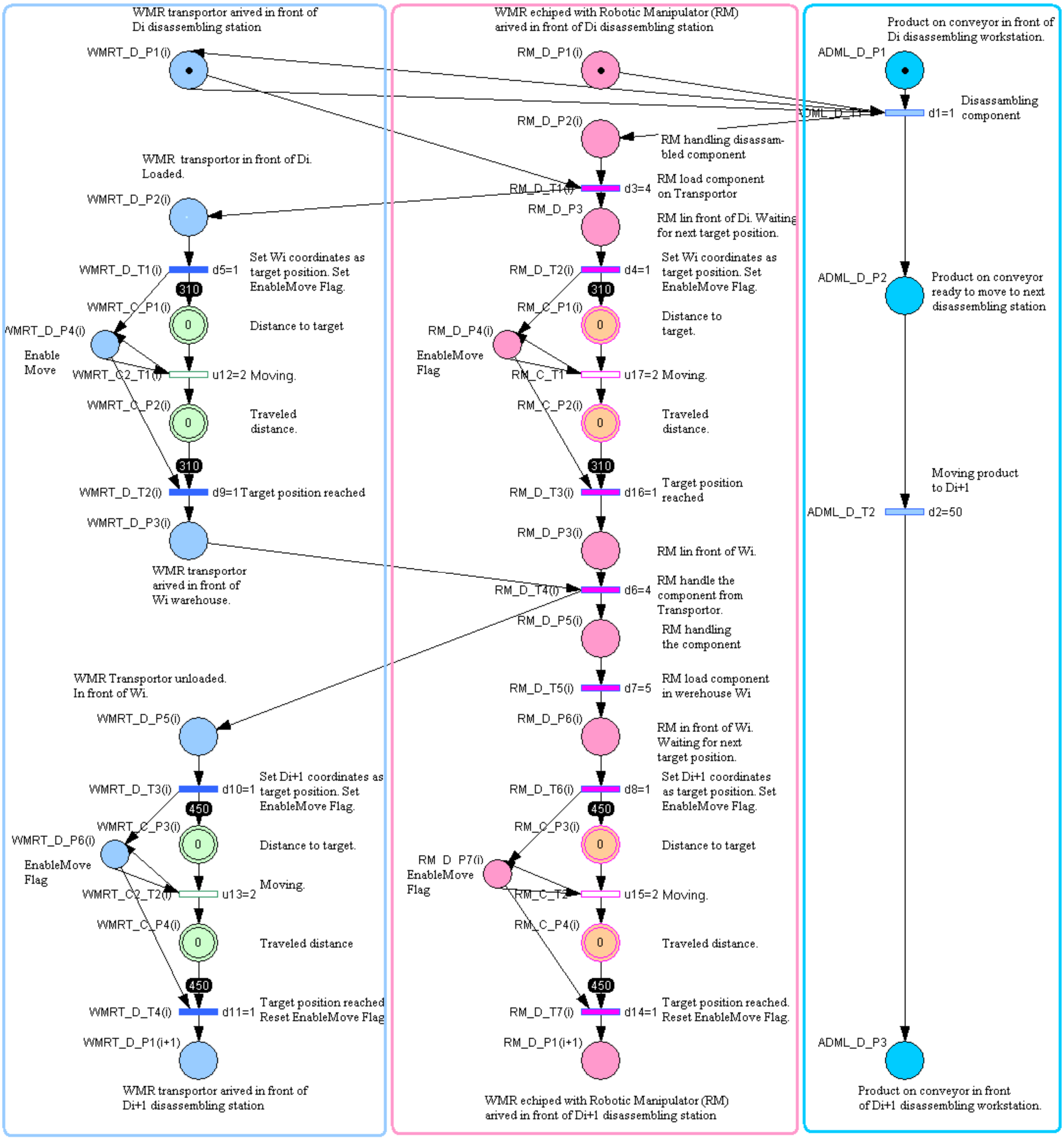

Figure 6. The HPN model for the *i*th elementary disassembly operation