Discrete modelling based control of a processing/reprocessing mechatronics line served by an autonomous robotic system*

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***Abstract*—In this paper it is approached the problem of random events appearing in an automated processing/reprocessing line. The purpose is to give a model of the processing/reprocessing line and to introduce in the process a wheeled mobile robot (WMR)equipped with a robotic manipulator (RM). Reprocessing starts after the processing and after the processed piece fails the quality test. Reprocessing is needed to bring the piece to the parameters required. The WMR with RM is used to transport the piece for reprocessing. For the development of these models, Petri Nets will be used. These models should be coherent with real time evolution of the process. Considering these conditions, solving the main problems concerning the processing line operations is achieved with the help of a robot capable of both transporting and manipulation tasks.**

Keywords*—Petri Nets, processing line, discrete modeling, mobile robot, robotic manipulator.

I. Introduction

In the last decade the industry is put in front of a new global evolution, driven by the technological progress. This improvement is extended in all industrial domains and triggers the evolution of new generations of advanced flexible production systems and new methods of centralized management distributed or supervised. Also this involves the evolution of new types of robots and processing machine tools and the need of efficient transport and manipulation systems [1], [2], [3].

Flexibility and process optimization have drawn the attention of the researches in this field. Most of the studies are based on the increase of the number of manufacturing operations with the same equipment and productivity growth, both having an impact on the quality of the final product [4], [5]. It is well known that the quality of the product and the manufacturing process are tightly bounded. In [6] flexibility characteristic and its impact on performance growth of the flexible manufacturing systems is analyzed. In flexible manufacturing systems appear parallel asynchronous events (time parallelism), also known as concurrent asynchronous events. Since these asynchronous events tend to achieve a common goal, that of the whole aggregate operation, these events coincide in time intervals that occur [7], [8].

Such asynchronous parallel events inflexible manufacturing systems can be simultaneous processing of parts on various stations (machine tools), made simultaneously with transport and/or handling of parts to (or from)other stations with the execution of different operations (processing, assembly, disassembly). These events are asynchronous because a synchronization system of this large number of events does not exist. Such a system could not be achieved, taking into account the complexity of the flexible manufacturing system and the fact that events do not unfold exactly according to predetermined sequences, but as a result of successive conditionings, that do not have invariableness character and the relative velocities of events developing could not be known before hand.

The existence of parallel asynchronous events require complex modelling techniques adopted for driving a flexible manufacturing system and the relatively small number of techniques used to date has been determined by this inconvenience, and the requirements imposed to the model: generality of application ease of use and representation fidelity. The main analysis and modelling techniques currently used and described to highlight the flexible manufacturing systems served by robots with parallel asynchronous events are Petri Nets.

In this paper, the main objective is the analysing and modelling of FESTO MPS-200 processing system dynamics at the occurrence of events using classic Petri Nets. Also it is shown an approach on the simulation of the mobile platform Pioneer P3-DX when serving the FESTO processing system.

II. Initial Conditions

The mechatronics system FESTO MPS-200 is a flexible teaching line for processing, sorting and storage. It is composed of four stations (cells), each performing different operations. When asynchronous events appear, the Pioneer P3-DX mobile robot equipped with a robotic arm intervenes in the process and transports the parts from the storage station. In the analysis and modelling of the flexible processing line FESTO MPS-200 (fig. 1), are introduced initial operating assumptions process regarding.

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Processing analysis of flexible line FESTO MPS-200 shows the following aspects:

At the start of the flexible line FESTO MPS-200 the processing is triggered;

Initially, at the first sorting station there is a component to be processed, which it is passed through a validation test;

Following the validation test the components declared scrap are stored in a separate line. Those that have been validated are sent to the next station. Validation or invalidation of a part is based on the colour of the pieces;

At the processing station two types of operations are performed: reaming and drilling of components from previous station and the piece will be transferred to the next station;

The buffer station accumulates pieces for storage in the warehouse. Accumulation station transfers pieces to the next station using a conveyor belt;

The accumulated pieces are released one by one in order to be taken with an axial manipulator for storing.

Before the taking of the piece with the pneumatic gripper of the axial manipulator a colour validation test is performed. At the storing operation the pieces are sorted by colour. Each colour corresponds to a specific location in the warehouse, which has two levels. Pieces stored on the upper level are considered scrap pieces and will be put back on line for a new flexible machining operation. Bringing of the declared scrap parts to the processing line again is done using the mobile robot equipped with a manipulator. Under the assumptions described above, in fig.2, are presented the sections and trajectories which the mobile platform equipped with manipulator makes in the process of servicing the flexible manufacturing line FESTOMPS-200, where:

R_L^1 represents the number and position of the location where the mobile robot equipped with manipulator is set in the process of taking the piece;

R_L^2 represents the number and position of the location where the mobile robot equipped with manipulator is set in the process of depositing the piece;

T_L^1 is the number of the location to store the piece so that it could be taken by the mobile robot equipped with a manipulator;

T_L^2 is the number of the location into which the piece is deposited by the WMR equipped with RM for a new processing operation.

Considering the analysis described in the previous section, in fig. 3 is proposed the planning of tasks related to flexiblelineFESTOMPS-200.Strategiesfor sorting, processing and storage are based on a graph representation of the processed product where relations between the stations are expressed by arrows. Using this graph is developed a planning of the tasks which will determine the sequence in which the components are processed. If a component is not validated at the colour test or has been validated, tasks planning provide the best sequence to perform its processing and storage in the warehouse.

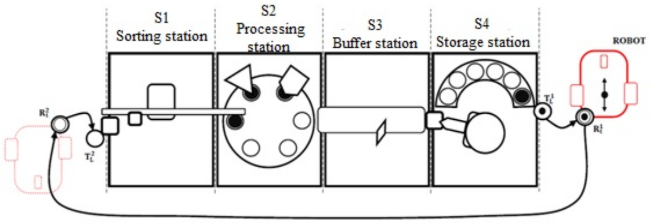

Fig. 1. Complete cycle of the mobile robot equipped with a manipulator serving the flexible line FESTO MPS-200

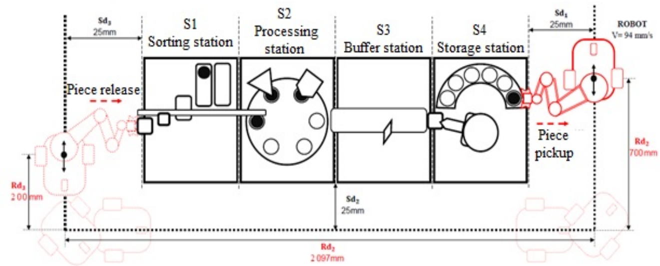

Fig. 2. Fig.2.Division into sections and path passed by the mobile robot

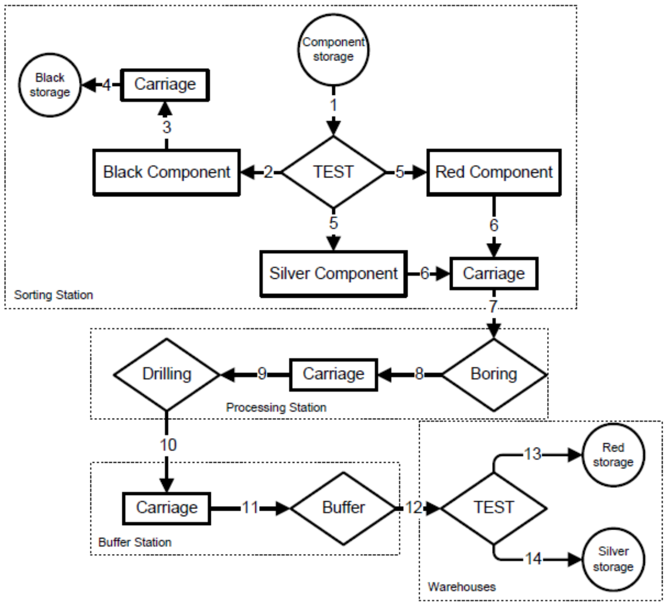

Fig. 3. Task planning for sorting, reaming, drilling and storage operations

III. Modelling of the Mechatronics Processing Line

Considering the planned tasks in fig. 3 and the process description in section II, in fig. 4 it is shown a non-timed Petri net that represents the FESTO MPS-200 flexible line model in the processing operation, by discrete event system (DES) approach.

There are some notations to be made:

$$P^P = \{P_{p_1}, \quad P_{p_2}, \quad \ldots . \quad P_{p_n}\} \tag{1}$$

$$P^P = \{P_{p_i}\}_{i=\overline{1,13}} \tag{2}$$

where: $\{P_{p_i}\}_{i=\overline{1,13}}$ is the set of locations for processing operation.

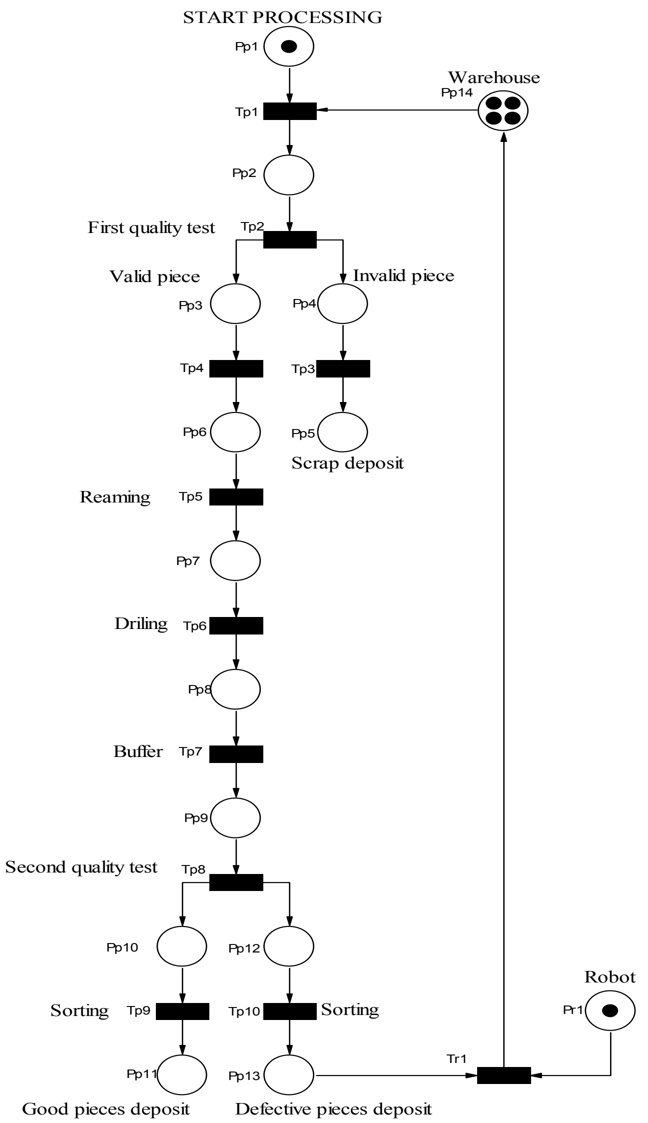

Fig. 4. Non-timed Petri Net model of the flexible processing line FESTOMP S-200 in DES approach

$$T^P = \{T_{p_1}, \quad T_{p_2}, \quad \ldots . \quad T_{p_n}\} \tag{3}$$

$$T^P = \{T_{p_i}\}_{i=\overline{1,10}} \tag{4}$$

where: $\{T_{p_i}\}_{i=\overline{1,10}}$ is the set of transitions for processing operation;

$M0 : P_{p_1}$ is a function of the initial marking.

Next, the modelling of the flexible processing line FESTO MPS-200 served by a mobile robot equipped with a manipulator using timed Petri net is shown in fig. 5. Considering the task planning in fig. 3 and the process description in section 2, the timed Petri Net represents the model of the flexible line, mode lout lining the actual process of machining served by a mobile robot with manipulator in discrete event system approach.

During processing, the timed transitions are:

$T_{p_1} = 3.5s$; $T_{p_3} = 4.8s$; $T_{p_4} = 6.9s$; $T_{p_5} = 3.9s$; $T_{p_2} = 0$ and $T_{p_8} = 0$ are assigned a value of zero, since each transition corresponds to a state of process that happens instantly;

$T_{p_6} = 3.4s$; $T_{p_7} = 10.9s$; $T_{p_9} = 11.8s$; $T_{p_{10}} = 13.3s$; $T_{r_1} = 121.7s$.

IV. Real-Time Control of WMR Serving Mechatronics Processing Line

A. Kinematic Model of the Mobile Platform

The mobile platform has two differential drive wheels and a guiding wheel as shown in fig. 6.

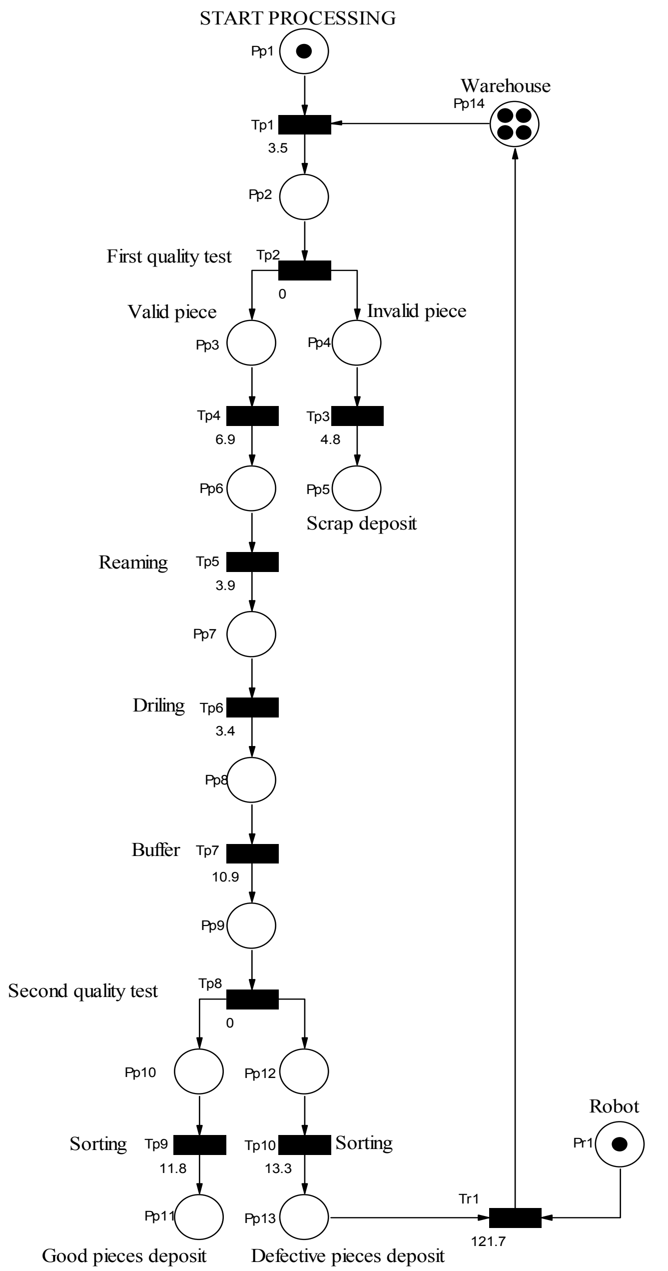

Fig. 5. Timed Petri NET model of the flexible processing line FESTO MPS-200 in DES approach.

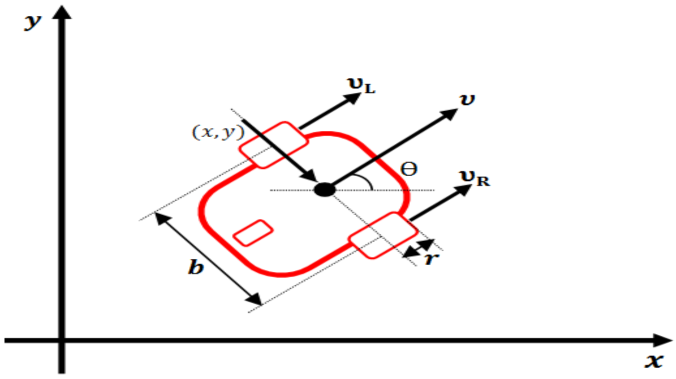

Fig. 6. Kinematic variables of the mobile platform with two driving wheels and a rear free wheel.

Kinematics modelling of mobile platforms issue was explicitly addressed in the literature [9], [10]:

$$\begin{cases} \dot{x}_r = v_r \cdot \cos\theta_r \\ \dot{y}_r = v_r \cdot \sin\theta_r \\ \dot{\theta}_r = \omega_r \end{cases} \tag{5}$$

where x_r and y_r are Cartesian coordinates of the geometric centre of the mobile platform, v_r is the linear velocity of the mobile platform, θ_r is the steering angle, angular velocity of the robot is ω_r and b is the distance between the planes of the driving wheels.

B. Sliding Mode Driving of the Mobile Platform

Trajectory tracking errors can be characterized by $(x_e, \ y_e, \ \theta_e)$. The purpose of this section is to design a stable controller, which generates a control vector $(v_c, \ \omega_c)$. Trajectory tracking error vector is:

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta_d & \sin\theta_d & 0 \\ -\sin\theta_d & \cos\theta_d & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_r - x_d \\ y_r - y_d \\ \theta_r - \theta_d \end{bmatrix} \tag{6}$$

where, $(x_d, y_d, {}_d)$is the virtual position of the mobile platform. The derived of the tracking error can be written,

$$\begin{cases} \dot{x}_e = -v_d + v_r \cdot \cos\theta_e + \omega_d \cdot y_e \\ \dot{y}_e = v_r \cdot \sin\theta_e - \omega_d \cdot x_e \\ \dot{\theta}_e = \omega_r - \omega_d \end{cases} \tag{7}$$

where, v_d and ω_d are the desired linear and angular velocities.Here it is supposed that $|\theta_e| < \pi/2$ which implies that the orientation of the mobile platform should not be perpendicular to the desired direction. A new sliding surface was introduced so that the lateral error, y_e, and the angular variable, θ_e ,are internally connected in the same area and both variables converge to zero. For this purpose the following areas have been defined:

$$\begin{cases} s_1 = \dot{x}_e + k_1 \cdot x_e \\ s_2 = \dot{y}_e + k_2 \cdot y_e + k_0 \cdot \mathrm{sgn}(y_e) \cdot \theta_e \end{cases} \tag{8}$$

where, k_1, k_2, k_3 are positive constant parameters, x_e, y_e and $_e$ are the tracking errors defined in equation (5).

If surface s_1 converges to zero, x_e converges to zero. If s_2 converges to zero, then y_2 becomes

$$\dot{y}_e = -k_2 \cdot y_e + k_0 \cdot \mathrm{sgn}(y_e) \cdot \theta_e \tag{9}$$

If $y_e > 0$ and $k_0 < k_2 \cdot |y_e| / |\theta_e|$ then $\dot{y}_e < 0$. Finally it is known from $s_2$that the convergence of y_e and $\dot{y}_e$ lead to the convergence of θ_e to zero.

The general practical driving law form is:

$$\dot{s} = -Q \cdot \mathrm{sgn}(s) - P \cdot s \tag{10}$$

where P and Q are positive constants. Adding the term $-Qs$, the state is forced to fast approach the switching zone when s is large. Knowing that:

$$\dot{\theta}_e = \dot{\theta}_r - \dot{\theta}_d = \dot{\omega}_r - \dot{\omega}_d \tag{11}$$

then, after the derivation of (8) and (9), it is obtained:

$$\dot{v}_c = \left(\begin{matrix} -Q_1 sign(s_1) - P_1 s_1 - k_1 \dot{x}_e - \dot{\omega}_d y_e \\ -\omega_d \dot{y}_e + v_r \dot{\theta}_e \sin\theta_e + \dot{v}_d \end{matrix} \right) \Big/ \cos\theta_e \tag{12}$$

$$\omega_c = \left(\begin{matrix} -Q_2 sign(s_2) - P_2 s_2 - k_2 \dot{y}_e \\ -\dot{v}_r \sin\phi_e + \dot{\omega}_d x_e + \omega_d . \dot{x}_e \end{matrix} \right) \Big/ \left(\begin{matrix} v_r \cos\phi_e \\ + k_0 \ \mathrm{sgn}(y_e) \end{matrix} \right) + \omega_d \tag{13}$$

The Lyapunov function is defined $V = 1/2 \cdot s^T \cdot s$, so the derivative in time is

$$\begin{aligned} \dot{V} &= s_1 \cdot \dot{s}_1 + s_2 \cdot \dot{s}_2 = s_1 \cdot (-Q_1 \cdot \mathrm{sgn}(s_1) - P_1 \cdot s_1) \\ &+ s_2 \cdot (-Q_2 \cdot \mathrm{sgn}(s_2) - P_2 \cdot s_2) \end{aligned} \tag{14}$$

In order to have a negative and semi defined $\dot{V}$ it is enough to choose Q_i and P_i $i \in \{1,2\}$so that $Q_i, P_i \geq 0$. Closed loop sliding-mode control of the WMR is shown in fig. 7. Using the above discussed equations, in the real time simulation, the trajectory passed by the Pioneer P3-DX robot along with the flexible line FESTO MPS-200 is shown in fig. 8.Before the simulation, some conditions had to be imposed: the total distance travelled by the mobile platform is 5634mm; the path is crossed over in two stages: retrieval-deposit and return to the initial position.

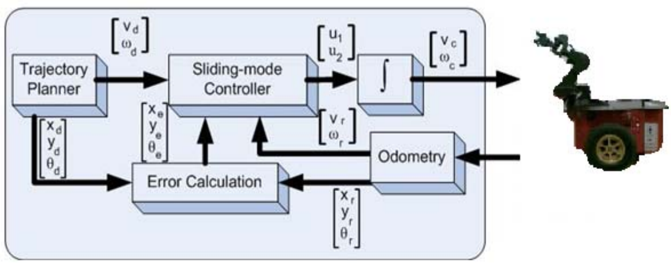

Fig. 7. Closed loop WMR control

Each stage has a 2817 mm distance and can be divided in three sections: the first section of 700mm the platform goes straight from the START position, then it executes a 90^o turning to the right and then again goes a straight distance of 2097mm which corresponds to the second section; after turning again 90^o to the right the robot goes 200mm until the STOP position, which is the third section of the trajectory. After completing three sections for transporting a piece, the mobile platform returns to the initial position following the same path; the mobile platform speed is 94 mm/s; it has not considered the time in which the platform does not move during the processing or deposit delays; the mobile platform equipped with manipulator takes only one work piece declared scrap and returns it to the processing line. After that, the mobile platform returns to the initial position.

C. Results via Simulation and Real Time Control

Figure 9 shows three kind of work pieces involved in the processing and the movement of the robot at the appearance of a defective piece. In fig. 10, it is shown the real and the imposed trajectories of the mobile platform. Both trajectories coincide on all distance passed. When the platform turns 90^o, a small deviation from the trajectory can be noticed. In fig. 11 are noticed variations of the real linear speed regarding the imposed speed. From simulation, has resulted that the necessary time for the mobile platform to pass the 5634 mm distance was of 121.7s. In fig. 12 is shown the tracking error on x axis. The maximum error consists of a 4 mm deviation of the mobile robot regarding the imposed distance. In fig. 13, it is shown the tracking error on y axis which has a maximum of 2mm.

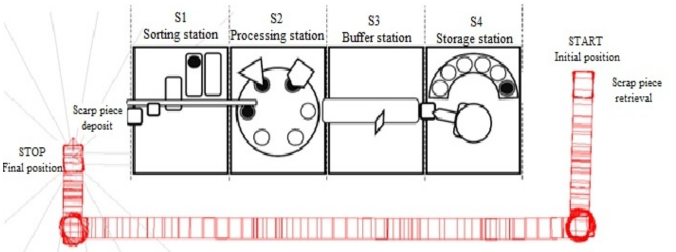

Fig. 8. WMR simulated response in trajectory tracking sliding mode control serving processing line FESTO MPS-200.

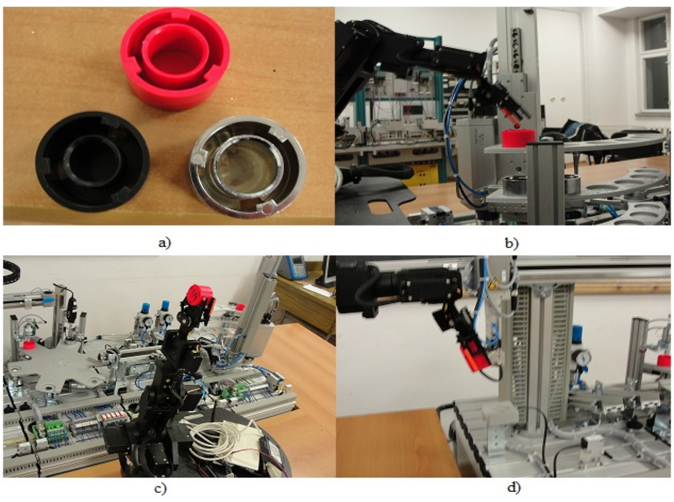

Fig. 9. a) Types of pieces; b), c) and d) WMR, Pioneer P3-DX, with RM, Pioneer 5-DOF, serving FESTO MPS-200.

When the robot makes last 90^o turn, the deviation reaches its maximum of 2.37 mm. In fig.14 it is shown the orientation error of the mobile platform which is of approximately 2^o and infig. 15 are shown the desired and the real angular speed, with an error between them of 0.5rad/s. In fig. 16 and 17 are shown the commands for sliding mode control of the mobile platform on $s_1$and s_2 surfaces.

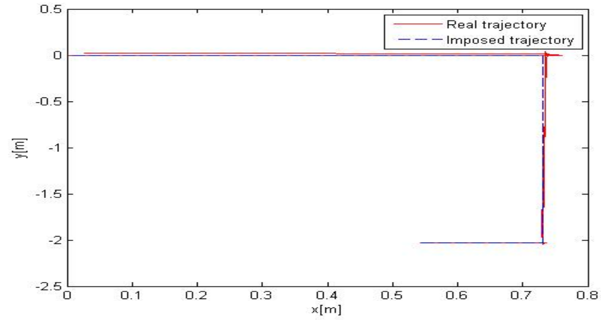

Fig. 10. Desired and real trajectories of the WMR

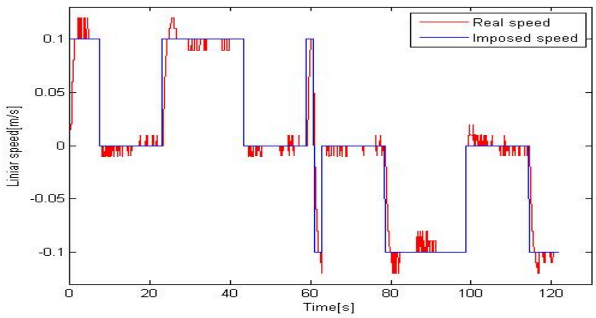

Fig. 11. Desired and real linear speeds of the WMR

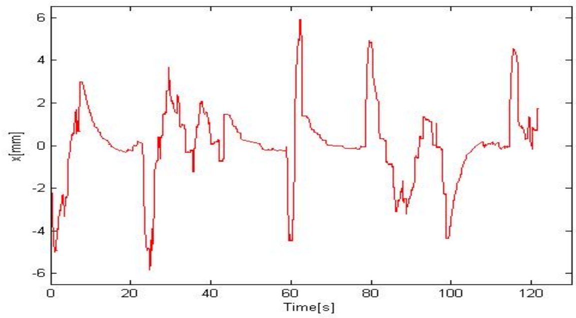

Fig. 12. X axis tracking error

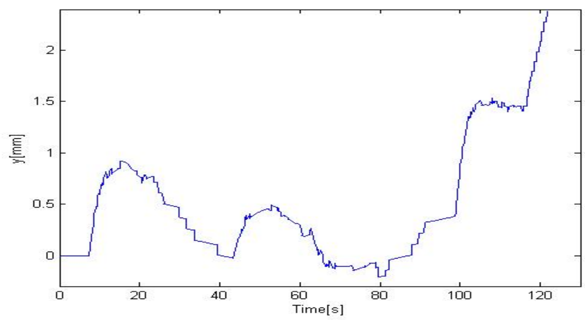

Fig. 13. Y axis tracking error

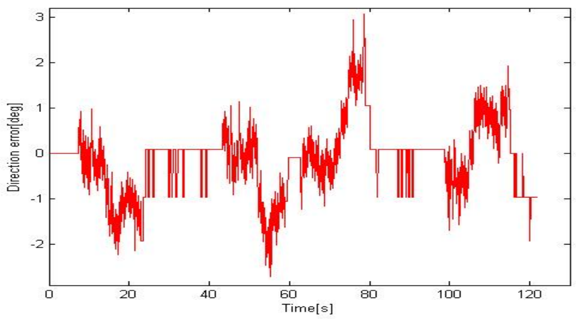

Fig. 14. Orientation error of the WMR

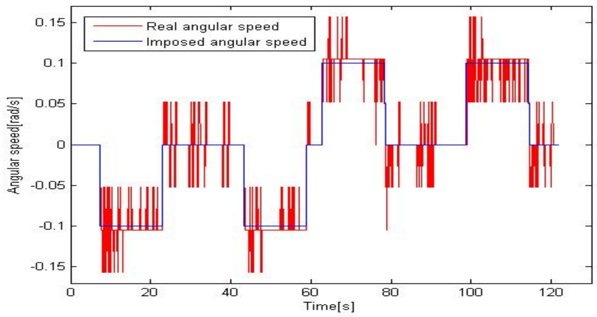

Fig. 15. Desired and angular speed of the WMR

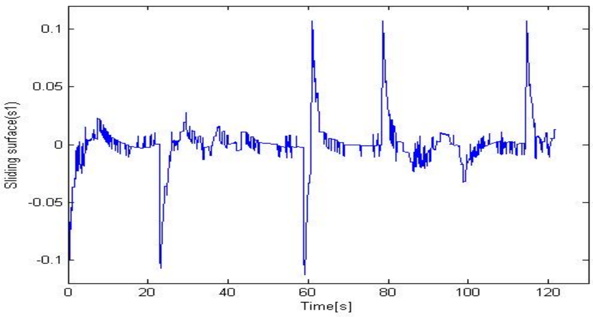

Fig. 16. Control input on sliding surface s_1

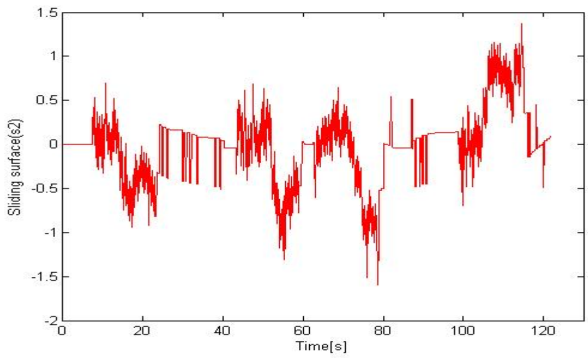

Fig. 17. Control input on sliding surface s_2

V. CONCLUSIONS

The main contribution of this paper is the optimization and management of the flexible processing line. In order to do that, were implemented different driving programs for the line and models with timed or not timed Petri Nets. The chosen modelling represents a good solution for accurately highlight the real process and to show different properties of the discreet event system. Validation of the simulation model can produce a limited set of states of the modelled system and thus can only show the presence (but not absence) of errors in the model and its basic specifications. In the simulation of the processing served by a mobile robot equipped with a manipulator for the flexible line FESTO MPS-200 were eliminated errors, unwanted situations and events. In the simulation values were used for state transitions in real process of simulation to better reflect the behaviour of flexible lines. Based on the above presented results, some future research topics will be undertaken, such as developing a hybrid Petri Net model for the processing line and the implementation of a control loop for the manipulator using different processing techniques and recognition of video sequences.

REFERENCES

[1] Toni A. and Tonchia S. *Manufacturing Flexibility: a literature review.* International Journal of Production Research, 1998, vol. 36, no. 6, 1587-617.

[2] Chryssolouris G. *Manufacturing Systems – Theory and Practice.* New York, NY: Springer Verlag, 2005. 2nd edition.

[3] Tolio D.,*Design of Flexible Production Systems – Methodologies and Tools*. Berlin: Springer, 2009. ISBN 978-3-540-85413-5.

[4] F.F. Chen and E.E. Adams, *"The Impact of Flexible Manufacturing Systems on Productivity and Quality"*, IEEE Transactions of Engineering Management, vol. 38, pp. 33-45, 1991.

[5] G. Da Silverira, D. Borenstein and F.S. Fogliatto, *"Mass Customization: Literature Review and Research Directions"*, International Journal of Production Economics, vol. 72, pp. 1-13, 2001.

[6] 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.

[7] 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

[8] E. Minca, A. Filipescu and A. Voda *"New Approach in Control of Assembly/Disassembly Line Served by Robotic Manipulator Mounted on Mobile Platform,* 2012 IEEE International Conference on Robotics and Biomimetics (ROBIO 2012), ISBN;978-1-4673-2126-6, pp.235-240, 11-14 Dec, 2012, Guangzhou, China.

[9] Fukao T., Nakagawa H., Adachi N., *Adaptive tracking control of a nonholonomic mobile robot*, IEEE Transactions on Robotics and Automation, vol. 16, nr.5, pag. 609-615, 2000.

[10] De Luca A. and Oriolo G. (1995). *Modelling and Control of Nonholonomic Mechanical Systems*, in: J. Angeles, A. Kecskemethy (Editors), Kinematicsand Dynamics of Multi-Body Systems, Springer-Verlag, 277–342.