„Dunărea de Jos" University of Galaţi

Doctoral School of Fundamental and Engineering Scieneces

DOCTORAL THESIS

CONTRIBUTIONS IN FLEXIBLE MANUFACTURING LINES CONTROL WHILE SERVICED BY MOBILE ROBOTS EQUIPPED WITH MANIPULATORS AND VISUAL SERVOING SYSTEMS

Resume

Phd student

Eng. George Petrea

Supervisor

Prof. dr. eng. Adrian Filipescu

Series I8, No. 5,

GALAŢI,

2018

„Dunărea de Jos" University of Galaţi
Doctoral School of Fundamental and Engineering Scieneces

DOCTORAL THESIS

CONTRIBUTIONS IN FLEXIBLE MANUFACTURING LINES CONTROL WHILE SERVICED BY MOBILE ROBOTS EQUIPPED WITH MANIPULATORS AND VISUAL SERVOING SYSTEMS
Resume

Phd student

Eng. George Petrea

President,	Prof. dr. eng. Barbu Marian
Supervisor,	Prof. dr. eng. Adrian Filipescu
Scientific reviewers	Prof.dr.eng. Dan Popescu Prof.dr.eng. Dorian Cojocaru Prof.dr.eng. Sergiu Caraman

Series I8, No. 5,
GALAŢI,
2018

The series of PhD thesis publicly held in UDJG since 1 October 2013 are:

Domain: **ENGINEERING SCIENCES**

Series I 1**: Biotehnologies**
Series I 2**: Computers and information technology**
Series I 3**. Electrical Engineering**
Series I 4**: Industrial Engineering**
Series I 5: **Materials Engineering**
Series I 6**: Mechanical Engineering**
Series I 7**: Food Engineering**
Series I 8: **Systems Engineering**

Domain: **ECONOMIC SCIENCES**

Series E 1: **Economy**
Series E 2: **Management**

Domain: **HUMAN SCIENCES**

Series U 1: **Philology - English**
Series U 2: **Philology - Romanian**
Series U 3**: History**

Contents

Notations and abbreviations **6**

Introduction **7**
Considerations on flexible manufacturing lines served by mobile robots........................ 7
Purpose and objectives of the research on flexible manufacturing lines control................ 7
Structura și conținutul tezei 8

Chapter 1. The present stage of flexible manufacturing lines control while serviced by mobile platforms and robotic manipulators **9**
1.1 VS systems integrated into manufacturing lines for robotic systems control 10

Chapter 2. Flexible manufacturing lines analysis while serviced by mobile robots **11**
2.1 The basic structure of a flexible manufacturing system 11
2.2 Flexible manufacturing systems classification 12
2.3 Festo MPS-200 processing line 13
2.4 Pioneer P3-DX mobile platform equipped with the Pioneer 5-DOF Arm structure 13
2.5 PeopleBot mobile robot 14
2.6 Cyton Gamma 1500 robotic manipulator 14

Chapter 3. Modeling of processing lines serviced by complex autonomous systems **15**
3.1 Working assumptions for modelling the Festo MPS-200 line 15
3.2 Processing tasks organizational chart for Festo MPS-200 line 16
3.3 Discrete modeling of the Festo MPS-200 mechatronic line using non-timed Petri nets 16
3.4 Discrete modeling of the Festo MPS-200 mechatronic line using timed Petri nets 17
3.5 Modeling the processing line serviced by autonomous systems using synchronized hybrid Petri Nets 18

Chapter 4. Simulation of the processing line model serviced by autonomous systems **21**
4.1 Synchronized hybrid Petri Nets model simulation 21
4.2 MobileSim simulation of the sliding mode control of the mobile platform servicing Festo MPS-200 mechatronic line 22

Chapter 5. VS systems used for controlling complex autonomous systems while servicing flexible manufacturing lines **24**
5.1 Visual features used in VS systems 24
5.1.1 Defining moments of image features 25
5.2 Modeling the VS system 25
5.3 Interaction matrix for moments of image features 25
5.4 Proportional control law for robotic manipulator 26
5.5 Real-time control of the processing line using an eye-to-hand VS system 26
5.5.1 Synchronizing and video control of the mobile robot application using an eye-to-hand VS system 27
5.6 Real-time control of the processing line using an eye-in-hand VS system 28
5.6.1 Synchronizing and video control of the mobile robot application using an eye-in-hand VS system 28

Chapter 6. Conclusions and contributions **30**
6.1 Contributions 30
6.2 Results dissemination 31

Notations and abbreviations

ARIA – advanced robotic interface for aplications;
CAD – computer aided design;
CAE – computer aided engineering;
CAM – computer aided manufacturing;
CAP – computer aided planning
CAQ – computer aided quality;
CAS – computer aided service;
CNC – computer numerical control;
DOF – degree of freedom;
DW – driving wheel;
FW – free wheel;
GUI – graphical user interface;
HPN – hybrid Petri net;
I/O - input / output;
ML – mechatronic line;
DH - Denavit–Hartenberg;
PLC – programmable logic controller;
PN – Petri net;
P/R – processing / reprocessing;
P/RML – processing reprocessing mechatronic line;
Profibus DP – process field bus with descentralised peripherals;
RM - robotic manipulator;
SHPN – synchronised hybrid Petri net;
TPN - timed Petri net;
THPN - timed hybrid Petri net;
VS – visual servoing;
WMR – wheeled mobile robot.

Introduction

Current developments in the production market force industry companies to take note of technical progress and implement measures to increase productivity and improve user relationships. An important role in adapting to these requirements is the use of flexible manufacturing systems due to their adaptability and flexibility characteristics. This systems have flexibility characteristics, given by the capactity of assamble or process different products by reconfiguring the workstations and reverisility characteristics along with the concept of reusing or reprocessing products that do not satisfy the imposed conditions

The use of complex autonomous systems integrated in manufacturing lines is currently one of the possible solution to respond to this galloping evolution. This systems may be composed of mobile robots and robotic manipulators.

Considerations on flexible manufacturing lines served by mobile robots

The need to optimize processing stages has led in many studies to the use of robotic structures to increase the reliability of the system, of the automated process, but also to eliminate the uncertainties and dangers specific to human factor intervention in the process, thus enabling system control to be streamlined.

At the same time, for reducing the security risks for the human factor, the robotic structures control requires field sensors that aid to maximize efficiency. Thus, in many processes, the concept of VS of robotic structures has been developed to capture and process visual field images for use in system control.

Purpose and objectives of the research on flexible manufacturing lines control

As far as the objectives of this research are concerned, they primarily refer to the modeling of a flexible processing system. Previous studies have shown that an efficient tool for modeling discrete events systems is represented by Petri Nets. In the modeling of the processing system, different types of Petri Nets will be used, precisely because subsequently the models obtained help to implement the real-time control of the structure. Various Petri Nets models will refer both to modeling the duration of operations, but also to modeling the movements of the mobile robot in order to transport the pieces.

Also, in this thesis it is desired to customize the model obtained for improving the performance of the mechatronic system represented by a flexible processing line, served for the handling and transport operations by a robotic assembly consisting of a mobile robot and a manipulator. At the end of the implementation of the control structure, the mechatronic system will become fully automated allowing the developing of processing, manipulation and transport, without the intervention of the human operator. Regarding the timeline, the processing operation is a periodic repetitive activity, while the transport and reprocessing of the piece will be accidental processes triggered by the invalidation event of the product at the quality test.

At the same time, it is envisaged in the paper to establish a method of synchronization between the flexible line and the mobile robot equipped with a manipulator for the detection of the part declared as scrap and for its takeover, respectively delivery for reprocessing.

Structure and content of the thesis

The paper is divided into 6 chapters, each having the content described below:

Chapter 1 presents the current state of research on the control of flexible manufacturing systems, describes the characteristics of flexible manufacturing processes and assembly / disassembly and processing systems, and presents general aspects of the modeling and processing tools used.

In the first part, **Chapter 2** presents, a summary of the general features of flexible manufacturing systems. Here is schematically described the architecture of such a flexible manufacturing system and its main functions. The emphasis then falls on the current trend in the collaboration between mobile robots and flexible manufacturing systems and highlights the main functions they can perform within an industrial facility. The chapter ends with the general presentation of the didactic platforms used in the research, namely: the FESTO MPS-200 processing line, the Pioneer P3-DX robot having a Pioneer 5-DOF Arm robotic manipulator, the PeopleBot robot and Cyton Gamma 1500 robotic manipulator.

In **Chapter 3** are highlighted the initial assumptions regarding the analysis and determination of a model for the dynamics of flexible manufacturing lines. Process modeling is done using Petri nets and various types of modeling, not-timed and timed, are being approached and because of task planning and system composition is choosen the hybrid synchronized modeling, to control the systems served by the mobile robot. Contributions in this chapter will mainly refer to the determination of the hybrid model of the flexible processing line synchronized with the mobile robot using a VS application.

Based on the analysis in the previous chapter, **Chapter 4** presents contributions to the simulation of the resulting models using specialized programs Sirphyco and VisualObject Net ++, specific modeling and simulation tools for Petri networks.

Chapter 5, using the results of previous chapters, shows real-time implementation of process line control in collaboration with the mobile robot and manipulator and also the Matlab application for synchronization and VS. Also here is implemented the second control structure based on using a second mobile robot PeopleBot for transport operation of the work pieces that need reprocessing and a Cyton Gamma 1500 robotic manipulator for work piece return to the processing line.

Chapter 6 presents the conclusions, contributions, dissemination of results and future directions of research.

Chapter 1.

The present stage of flexible manufacturing lines control while serviced by mobile platforms and robotic manipulators

Industry evolution over the last 20 years has been deeply marked by the appearance of flexible manufacturing systems and processes that have boosted technological progress. Such progress, involved in all areas of industry, unambiguously leads to the appearance and development of various flexible manufacturing systems. The basis for these systems is the development of control methods for robots and processing devices, as well as the appearance and integration of transport and handling systems.

Figure 1.1 shows the general structure of a manufacturing system as well as the classification of such a system according to the level of development. Extract from the figure, the manufacturing system can be defined as the ensemble of material or non-material components, each with a well-defined role in product development.

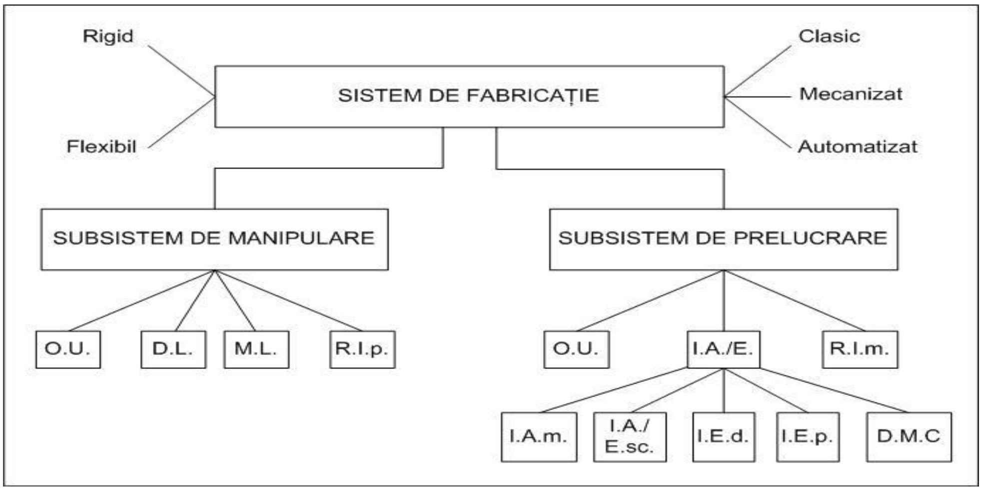
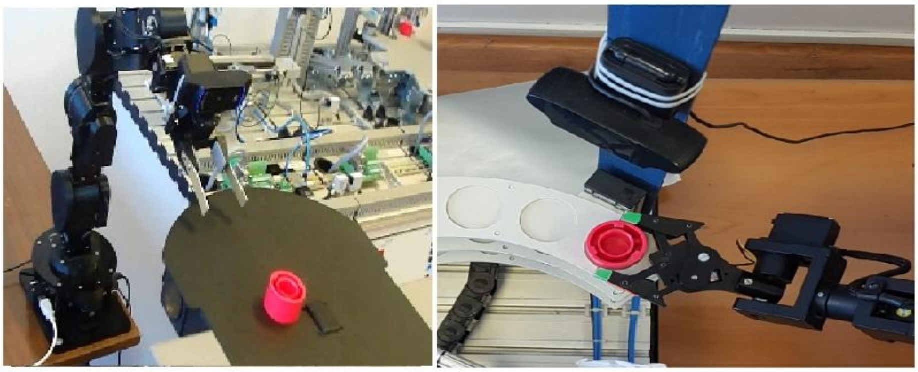


Fig. 1.1. - Structural representation of the manufacturing system

1.1 VS systems integrated into manufacturing lines for robotic systems control

Visual feedback requires visual features with well-defined properties such as stability, robustness and accuracy, so the quality of the results is high. This quality will ultimately lead to the ability to develop appropriate control laws for the application at work.

Depending on the location of the video camera, two VS architectures are distinguished. The visual sensor mounted in a fixed position in the workspace defines eye-to-hand architecture, and camera mounting on the last joint of the robotic manipulator defines eye-in-hand configuration. Each of these two types of architectures has advantages and disadvantages, and depending on them and the desired application, the configuration cand be chosen.



a) b)

Fig. 1.2. – Types of architectures: a) Eye-in-hand configuration b) Eye-to-hand configuration

Another classification of VS systems may be based on the visual information used by the control structure. Thus it is distinguished:

- **Position-based VS systems;**
- **Image-based VS systems.**

A block diagram of the position-based architecture is shown in Figure 1.3, where the difference between the reference v_c^* and the result v_c represents the error, which is then used in the position-based controller to compute the robot speed.

The control strategy strategy for image-based architecture systems using 2D images is the method of minimizing error between reference parameters and those extracted from the image. Figure 1.4 illustrates the block diagram of an image-based architecture.

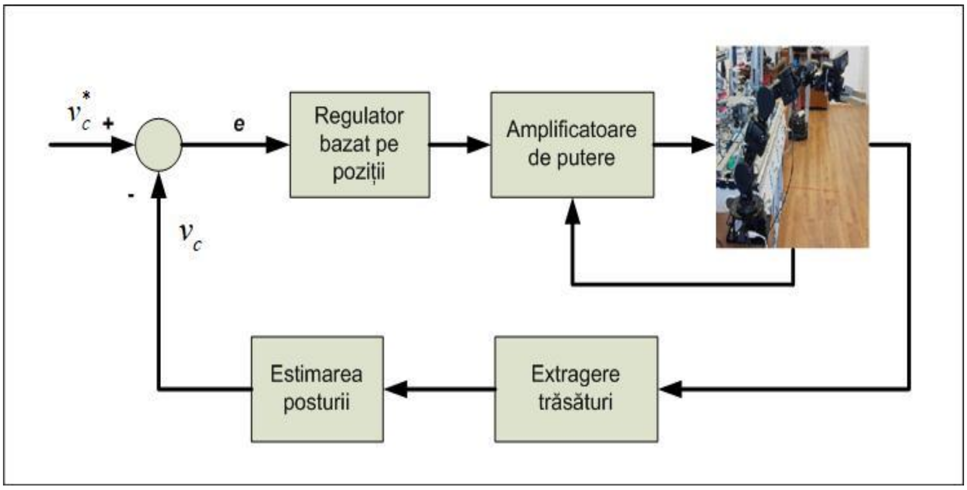


Fig. 1.3. - Block diagram for position-based architecture

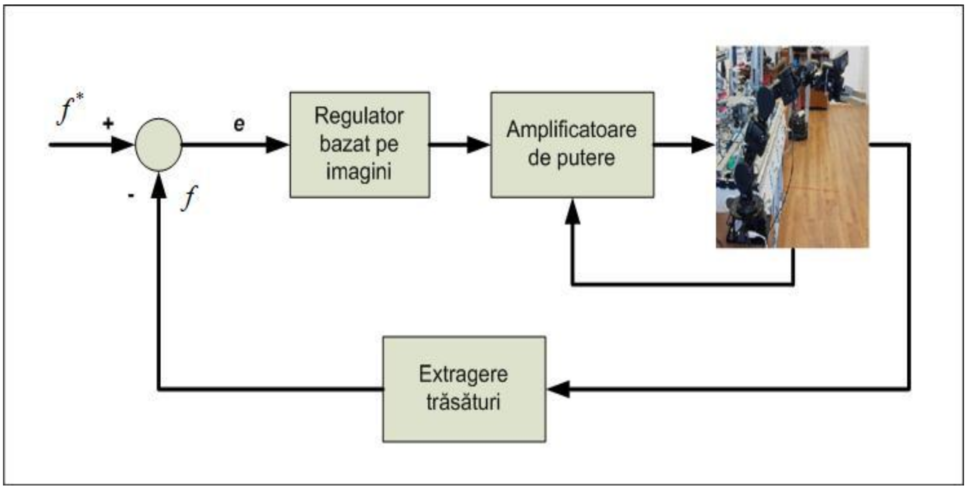


Fig. 1.4. - Block diagram for image-based architecture

Chapter 2.

Flexible manufacturing lines analysis while serviced by mobile robots

2. 1 The basic structure of a flexible manufacturing system

Figure 2.2, is the block diagram of a flexible manufacturing system, served by mobile robots.

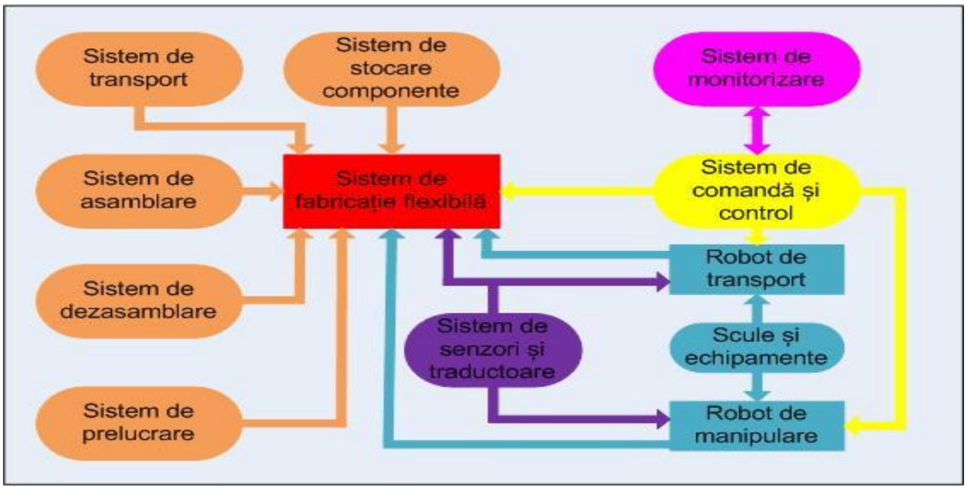


Fig. 2.2. – Classic flexible manufacturing system, serviced by robots

2. 2 Flexible manufacturing systems classification

Generally, manufacturing systems can be classified into two types:

1. Synchronized systems, whereby the transfer of the load from one workstation to another is coordinated and simultaneously. Thus, the number of tasks within the system remains constant, and it is not necessary to use buffers between stations. These systems can also be divided into two subtypes:
   - „Paced" time synchronized systems - refers to the fact that the time allocated to a workstation to perform a task is limited. When the allocated time has expired, it will not be possible to work on that task and the resulting product may be incomplete.
   - Non-time synchronized (unpaced) systems - refers to the fact that there is no defined time limit for the execution of a task.
2. Non-synchronized systems, where load distribution is not coordinated. Thus, the station may start executing a task as soon as possible (the conditions are met). These types of systems are often without time limit for task execution (unpaced).

The flexibility of a manufacturing system may have more connotations, depending on the system structure, the types of operations or the type of products obtained. Thus, flexibility can refer to:

- Flexibility with regard to reconfiguration capacity of stations to obtain different types of finished products.
- Flexibility with regard to the order of operations within a manufacturing system.
- Flexibility with regard to the ability to re-use or reprocess products of the same type on the same line or on a different manufacturing line specifically allocated for this purpose.

Reversibility, on the other hand, is a characteristic of a manufacturing system that can be classified as follows:

- The reversibility of an assembly line, involving the recovery of component parts of an assembly or subassembly that has not passed the quality test.
- The reversibility of a processing line, which refers to the reintroduction into the process of a piece that was rejected by the quality test.

2. 3 Festo MPS-200 processing line

The didactics line model FESTO MPS-200, illustrated in Fig. 2.5, is a modular production system, a flexible didactics line serving industrial processing. The variant used in this project consists of 4 independent stations, handling, processing, transport and storage.

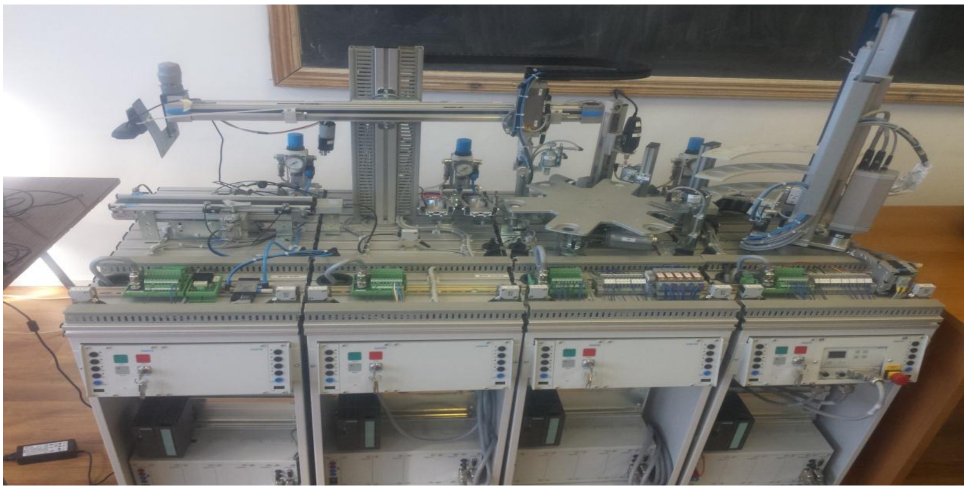


Fig. 2.5. - Flexible manufacturing line Festo MPS-200

2. 4 Pioneer P3-DX mobile platform equipped with the Pioneer 5-DOF Arm structure

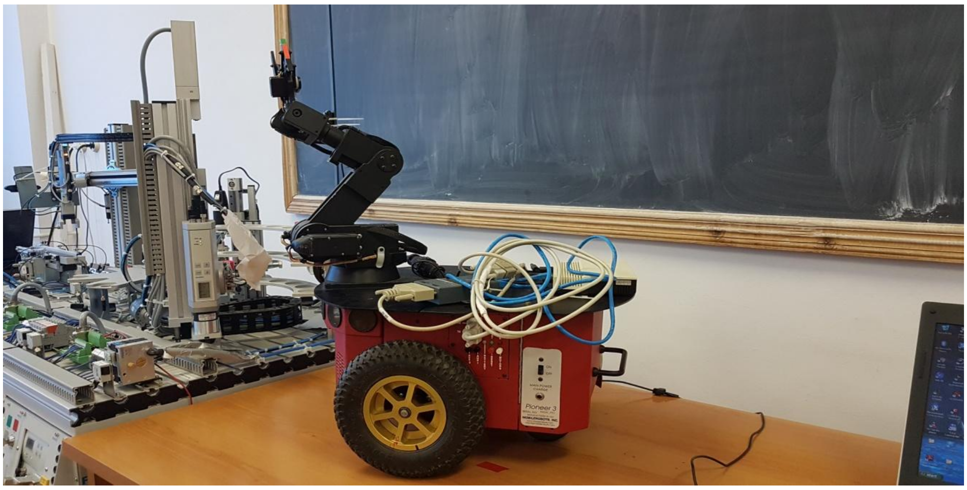


Fig. 2.11. - Pioneer 3-DX Mobile Robot and Robot Manipulator Pioneer 5 DOF Arm

2. 5 PeopleBot mobile robot

Fig. 2.12. - PeopleBot mobile robot

2. 6 Cyton Gamma 1500 robotic manipulator

The use in research of the Cyton Gamma 1500 robotic manipulator for the development of the mobile VS model with a visual sensor mounted on its effector will prove to be an optimal choice due to the ability to pick up and deliver objects in different positions and orientations. The 7 degrees of freedom allow the arm to manipulate objects with a special dexterity.

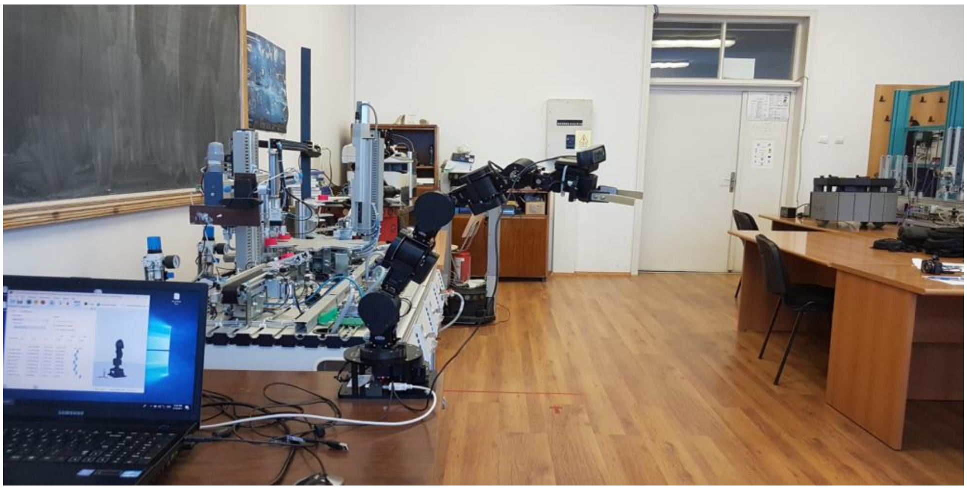


Fig. 2.13. - Cyton Gamma 1500 robotic manipulator

Chapter 3.

Modeling of processing lines serviced by complex autonomous systems

One of the objectives for this thesis is to analyze and develop models for the Festo MPS200 processing line served by complex autonomous systems in order to implement a monitoring and control structure for the flexible processing system that will also allow reprocessing. Hybrid models will be used in which the processing line generates events that will determine the discrete state of the process, and the mobile robots involved in serving the line represent the continuous part of the modeled process.

Modeling aims at simulating the system with the ultimate goal of developing the control strategy of the ensemble consisting of the robotic system and the processing line. To control the system, it is essential to synchronize the operation of the Festo MPS200 Flexible Line to the robotic systems that will serve it to transport defective parts that are processed again. To synchronize the line with the autonomous systems, the VS-based application version will be used, using the video processing results of the visual sensors.

3.1 Working assumptions for modelling the Festo MPS-200 line

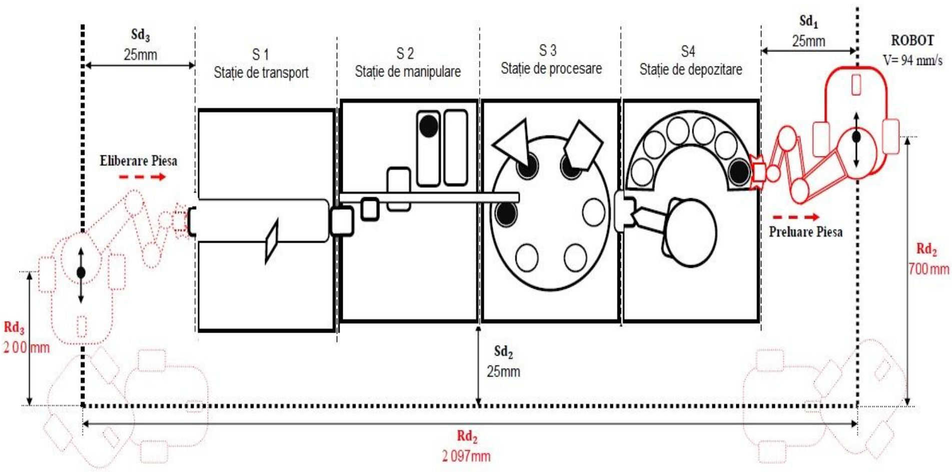


Fig. 3.1. - Flexible Mechatronic Line Festo MPS-200 – Overview

3.2 Processing tasks organizational chart for Festo MPS-200 line

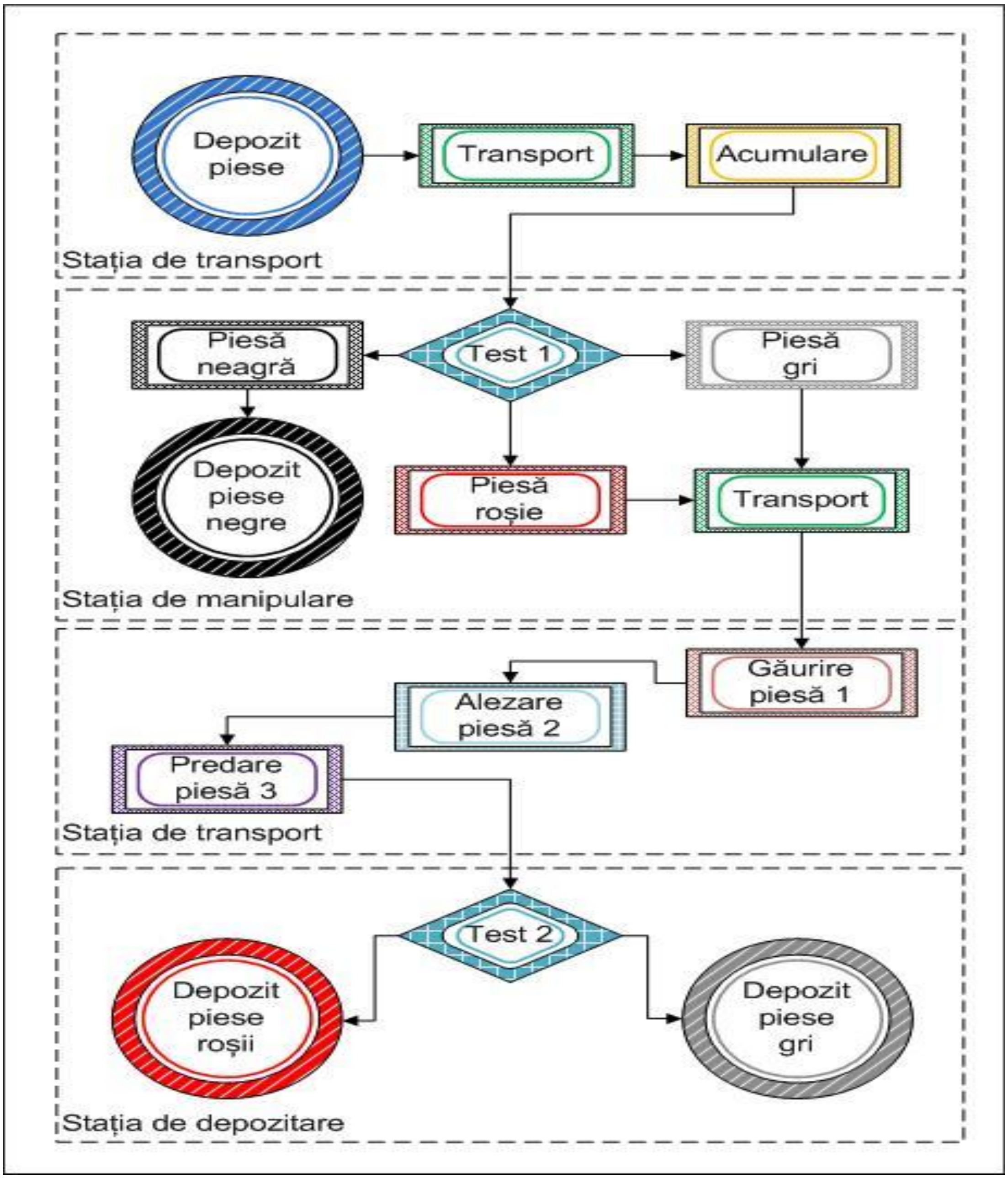


Fig. 3.2. – Organizational chart for defining the processing cycle

3.3 Discrete events model of the Festo MPS-200 laboratory line using non-timed Petri nets

By using non-timed Petri nets in a discreet approach for modeling the FESTO flexible line processing system, a state model is obtained. Thus, the entire behavior of the system is highlighted by the determination of the actions that take place in it, the states that precede the actions and future states in which the system will evolve.

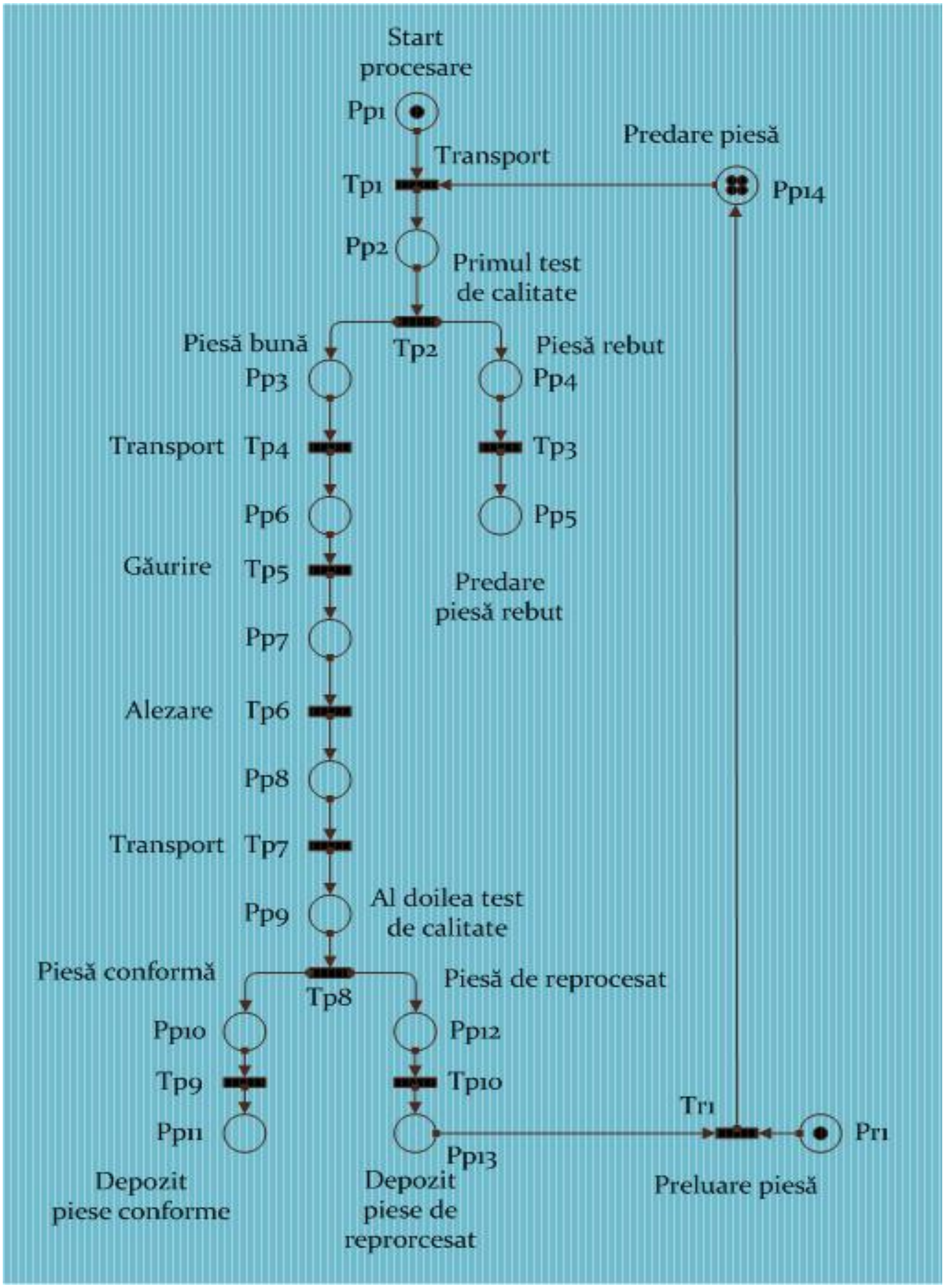


Fig. 3.3. - Petri Net graph resulting from discrete non-timed modeling of processing system on the Festo MPS-200 Line

3.4 Discrete events model of the Festo MPS-200 laboratory line using timed Petri nets

Given the initial assumptions, the task graph in Fig. 3.2 and description of operations, Figure 3.4 illustrates the model of the Festo MPS-200 flexible processing line represented as a timed Petri net:

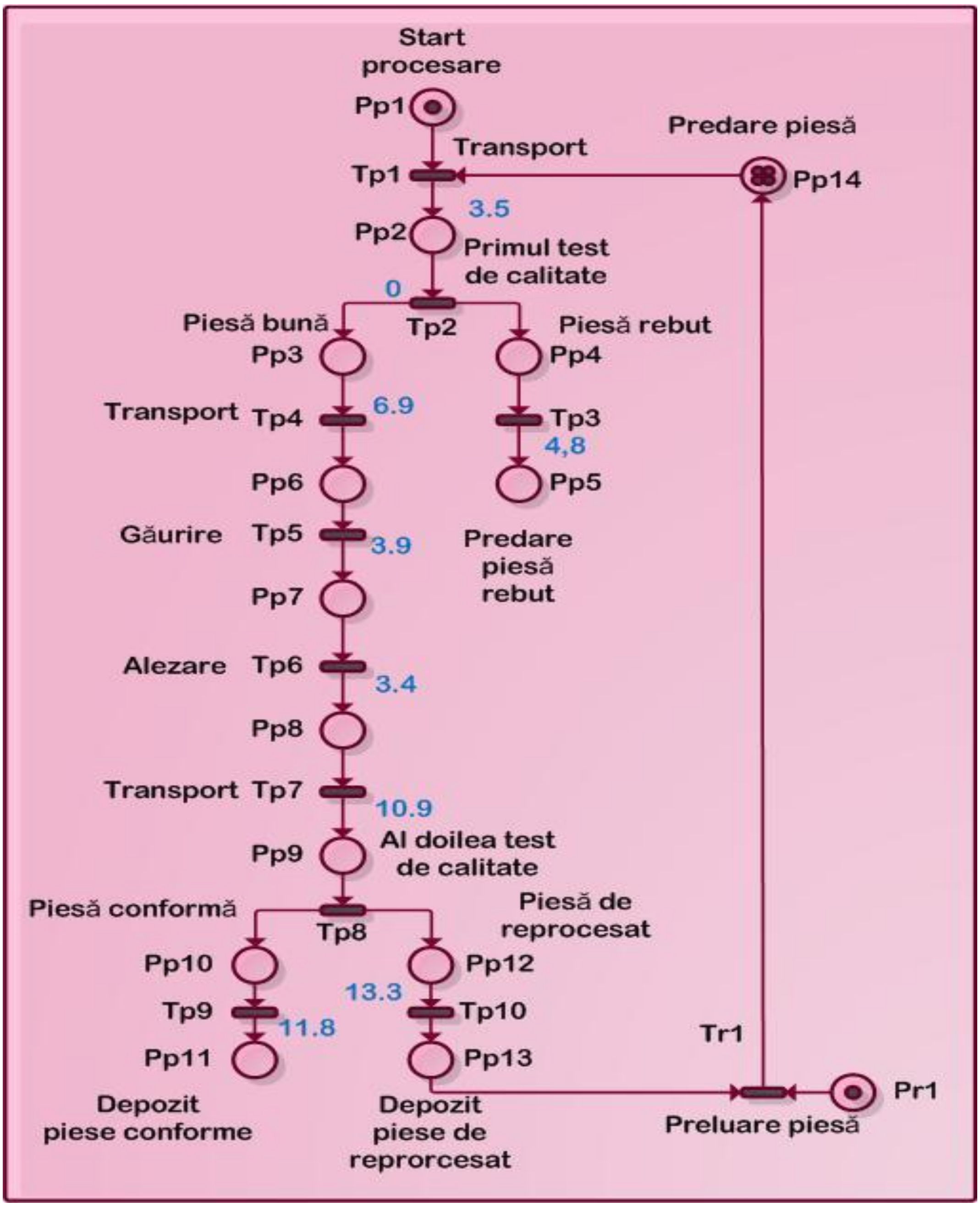


Fig. 3.4. - Petri net graph resulting from discrete timed modeling of the processing system on the Festo MPS-200 line

3.5 Modeling the processing line serviced by autonomous systems using synchronized hybrid Petri Nets

A hybrid Petri net will be a combination of a discrete Petri net and a continuous-type Petri net. In a hybrid Petri network, more emphasis is placed on the interactions between the execution subsystem and the control subsystem, the discrete part of the network designed to model structural and / or behavioral changes of the system, and the continuous part will deal with the evolution of the state between the actions of two external events.

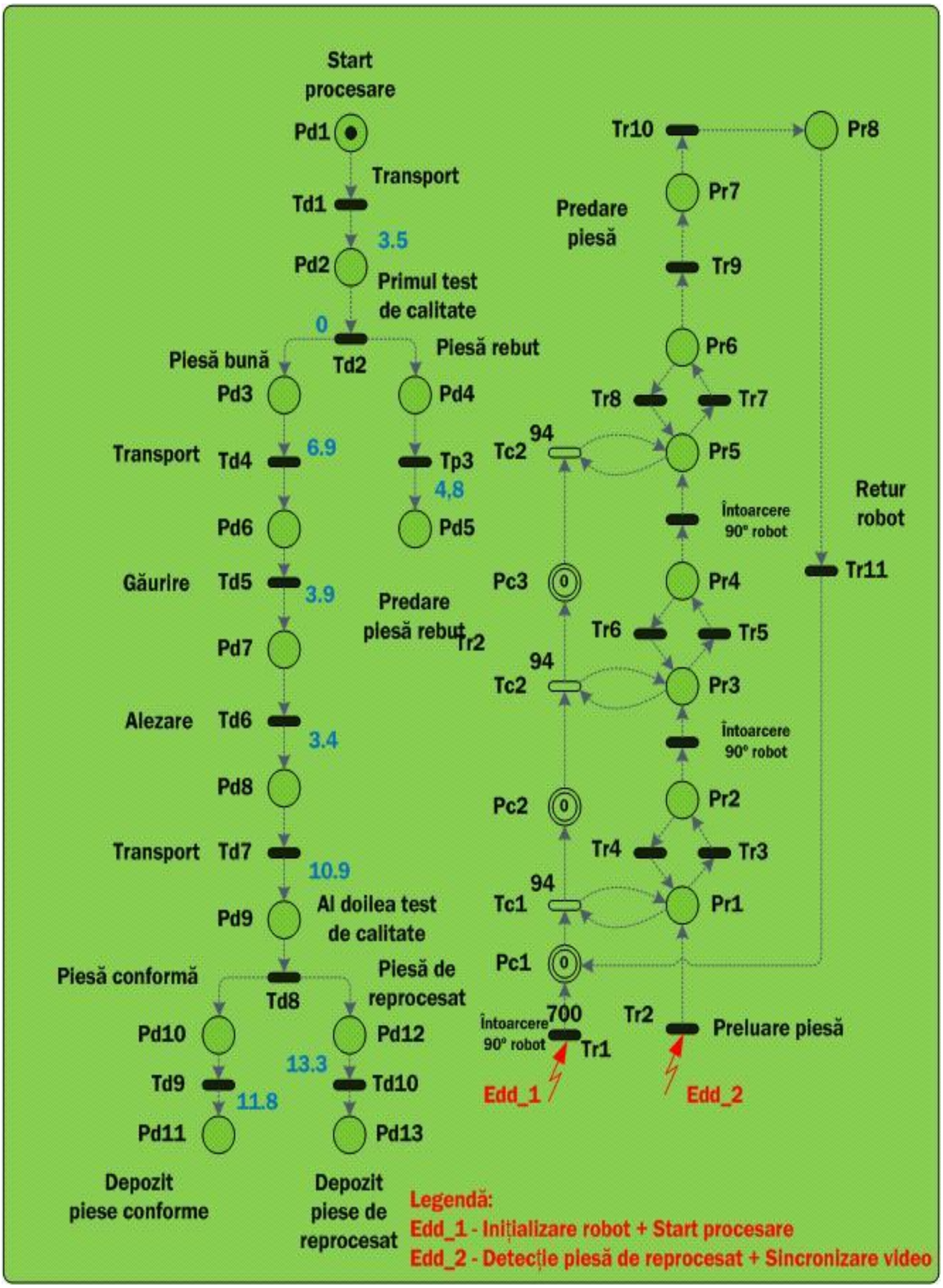


Fig. 3.5. - Hybrid Petri net model of the processing process served by 1 mobile robot equipped with manipulator

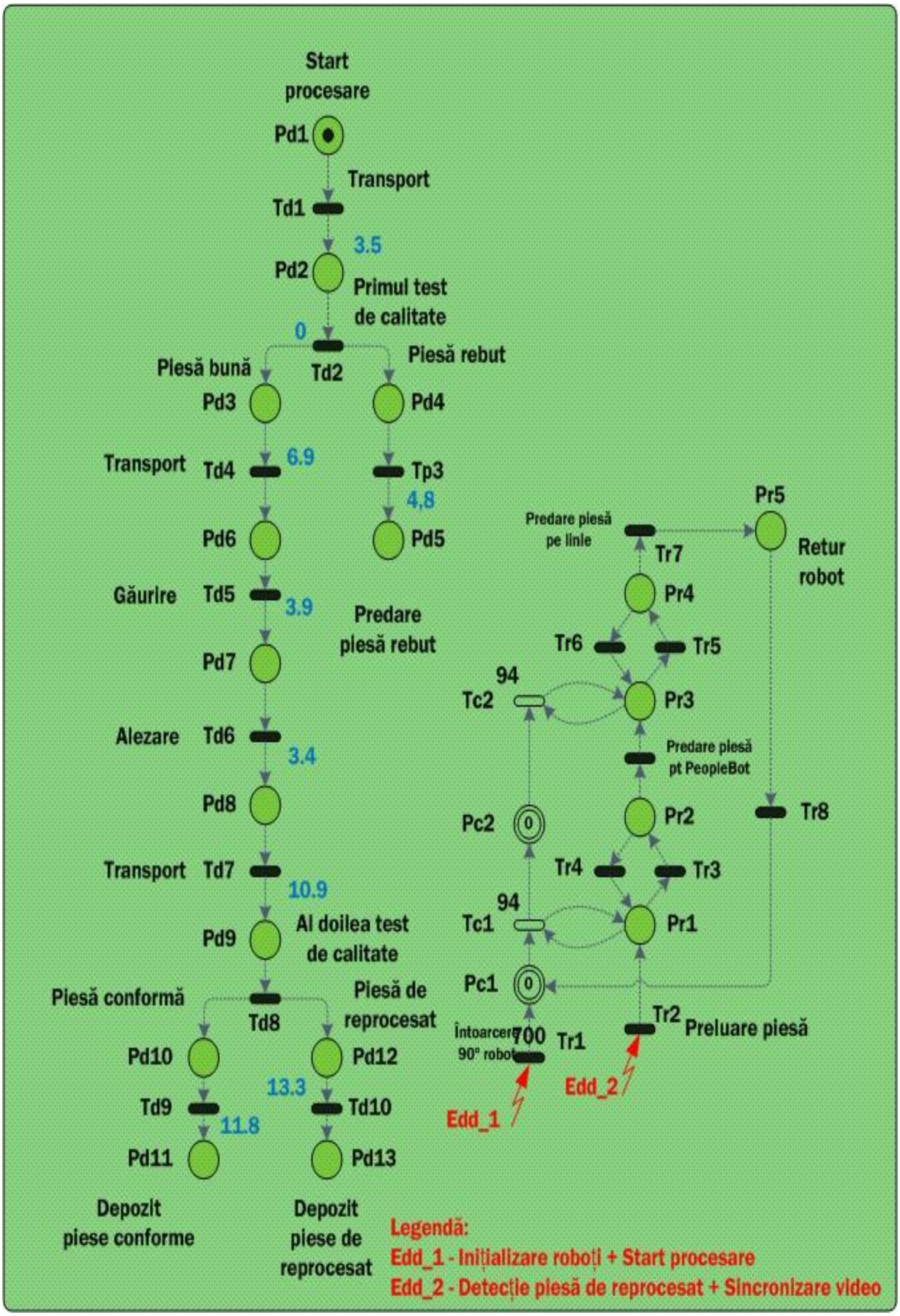


Fig. 3.6. - Hybrid Petri net model of the processing process served by 2 mobile robots and a fixed manipulator

Chapter 4.

Simulation of the processing line model serviced by autonomous systems

4. 1 Model simulation with synchronized hybrid Petri Nets

Using the hybrid Petri net models obtained in the previous chapter, the necessity of their simulation was outlined in order to analyze and determine the correctness of the chosen models. Simulation was performed using the Sirphyco simulation environment.

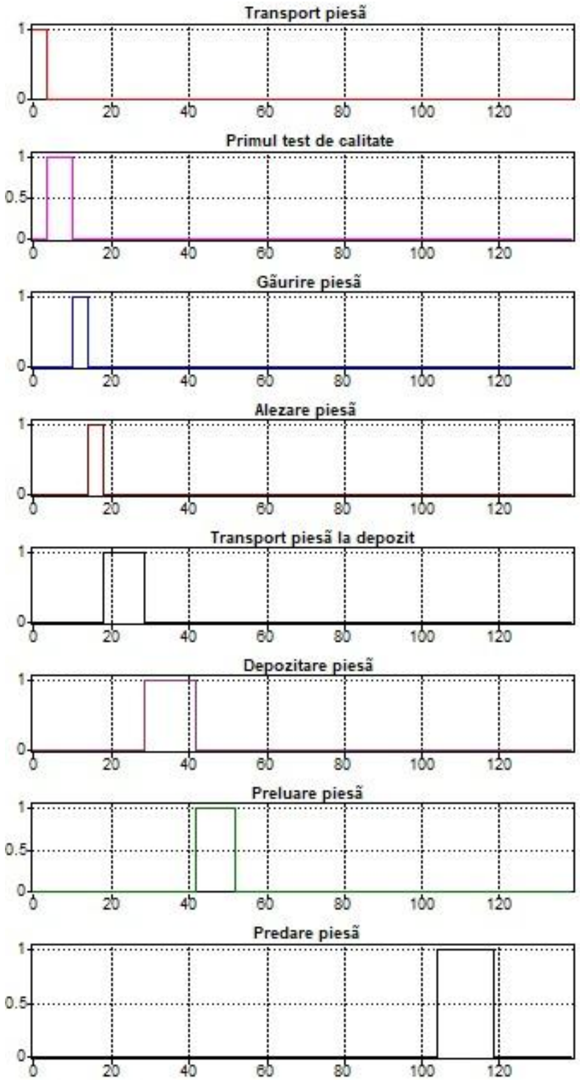


Fig. 4.1. - Evolution of discrete transitions of the processing system served by a single mobile robot with a manipulator

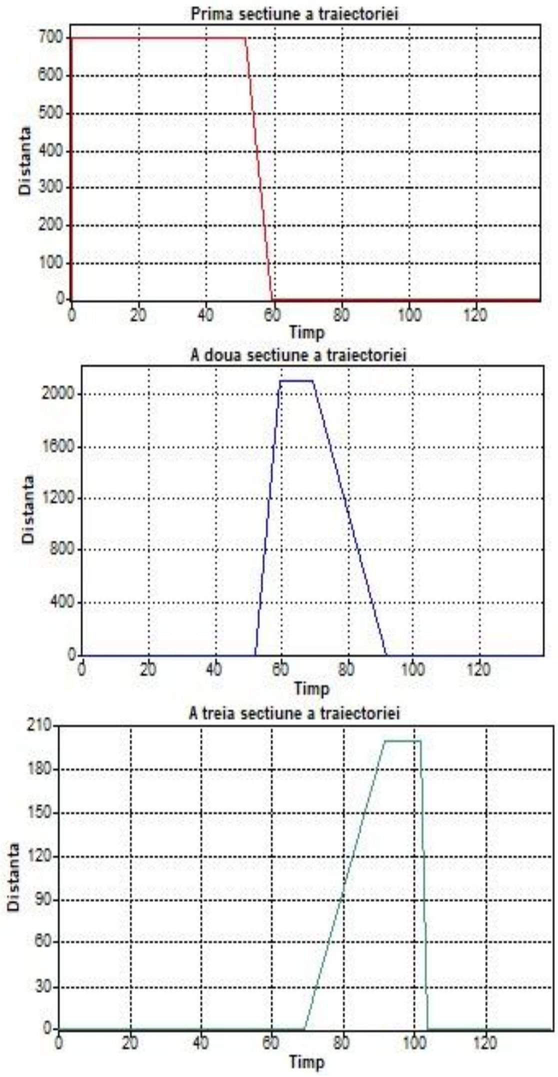


Fig. 4.2. - Evolution of continuous states of the mobile robot equipped with robotic manipulator

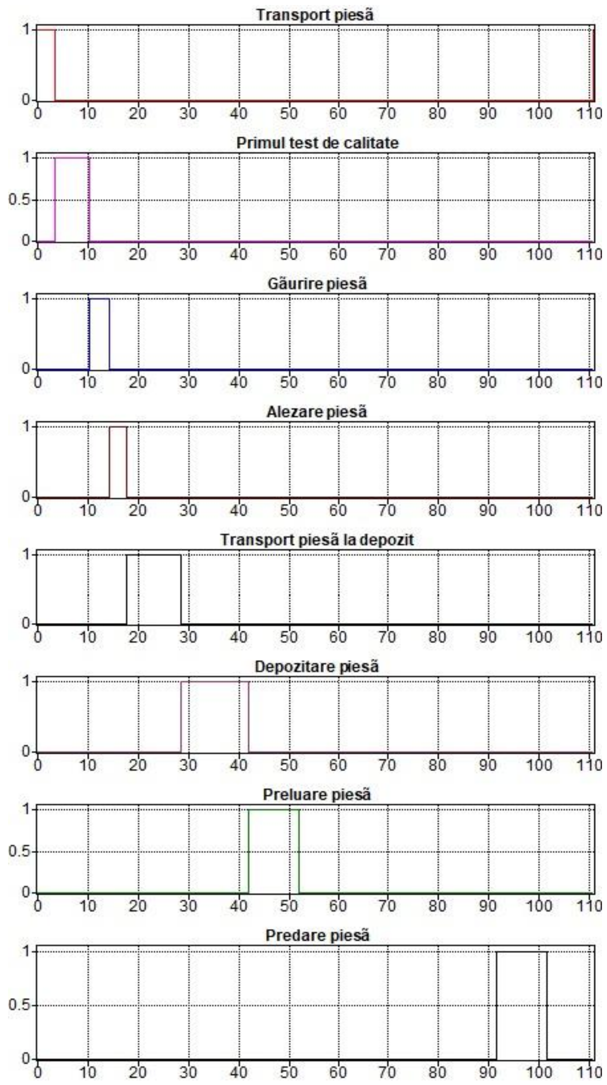


Fig. 4.3. - Evolution of discrete transitions of the processing system served by two mobile robots and fixed manipulator.

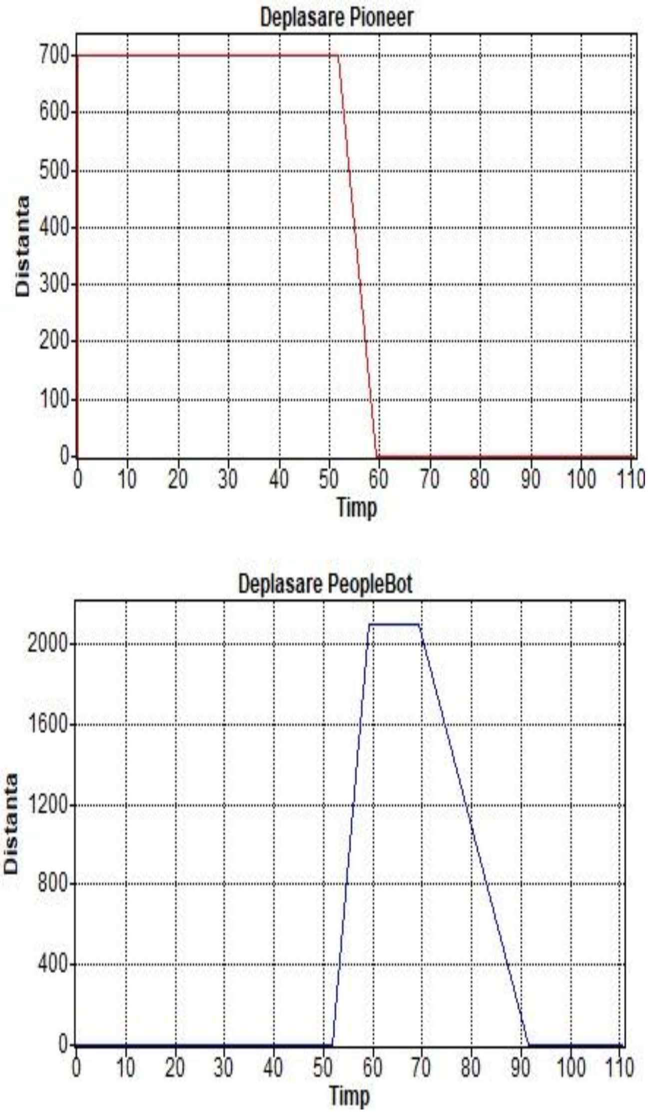


Fig. 4.4. - The evolution of the continuous transitions of the two mobile robots servicing the laboratory processing line

4. 2 MobileSim simulation of the sliding mode control of the mobile platform servicing Festo MPS-200 laboratory line

Using the MobileSim software, it was possible to test by simulating the closed-loop routing of mobile robots in trajectory tracking. MobileSim is a software to simulate MobileRobots / ActivMedia platforms. This software version comes in replacing SRIsim previously distributed with ARIA.

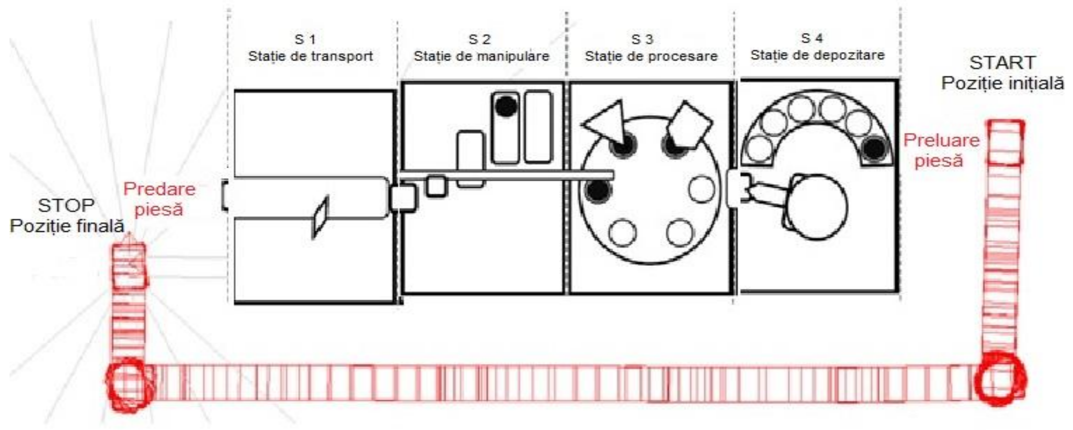


Fig. 4.7. – Mobile robot displacement simulation for transport operation while serving Festo MPS-200 Flexible Processing Line

The following figures show some simulation results. Thus, in figure 4.8 a) are shown the imposed and real trajectory that is travelled by the mobile robot. When the mobile platform executes a 90° turn we can see a little deviation of the trajectory. Also, in Figure 4.8 b), the graph of the mobile platform linear speed variation was plotted against the imposed linear speed. According to the data obtained from the simulation graphs, the time required to complete the total distance was 121.7 s

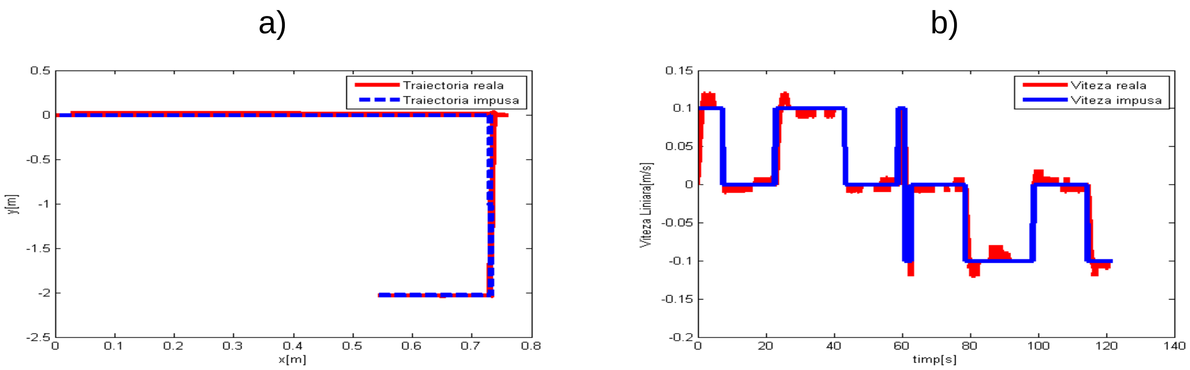


Fig. 4.8. - Simulation of movement (a) and velocity (b) of the mobile platform using sliding mode control.

Fig. 4.9 a) shows the evolution of the tracking error on the x axis. It can be seen that the maximum error represents a deviation of 4 mm relative to the travel distance. In b) it can be seen that the deviation on the y-axis is approximately 2 mm, and at the time of the last 90^{o} turn, for getting back to the initial position, a maximum deviation value of 2.37 mm is reached.

a) b)

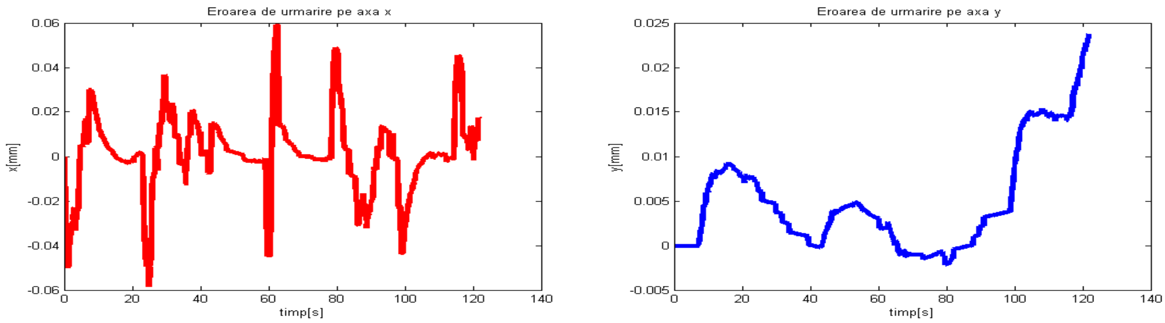


Fig. 4.9. - Evolution of tracking error during sliding mode control: a) Evolution on x axis; b) Evolution on y-axis.

Fig. 4.10 a) shows the deviation of the direction of the mobile platform and an error of approximately 2^o is observed, and the real angular velocity value shown in Fig. 4.10 b) shows oscillations around the imposed value of about 0.5 rad / s.

a) b)

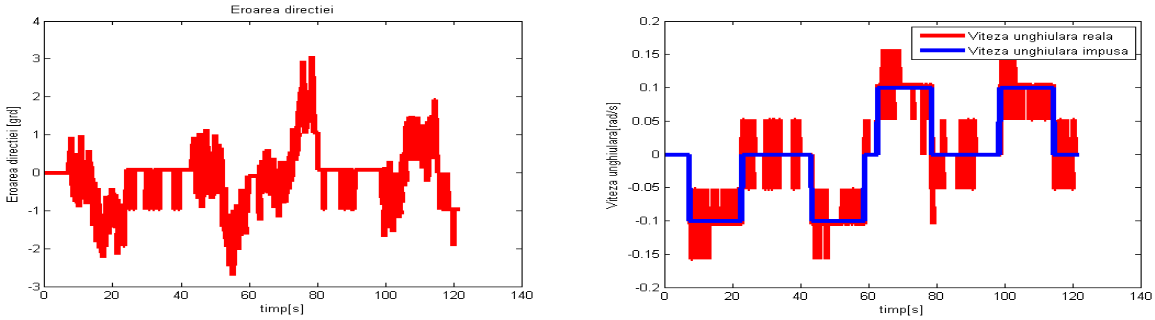


Fig. 4.10. - a) Direction error; b) Angular speed;

Chapter 5

Sisteme VS utilizate în conducerea sistemelor autonome complexe pentru deservirea liniilor de fabricație flexibilă

5.1 Trăsături vizuale utilizate în sistemele VS

There are two major categories of 2D geometric features in the literature, and these are defined as point-of-interest features or moments of image features. A point of interest type feature is represented by the planar coordinates of that point, which has a well-defined position and can be easily detected. These types of points of interest can define lines, curves, regions of interest, corners, etc. Moments of image features bring a significant increase in the performance of a visual system due to the ability to represent objects of unknown shapes, to provide the overall features of an image.

5.1.1 Defining moments of image features

Due to the advantages of the moments of image visual features, there are very common in forms recognition, object classification, etc. and used for artificial view and robotic purposes.

In image processing, the object is defined as a set of pixels of coordinates (x, y) for which $I(x, y) = 1$. This way 2D moments m_{ij} of $(i + j)$ order can be defined as:

$$m_{ij} = \iint_O x^i y^j dxdy$$

5.2 Modeling the VS system

A VS system is based on the following components: a manipulator robot assembly, a visual sensor, and a regulator. Modeling a VS system will resume to minimization of the error between the real system features drawn from the visual sensor and the desired features of the work frame. Figure 5.3 shows the structure of a VS system.

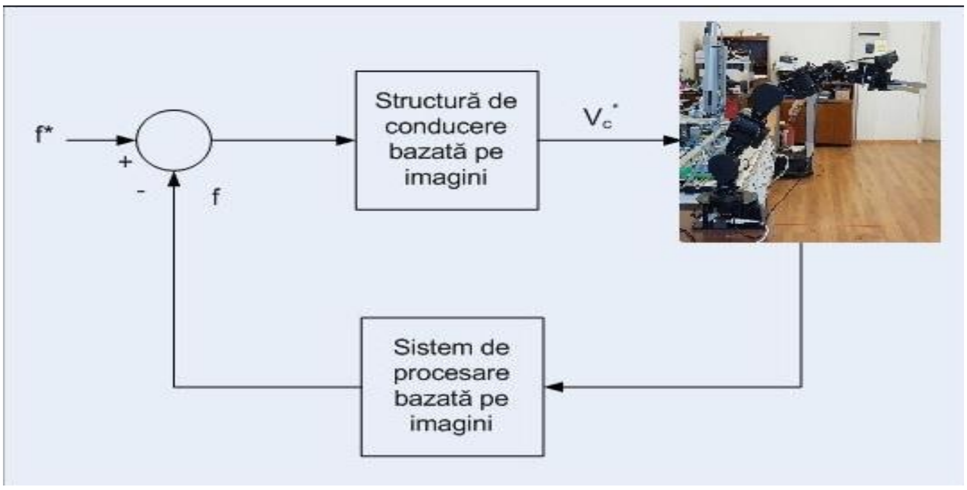


Fig. 5.3. – VS control structure for a robotic manipulator

5.3 Interaction matrix for moments of image features

The interaction matrix is the specific mathematical analysis tool that is used in generating the control law for VS systems.

Given the definition of moments m_{ij} of $(i+j)$ order described above, the analytical form of variation over time $\dot{m}_{ij}$ can be written, depeding on the camera speed.

$$\dot{m}_{ij} = L_{m_{ij}} v_c$$

Assuming for the robotic system a set of moments as points of the image, $f = [x_n, y_n, a_n, \tau, \xi, \alpha]^T$ we deduce the shape of the interaction matrix corresponding to the moments of the image defined by n points:

$$L_f = \begin{bmatrix} -1 & 0 & 0 & a_n e_{11} & -a_n(1+e_{12}) & y_n \\ 0 & -1 & 0 & a_n(1+e_{21}) & -a_n e_{11} & -x_n \\ 0 & 0 & -1 & -e_{31} & e_{32} & 0 \\ 0 & 0 & 0 & \tau_{\omega_x} & \tau_{\omega_y} & 0 \\ 0 & 0 & 0 & \xi_{\omega_x} & \xi_{\omega_y} & 0 \\ 0 & 0 & 0 & \alpha_{\omega_x} & \alpha_{\omega_y} & -1 \end{bmatrix}$$

5.4 Proportional control law for the robotic manipulator

If f, a set of visual features is chosen and the state at t moment between the camera and the work frame as $r(t)$, features variation $f(r(t))$ can be defined reported to the relative movement between the visual sensor and the work space:

$$\dot{f} = \frac{\partial f}{\partial r}\frac{dr}{dt} + \frac{\partial f}{\partial t} = L_f v_c + \frac{\partial f}{\partial t}$$

For good results of the robotic manipulator control, it is desired that the variance of the error is exponentially negative, of the shape $\dot{e} = -\lambda e$ and results $\dot{e} = L_f v_c^* = -\lambda e$, thus:

$$v_c^* = -\lambda L_f^+ e$$

$$v_c^* = -\frac{1}{2}\lambda(L_f + L_f^*)^+ e$$

5.5 Real-time control of the processing line using an eye-to-hand VS system

Conducerea în timp real a sistemului complex format din linia de prelucrare flexibilă Festo MPS-200 în colaborare cu robotul Pioneer P3-DX și manipulatorul robotic aferent are la bază, pe de o parte, conducerea procesului prin bucla de conducere aferentă automatelor programabile Siemens S7-300 cu procesoare 313C-2 DP și pe de altă parte, conducerea robotului mobil și a manipulatorului robotic.

Real-time control of the complex system consisting of the Festo MPS-200 processing line serviced by the Pioneer P3-DX robot and its associated robotic manipulator is based on the process controlled by the Siemens S7- 300 with 313C-2 DP processors and on the other hand, the control of the mobile robot and the robotic manipulator.

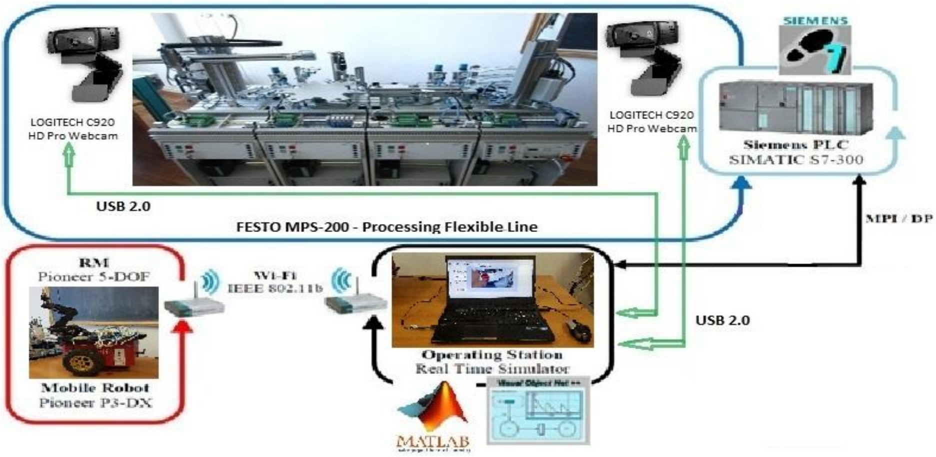


Fig. 5.5. – The control and communication structure of the processing line served by an autonomous system and two fixed VS systems.

Communication for video data transmission as well as between the VS application and the sliding-mode control for the robot have been chosen in such a way that they do not affect the processing speed and processing times of the applications.

5.5.1 Synchronizing and video control of the mobile robot application using an eye-to-hand VS system

To achieve synchronization between the occurrence of a replicable piece and the launch of the mobile robot in order to retrieve the piece and position it at the beginning of the Festo line for reprocessing, an application has been implemented in Matlab. The application is based on image processing.

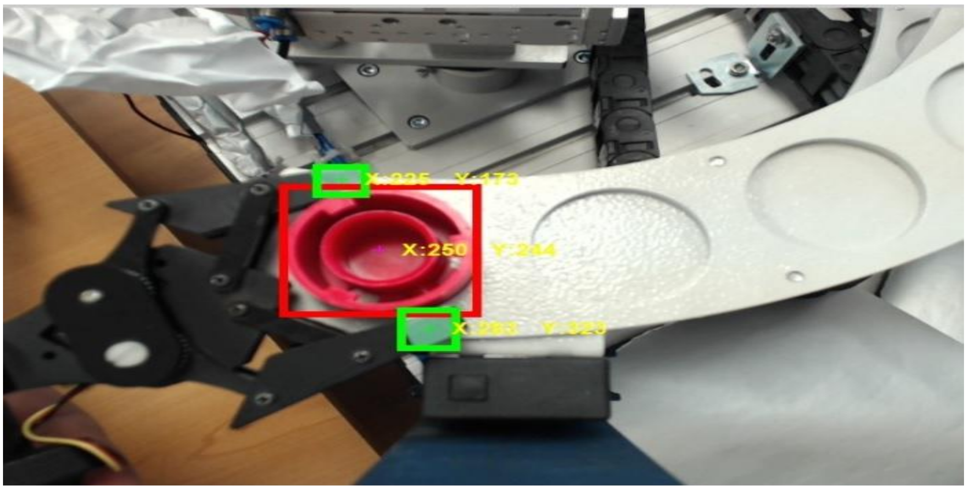


Fig. 5.6.c. – Piece recovery using fixed VS

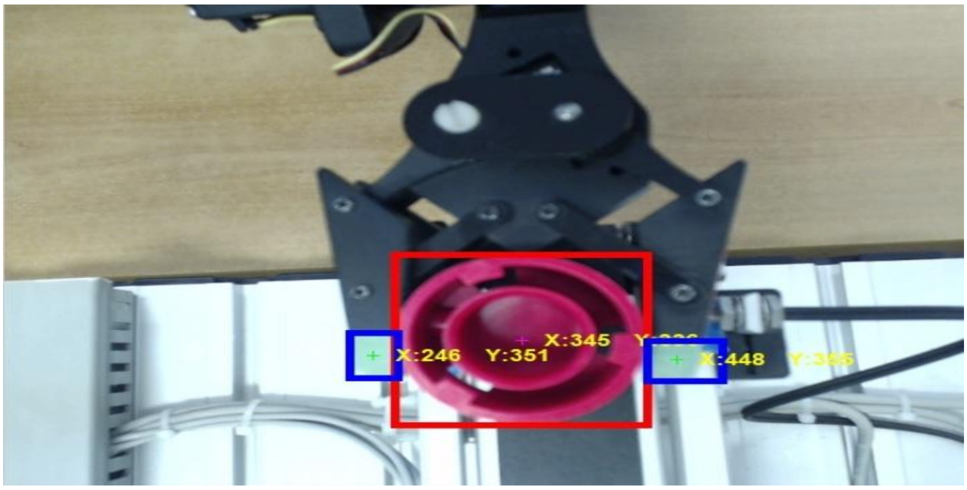


Fig. 5.8.c. – Piece return using fixed VS

5.6 Real-time control of the processing line using an eye-in-hand VS system

The structure outlined above can be improved in order to reduce transport time and make more efficient use of available resources. For this purpose, within the previously defined P / RML system, a PeopleBot robot has also been integrated to transport reprocessed parts and a Cyton Gamma 1500 robotic manipulator for retrieving and re-introducing pieces for reprocessing.

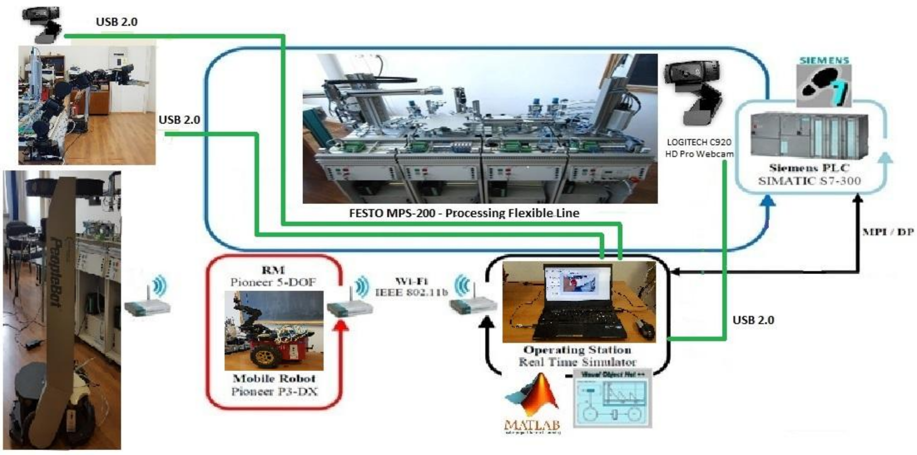


Fig. 5.10. - The control and communication structure of the processing line served by 3 autonomous systems and fixed and mobile VS systems.

5.6.1 Synchronizing and video control of the mobile robot application using an eye-in-hand VS system

The novelty of this new structure is the use of the PeopleBot robot to carry the parts and the use of the Cyton Gamma 1500 handler for reintroduction of pieces in the line

Fig. 5.11. – PeopleBot tacking the piece for reprocessing

The advantages of this new structure are to improve the delivery times of reprocessing parts, to relieve the Pioneer robot from the transport task and to transport multiple parts at the same time. The PeopleBot robot is also controlled using asliding-mode.

Fig. 5.14.c – Piece recovery using mobile VS

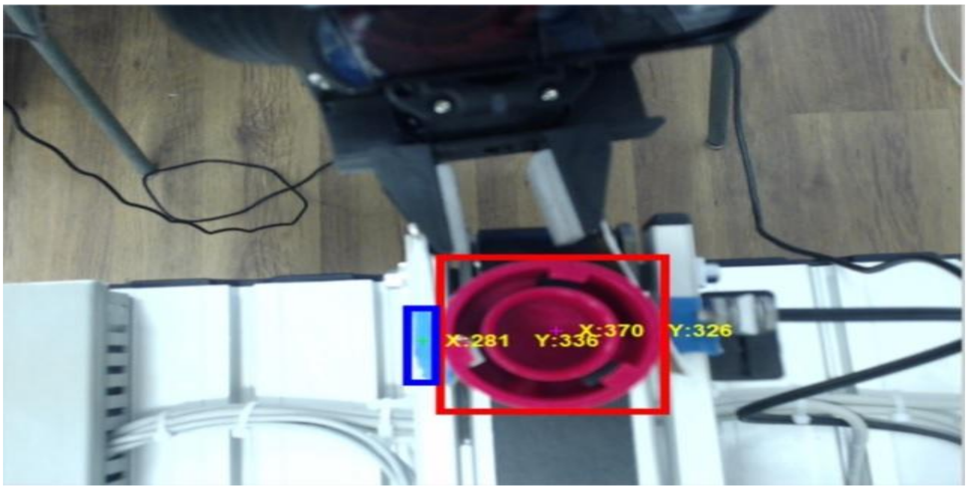


Fig. 5.15.c. – Piece returning for reprocessing

Cyton manipulator control will be consistent with the commands provided by the mobile VS system as a result of video processing provided by the high-resolution camera located on the manipulator's effector.

Chapter 6

Conclusions and contributions

6.1 Contributions

Contributions claimed from this research, disseminated and certified by published works that are part of the UEFISCDI project PN-II-PT-PCCA-2013-4-0686 entitled "Prototypes of autonomous robotic systems for medical and social care and service manufacturing processes in metallurgy, ceramics, glass and the automotive industry "are as follows:

- Establish working hypotheses for the processing line Festo MPS-200 served by complex autonomous systems, [PG1], [PG2], [PG3];
- Task planning related to the Festo MPS-200, [PG1], [PG2], [PG3];
- Modeling with non-timed and timed discrete Petri nets of the Festo MPS-200 processing line, [PG4], [PG5] ;
- Hybrid Petri nets modeling of the processing line Festo MPS-200 served by the autonomous system consisting of Pioneer P3-DX mobile robot equipped with Pioneer 5DOF Arm robotic manipulator, [PG1], [PG3], [PG7];
- Hybrid Petri nets modeling of the processing line Festo MPS-200 served by the complex autonomous system consisting of Pioneer P3-DX mobile robot equipped with Pioneer 5DOF Arm manipulator, PeopleBot mobile robot for transport and Cyton Gamma 1500 robotic manipulator for the return of the pieces, [PG10].
- Syrphico simulation of the SHPN model obtained for the processing line Festo MPS-200 served by Pioneer P3-DX mobile robot equipped with Pioneer 5DOF Arm manipulator, [PG1], [PG3], [PG7];
- Syrphico simulation of the SHPN model obtained for a processing line Festo MPS-200 served by Pioneer P3-DX mobile robot equipped with Pioneer 5DOF Arm manipulator, PeopleBot mobile robot for transport and Cyton Gamma 1500 robotic manipulator for returning the parts [PG10];

- MobileSim simulation of the Pioneer P3-DX mobile robot equipped with Pioneer 5DOF Arm manipulator trajectory while serving the processing line Festo MPS-200, [PG1], [PG6];
- Choosing optimal visual features for using fixed and mobile VS systems, [PG8], [PG9], [PG11];
- Determination of the VS driving law of the robotic manipulator serving the processing line Festo MPS-200, [PG8], [PG9], [PG11];
- Implementing the communication structure and real-time control of the processing line served by a Pioneer P3-DX mobile robot equipped with a Pioneer 5DOF Arm, [PG8], [PG9], [PG11];
- Implementation of the communication structure and real-time control of the processing line Festo MPS-200 served by a Pioneer P3-DX mobile robot equipped with a Pioneer 5DOF Arm robotic manipulator, a PeopleBot transport robot and a Cyton Gamma 1500 fixed manipulator, PG8 [PG8]], [PG11];
- Laboratory testing of fixed and mobile VS technology for robotic manipulators serving the processing line, [PG8], [PG9], [PG11];

6.2 Results dissemination

The models developed and tested and the contributions of this thesis were disseminated by publishing in various articles in conferences and magazines as follows:

[PG1] **Petrea, G**., Filipescu, A., Minca, E., Voda, A., Filipescu, A., Jr., Serbencu, A., - Hybrid Modelling Based Control of a Processing/Reprocessing Line Served by an Autonomous Robotic System, International Conference on System Theory, Control and Computing, Joint Conference SINTES 16, SACCS 12, SIMSIS 16, Proceedings of the 17th IEEE, International Conference on System Theory, Control and Computing, ICSTCC2013 11-13, Oct. Sinaia, 2013, pp: 410-415, ISBN: 978-1-4799-2228-4/13/$31.00 ©2013 IEEE(indexată WoS).

[PG2] Filipescu, A., Jr., **Petrea, G**., Filipescu, A., Minca, E., Filipescu, S., - Discrete modelling based control of a processing/reprocessing mechatronics line served by an autonomous robotic system, The 4th International Symposium on Electrical, and Electronics Engineering, ISEEE 2013, 11-13, Oct, Galati, 2013, ISBN: 978-1-4799-2442-4/13/$31.00 ©2013 IEEE(indexată WoS).

[PG3] Filipescu, A., Jr., **Petrea, G.**, Filipescu, A., Filipescu, S., - Modeling and Control of a Mechatronics System Served by a Mobile Platform Equipped with Manipulator, Proceedings of the 33rd Chinese Control Conference, July 28-30, 2014, Nanjing, China, pp: 6577-6582, ISBN:978-988-15638-4-2, IEEE Catalog number CFP:1441A-CDR(indexată WoS).

[PG4] Filipescu, A., Minca, E., Filipescu, A., Jr., **Petrea, G.**, - Modeling and Control of Assembly/Disassembly Mechatronic Line Served by Robotic Manipulator Mounted on Mobile Platform The Annals of “Dunărea de Jos” University of Galati Fascicle III, Year 2012: Volume

35, Number 1, Electrotechnics, Electronics, Automatic Control, Informatics, ISSN 1221-454X, pp:17-22.

[PG5] **Petrea ,G.**, Filipescu, A., Minca, E., Voda, A., Filipescu, A., Jr., - Hybrid Modelling Based Control of a Processing/Reprocessing Line Served by an Autonomous Robotic System, The Annals of "Dunărea de Jos" University of Galati Fascicle III, Year 2013, Volume 36, Number 1, pp:13-18, Electrotechnics, Electronics, Automatic Control, Informatics, ISSN 1221-454X.

[PG6] Dumitrașcu B., Filipescu A., Vodă A., Mincă E., Filipescu S., **Petrea G.** - Laser-based Obstacle Avoidance Algotithm for Four Driving/Steering Wheels Autonomous Vehicle - International Conference on System Theory, Control and Computing, Joint Conference SINTES 16, SACCS 12, SIMSIS 16, Proceedings of the 17th IEEE, International Conference on System Theory, Control and Computing, ICSTCC2013 11-13, Oct. Sinaia, 2013, pp: 187-192, ISBN: 978-1-4799-2228-4/13/$31.00 ©2013 IEEE(indexată WoS).

[PG7] Filipescu, A., Șolea ,R., **Petrea, G.**, Cernega D., C., Filipescu, A., Jr.,Ciubucciu, G., - SHPN Modelling, Visual Servoing and Control of WMR with RM Integrated into P/RML, International Conference on System Theory, Control and Computing, ICSTCC2017 19-21, Oct. Sinaia, 2017 (indexată WoS).

[PG8] Nicolau V., Andrei M., **Petrea, G.**, - Aspects of Image Compression using Neural Networks for Visual Servoing in Robot Control, The 5th International Symposium on Electrical and Electronics Engineering (ISEEE 2017), 20-22, Oct. Galați, 2017 (indexată WoS).

[PG9] **Petrea, G.**, Nicolau V., Andrei M., - Multiprocessor visual servoing system for mobile robots servicing mechatronic lines, IEEE 23rd International Symposium for Design and Technology in Electronic Packaging (SIITME), 26-29, Oct. Constanța, 2017 (indexată WoS).

Papers in review:

[PG10] **Petrea, G.,** Filipescu, A., Mincă, E., Filipescu, A. Jr., - Hybrid modelling and simulation of a P/RML with integrated complex autonomous systems, International Conference on System Theory, Control and Computing, ICSTCC2018, 10-12 Oct. Sinaia, 2018

[PG11] **Petrea, G.,** Filipescu, A., Șolea, R., Filipescu, A. Jr - Visual servoing systems based control of complex autonomous sytems serving a P/RML, International Conference on System Theory, Control and Computing, ICSTCC2018, 10-12 Oct. Sinaia, 2018