IOSUD – „DUNĂREA DE JOS" UNIVERSITY OF GALATI

Doctoral School of Fundamental and Engineering Scieneces

DOCTORAL THESIS

CONTRIBUTIONS TO THE CONTROL AND NAVIGATION OF AUTONOMOUS ROBOTIC SYSTEMS DESIGNED TO ASSIST PEOPLE WITH DISABILITIES AND THE SERVICING OF FLEXIBLE MANUFACTURING PROCESSES

Abstract

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Thesis Contents

Abstract Contents

Notations and abbreviations

A/DML - assembly/disassembly mechatronics line;
API - application programming interface;
ARIA - advanced robotic interface for applications;
CS - counting selection;
CPW - cirrus power wheelchair;
DOF - degree of freedom;
DW - driving wheel;
EOF - end efector ;
FW - free wheel;
GPS - global positioning system;
GUI - grapfic user interface;
I/O - input/output;
MAV - multidirectional autonomous vehicle;
PI - proportional integral;
PC - personal computer;
PLC - programmable logic controller;
P/R - processing/reprocesing;
P/RML - processing/reprocesing mechatronics line;
PRA - personal robot assistant;
PWM - pulse width modulation;
RM - robotic manipulator;
SIPs - server information packets;
SW - Steering wheel;
SM - sliding-mode;
SMC - sliding-mode control;
SOSMC - second order sliding mode control;
STSMC - super-twisting sliding-mode control;
VSS - visual servoing sistem;
TT - trajectory tracking;
WMR - wheeled mobile robot.

Introduction

The latest technological and research advancement in the robotic field has made the integration of robotic vehicles in the day to day life possible, resulting in increased safety, efficiency, productivity and performance in areas such as cars building industry, agriculture, mining, manufacturing and health.

The whealchair, one of the objectives of this paper, is part of the autonomous vehicles category and is asimilated with a mobile robot with two driving wheels and two free wheels (2DW/2FW).

The real time navigation with access through narrow spaces, based on information received from laser, as well as the navigation structure based on image processing of eyeball movement for wheelchair assistance for people with severe neurolocomotor disabilities, can eliminate at least one part of the support services. The wheelchair facilitates the movement and access to medical assistance of the patients with severe neurolocomotor disabilities in emergency hospitals, intensive care units, orthopedy and neurology.

Another type of problems that are treated in this paper are the control and navigation of the autonomous robotic systems equipped with visual servoing systems and processing of images intended to operate in collaborative mode to service flexible manufacturing lines, industrial and laboratory (mechatronics lines).

State of the art

The most important and recent achievements in the control and navigation of autonomous robotic systems are aimed at tracking a trajectory (TT), avoiding fixed and/or mobile obstacles, satisfying performance indicators, and stability. If it comes to the wheelchair ensuring comfort, in addition, the comfort of the user is taken into account.

Mobile robots' controlling problems have attracted considerable attention in recent years. Most mobile robots can be classified as nonholonomic systems. Both wheeled mobile robots (WMR) and Autonomous Vehicles (AV) require reliable information about position, speed and distance from obstacles. For this reason, sensors such as GPS, sonar sensors, encoders or lasers are used.

The objectives of the research pursued through this doctoral thesis are:

- The kinematic and dynamic modelling of the wheelchar for the assistance of people with disabilities;
- Real-time development, implementation and real-time testing *of super-twisted sliding mode algorithm* (STSMC);
- Designing the SMC and STSMC control structure to track a required trajectory based on the kinematic model and/or the dynamic model;
- avigation of autonomous robotic systemes designed to assist people with neurological and elderly deficiencies;
- Development, implementation and real-time testing of a navigation algorithm that uses a laser sensor to detect and avoid obstacles (fixed or mobile);
- Real-time development, implementation and testing of a narrow space algorithm;
- Design of the CPW navigation system based on the movements of the eyeball;

- Modeling and management of robotic manipulators serving the flexible manufacturing line;
- Modelling and controling flexible manufacturing, processing/reprocessing lines, serviced by autonomous robotic systems equipped with manipulators.

Structure and content of the thesis

Chapter 1 describes hardware equipment used for real-time testing: Cirrus Power wheelchair; mobile robots: Pioneer P3-DX, PowerBot, PeopleBot, PatrolBot; robotic manipulators: Cyton 1500 7-DOF Arm, Pioneer 5-DOF Arm; laser sensors; acquisition boards; routers; etc. Also there are presented software packages for communication, data acquisition and control of mobile robots: Visual C ++, Matlab, MobileSim software, as well as ARIA software, through which the algorithms of control, simulations and graphic user interfaces are designed, implemented and tested.

Chapter 2 is dedicated to the design, simulation and real-time testing of advanced control techniques (SMC and STSMC) to control autonomous systems and obtaining kinematic and dynamic models. Also in this chapter are presented modeling, simulation and real-time testing of the RM Cyton 1500 and a comparative study of the two control methods, SMC and STSMC.

Chapter 3 presents a comparative study between sonar and laser sensors, followed by real-time implementation and testing of navigation algorithms with obstacle avoidance using specific sonar and laser systems. Also in Chapter 3, the algorithm and the program for real-time of CPW control through narrow spaces is presented, based on the information received from the laser.

In **Chapter 4**, following the studies carried out in the previous chapters, the navigation structure based on image processing of the eye movement for the CPW autonomous system is designed, implemented and tested in real-time for the assistance of people with severe neurolocomotor disabilities. The chapter ends with the control and navigation of autonomous systems integrated in assistive technologies of precision manufacturing lines.

The final conclusions, contributions, future research directions and dissemination of the results are presented in **Chapter 5.**

Chapter 1. Hardware and software packages used in the control and navigation of autonomous robotic systems

This chapter presents hardware equipment and software packages used in the management and navigation of autonomous robotic systems, WMR with 2DW/1FW and 2DW/2FW, CPW chair, WMR Pioneer P3-DX, PeopleBot, PowerBot, PatrolBot, equipped with laser, Hokuyo URG-04LX-UG01 and MAV Seekur, 4DW/SW, as well as hardware equipment for control and handling of RM Pioneer 5-DOF Arm and Cyton 1500 7-DOF Arm.

The software packages used for designing and implementing autonomous robotic systems' control and navigation algorithms are: Visual Studio, Aria, MobileSim and Matlab.

Wheeled mobile robots (WMR): Pioneer P3-DX (Fig.1.8), PowerBot (Fig.1.9), PatrolBot (Fig.1.10), PeopleBot (Fig.1.11), are part of the Pioneer mobile robot family. The company that produces these WMRs is MOBILE ROBOTS. These mobile robots share architecture (with two drive wheels and one or two free wheels) and software.

MAV Seekur (4DW/SW) is a robot prepared for any season and any kind of weather, which can cross rough terrain, (Fig.1.12). It has an autonomy of 8-12 hours, 4x4 traction and independent suspension on each wheel, can cover a large area of research and can be equipped with heavy payloads.

Fig.1.8. WMR Pioneer P3-DX

Fig.1.9. WMR PowerBot

Fig.1.10. WMR PatrolBot

Fig.1.11. WMR PeobleBot

Fig.1.12. MAV Seekur

RM Pioneer 5-DOF Arm (Fig.1.14) which can handle objects up to 150g, with a range of 50 cm from the rotary base to the gripper tip. It consists of: rotary base, 2 movable joints, a pivoting and rotating joint and a pivoting gripper. All joints except the gripper can pivot and rotate at least 180^o.

RM Cyton 1500 7-DOF Arm (Fig.1.15) has a range of 68 cm and can handle objects up to 1.5 kg. This type of humanoid manipulator offers many advantages: due to the large number of degrees of freedom, it can easily extend around an obstacle.

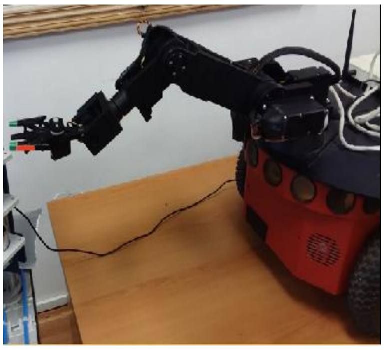


Fig.1.14. RM Pioneer 5-DOF Arm

Fig.1.15. RM Cyton 1500

Chapter 2. Modeling and control of autonomous systems integrated into technologies in social medical personal assisting and service of flexible manufacturing lines

There will be used two types of representation, L_h coordinate representation presented in Fig.2.1.and absolute coordinate representation presented in Fig.2.2. L_h coordinate representation delivers superior performance in trajectory tracking that includes tight corners. An example of using this technique is the driving of road vehicles, where the driver's gaze is concentrated at a point in front of the car (thus keeping a distance from the maximum limits of the road).

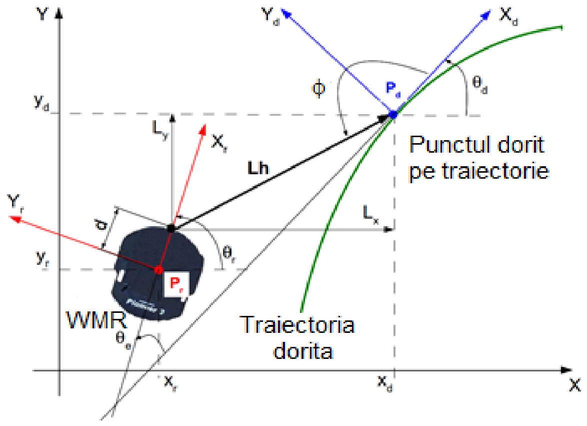


Fig.2.1. L_h coordinate representation

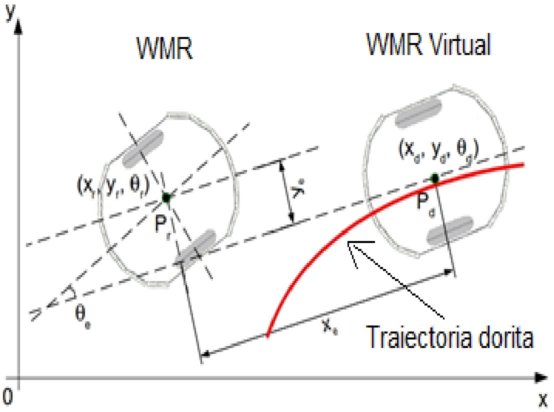


Fig.2.2. Absolute coordinate representation

2.1. The kinematic modelling of the CPW for the elderly and people with disabilities

The geometric model of the wheelchair, which defines the main variables needed to obtain the kinematic model, is shown in Fig.2.3. To determine the position and speed of movement of the wheelchair, servo amplifiers and encoders were installed on the two driving wheels. The two free wheels are required for the wheelchair's balance and are not equipped with any sensors, which are ignored in the kinematic model below.

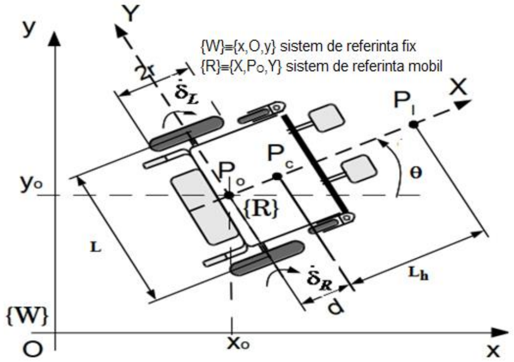


Fig.2.3. The kinematic model of CPW (2FW /2DW)

where: P_C - the center of gravity of the CPW in the fixed coordinate system (x_C, y_C) located on the X axis at a distance d of P_O; P_O the middle distance between the CPW in the fixed coordinate system (x_O, y_O); P_l - represents a virtual reference point attached to the platform with coordinates (x_l, y_l) located on the X axis at a distance L_h of P_C; θ - the angle formed between the x-axis of the fixed system and the X-axis of the mobile system; d - the distance between P_O și P_C; r - radius of driving wheels; δ_R, δ_L și $\dot{\delta}_R, \dot{\delta}_L$ - the angular displacements, respectively the angular velocities, of the right and left drive wheels; and L - is the distance between the two drive wheels (x_l, y_l).

2.2. Modelling and identification of the CPW driving wheels

To control the DC motors comanded by the rotor winding, one starts from the mathematical model of the system. In order to comand the movement of the wheelchair, the control loop of steering wheels motors must be accomplished. The system consisting of servo amplifier, DC motor and speed reducer generates the movement of the wheelchair.

2.3. Granting PI regulators and their implementation on the material platform

With the confirmation of a similar operation of the two motors controlled by PI controllers determined, it will be implemented on CPW, Figure 2.18.

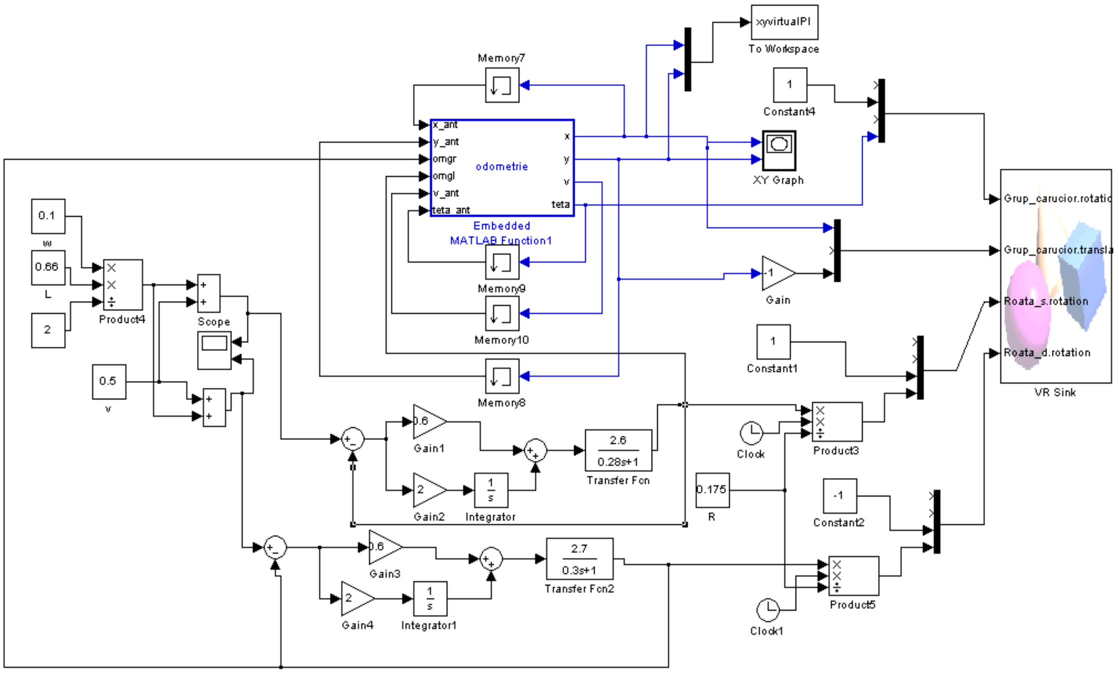


Fig.2.18. Simulink scheme of CPW with PI controller

It can be seen from Fig.2.20 and Fig.2.21 that the system tries to track the reference. The difference that appears is that the simulation of the system was made with continuous time, as opposed to the real-time answer of the system where it was made with discrete time, with a retention element of order 0 and a sampling time of 0.25 sec.

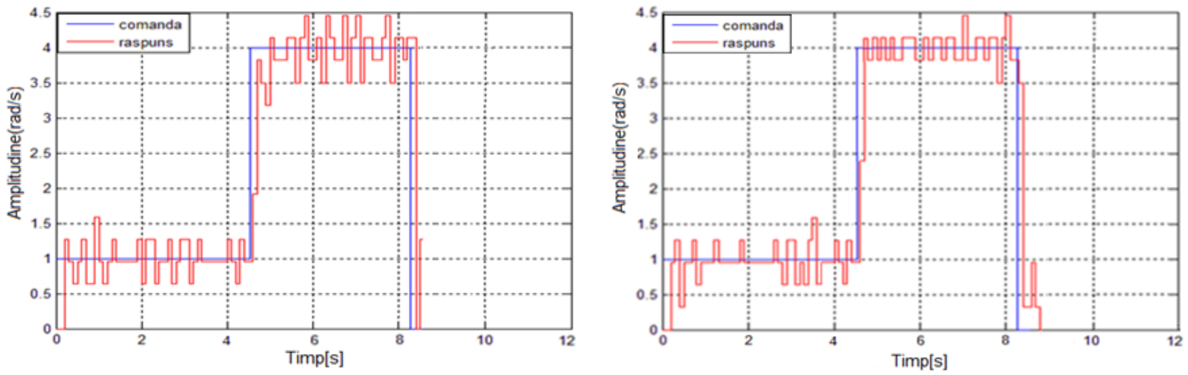


Fig.2.20. Closed loop system for left and right wheel, CPW, real answer

2.4. RM Cyton 1500 Results of simulation and real-time control based on inverse kinematic model of RM Cyton 1500

The angles used for the manipulator joints correspond to the EOF trajectory in order to retrieve a piece from the WMR PeopleBot and place the piece on the P/RML in Fig. 2.31. The path corresponds to a task that belongs to the service of a mechatronics line with robotic systems and visual servoing systems.

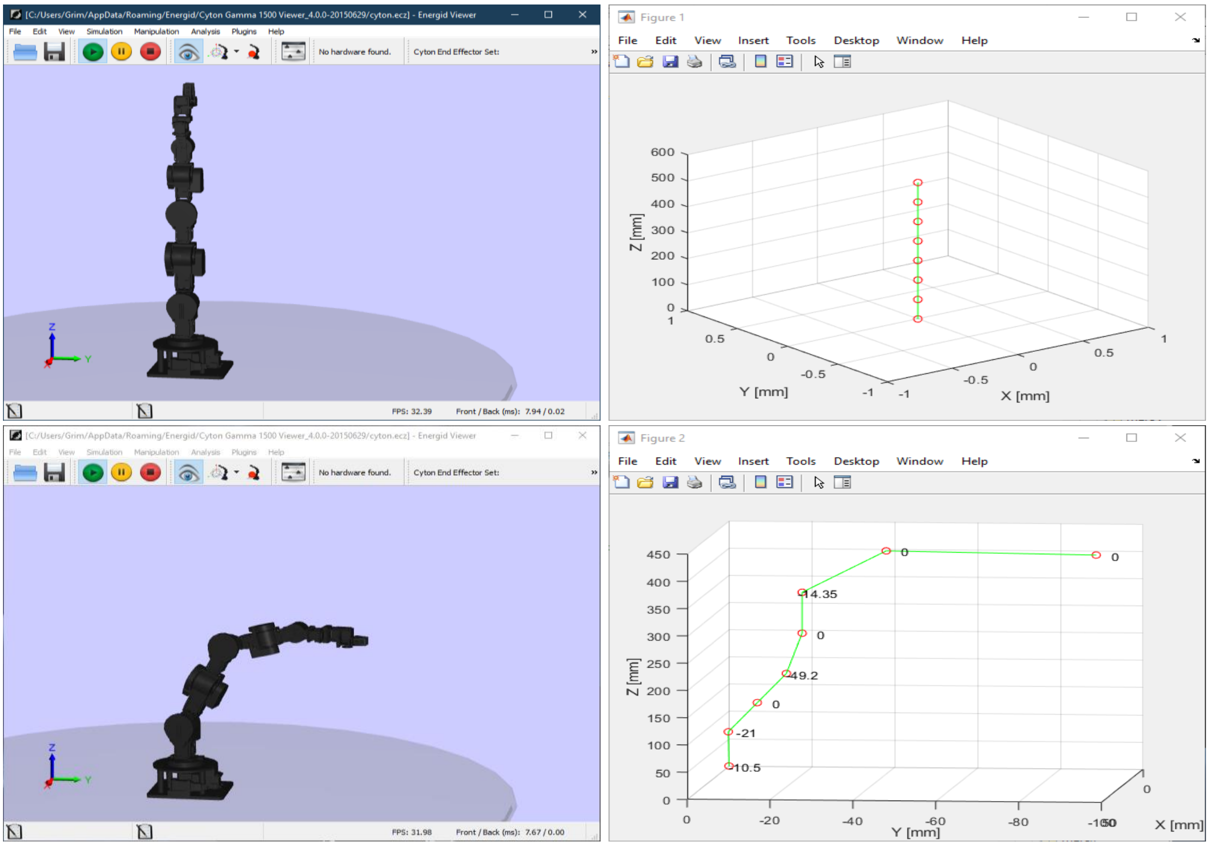


Fig.2.31. The EOF trajectory of the robotic arm Cyton 1500 7-DOF Arm in simulation

The execution starts from the initial position, Fig. 2.32 a) after which it descends at a constant speed and takes the part b) to be placed on the flexible manufacturing line c) and ends at the initial position.

In Fig.2.33, Fig.2.34 and Fig.2.35 the three positions corresponding to the EOF trajectory of the robotic arm Cyton 1500 7-DOF Arm are represented in Matlab

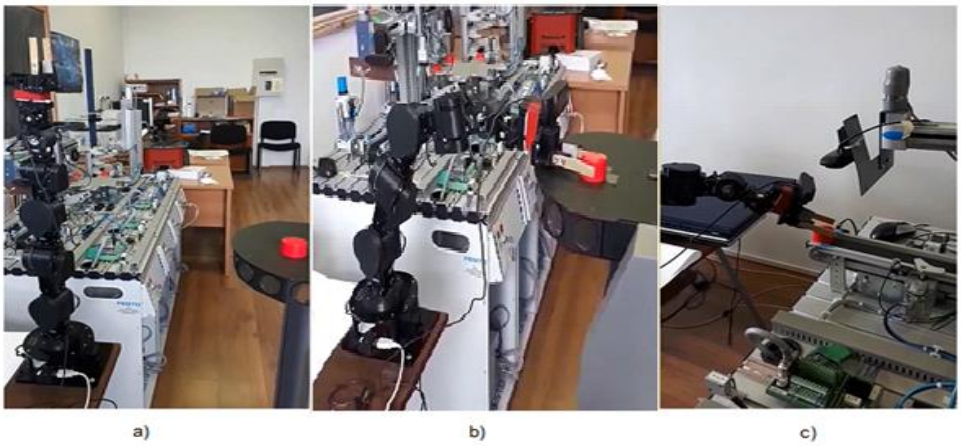


Fig.2.32. RM Cyton 1500: a) initial position, b) part pick-up, c) part storage

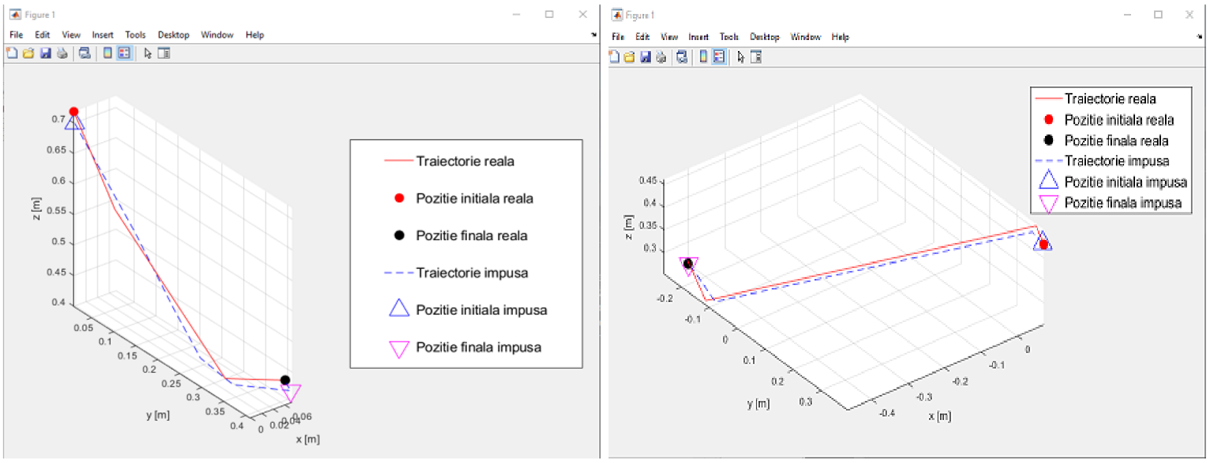


Fig.2.33. Part pick-up and part storage

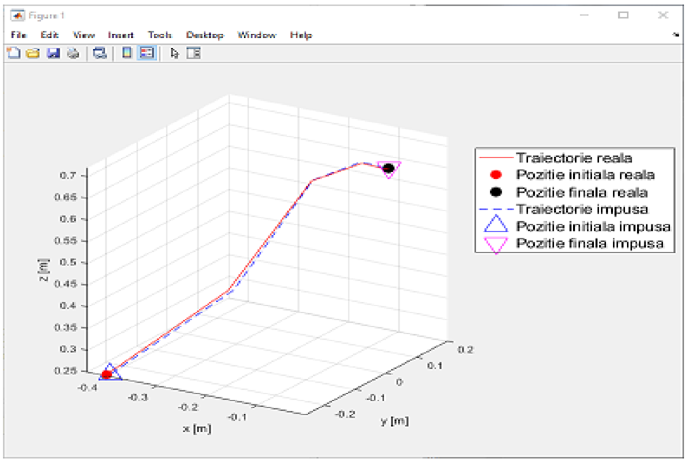


Fig.2.35. Return to the initial position

2.5. Design and real-time implementation of the SMC structure based on kinematic or dynamic model

The SMC method ensures the robustness of the closed-loop system, due to the fact that it provides satisfactory performances at uncertainties, model and parametric and exogenously disruptive. The purpose of the SMC is to constrain the trajectories of the system to reach and remain, after a finite period of time, on a certain manifold in the state space, as shown in [54].

2.5.1. Designing the SMC structure of WMR (2DW/2FW) based on the kinematic model

The block diagram for the SMC is presented in Fig.2.36.

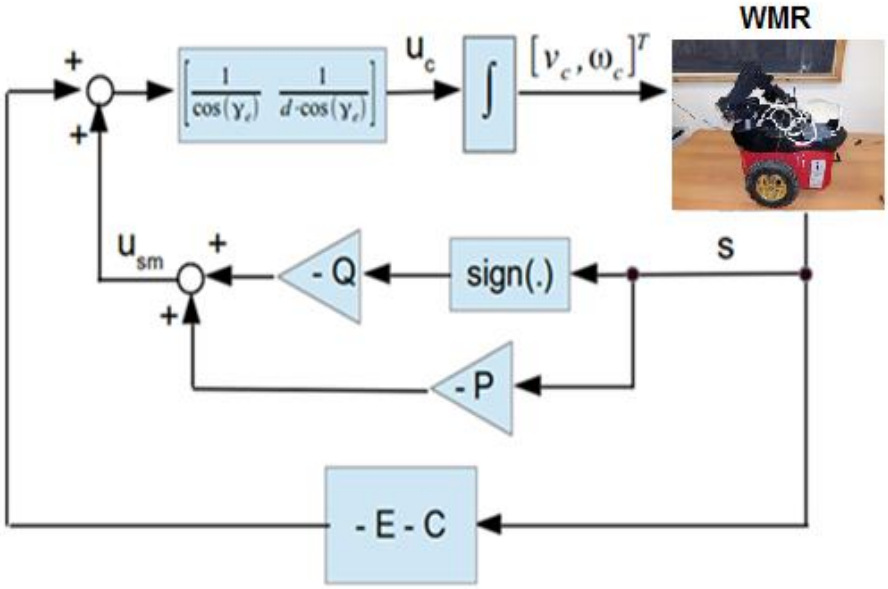


Fig.2.36. Block diagram for SMC

2.5.2. Real – time implementation and testing of the SMC structure of WMR Pionner P3-DX based on the kinematic model

Fig. 2.37 shows the desired trajectory and the desired WMR speeds. In Fig. 2.39 it is easy to see that WMR moves along the desired trajectory (red path) and the evolution of linear and angular velocities. During this movement it maintains the desired distance $\left(L_{h_d} = 0.3m\right)$ and the desired angle $\phi_d = -135^\circ$ with respect to the median axis of the trajectory. The simulated and real-time tracking errors presented in Fig. 2.40.

In Fig.2.42 is represented the trajectory obtained from the real-time algorithm implementation. From this figure, it is easy to see that WMR moves along the desired trajectory and the real-time trajectory is very close to the simulated trajectory. It can be seen that the biggest differences between the control speeds and the robot speeds are at the beginning of the real-time implementation.

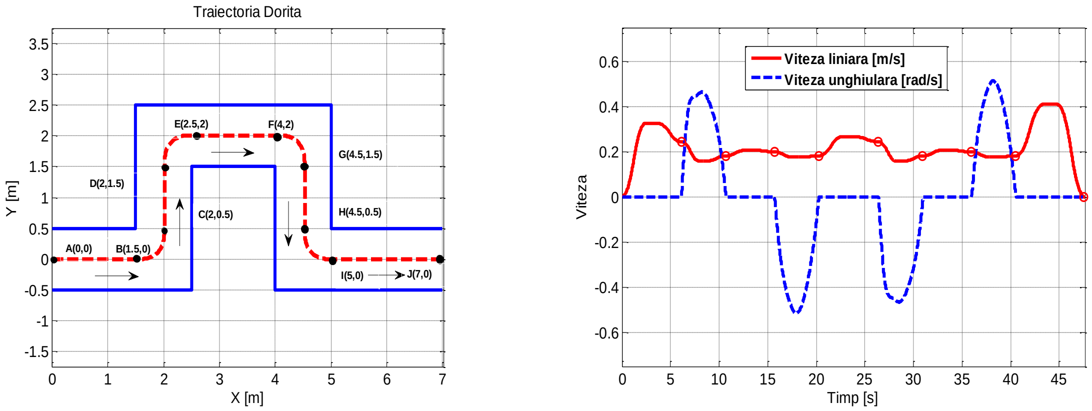


Fig.2.37. The desired path, linear and angular velocity of the WMR in L_h coordinates

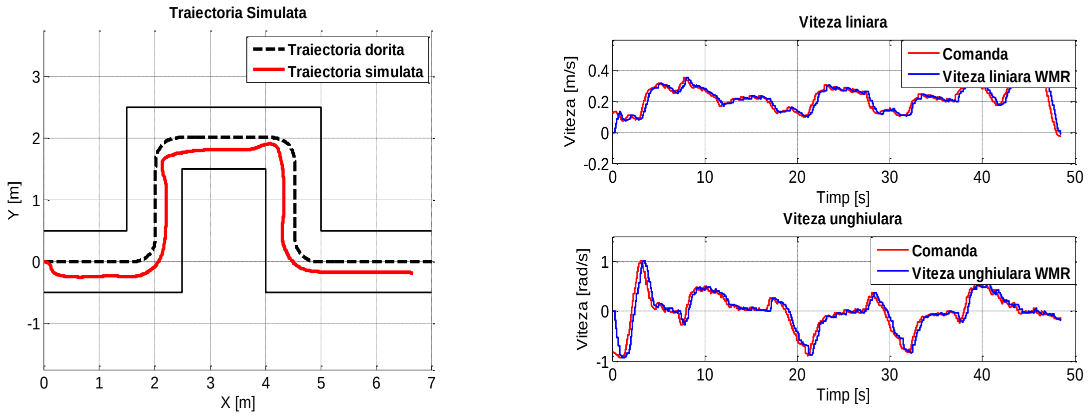


Fig.2.39. The desired, simulated trajectory and the evolution of linear and angular velocities of WMR in L_h coordinates

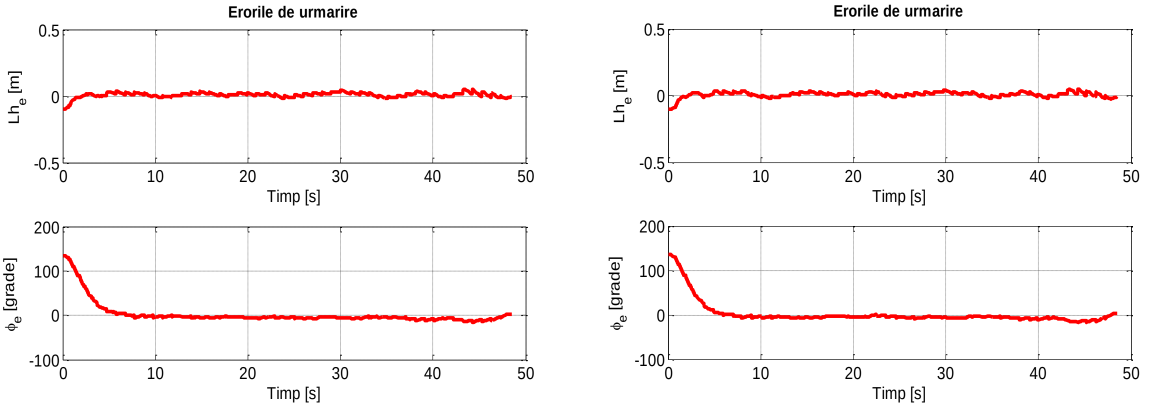


Fig.2.40. Simulated and real-time tracking errors of WMR in L_h coordinates

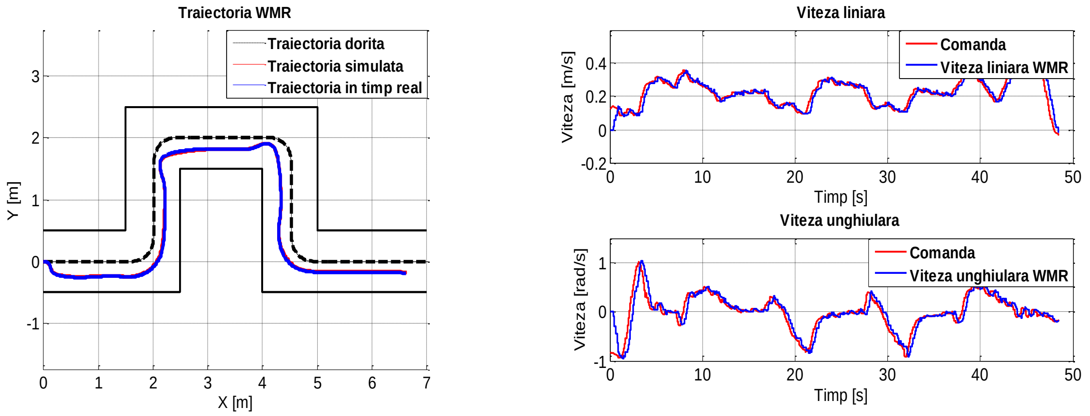


Fig.2.42. The desired simulated trajectory and the evolution of real-time linear and angular velocities of WMR in L_h coordinates

2.5.3. Designing the SMC structure of WMR (2DW/2FW) based on the dynamic model

Fig. 2.46 shows the control structure of WMR 2DW/2FW, where: N_L, ω_L and N_R, ω_R, represents the number of impulses, respectively the angular speeds, from the left and right wheel.

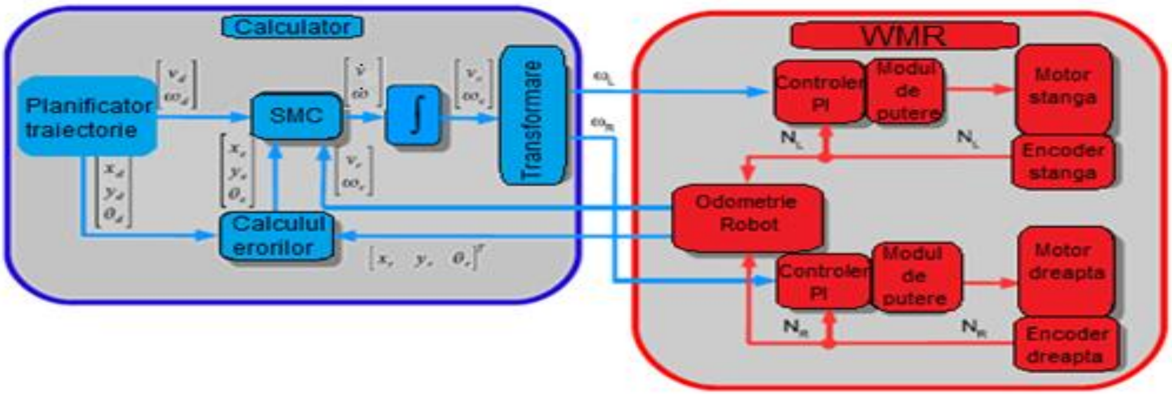


Fig. 2.46. Control architecture of WMR

2.5.4. Real-time implementation and testing of the SMC structure of WMR PatrolBot based on the dynamic model

For the trajectory 1, 3 experiments without additional mass were performed, and 3 other experiments with the additional mass, the same was done for the trajectory 2.

The simulation results show that the lateral, longitudinal and angular errors tend to be zero, with or without additional mass. The trajectories and profiles associated with them are shown in Fig. 2.47 and Fig. 2.48 and were obtained using the algorithm described in [59].

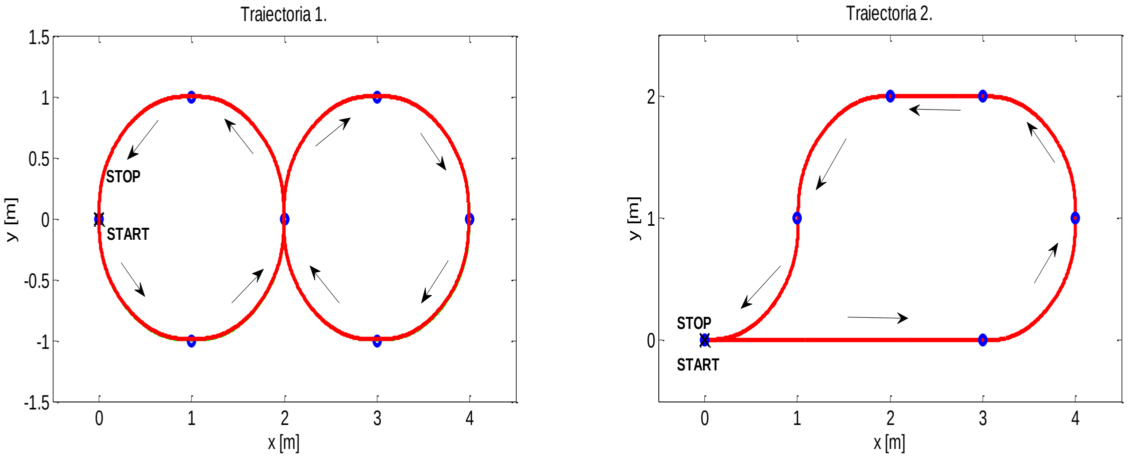


Fig.2.47. Proposed trajectories for simulation

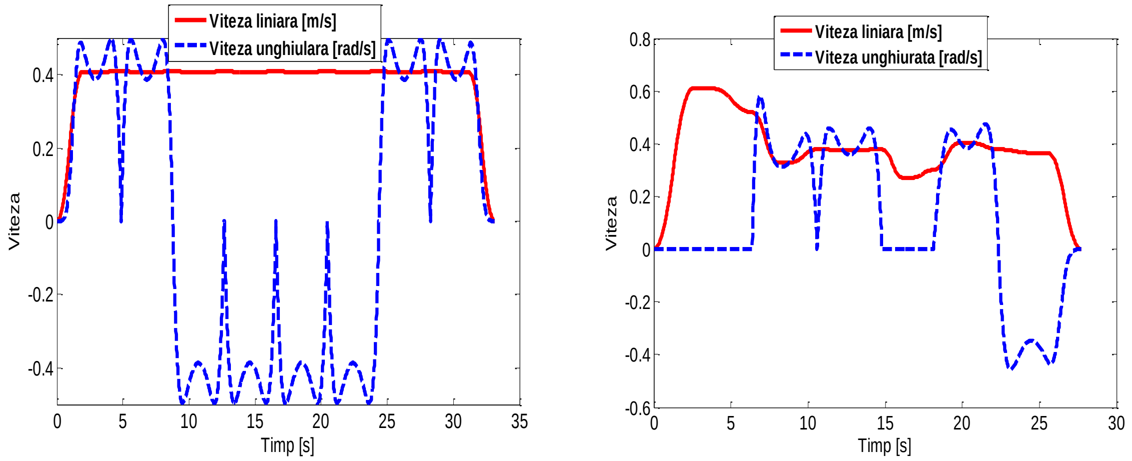


Fig.2.48. The velocity profiles (linear and angular) associated with the two trajectories in simulation in absolute coordinates

Fig. 2.49 shows the real-time results using the PatrolBot robot with additional mass of 3 kg and without additional mass for both trajectories. It can be observed that the SMC control structure is robust in terms of parametric uncertainties (additional mass).

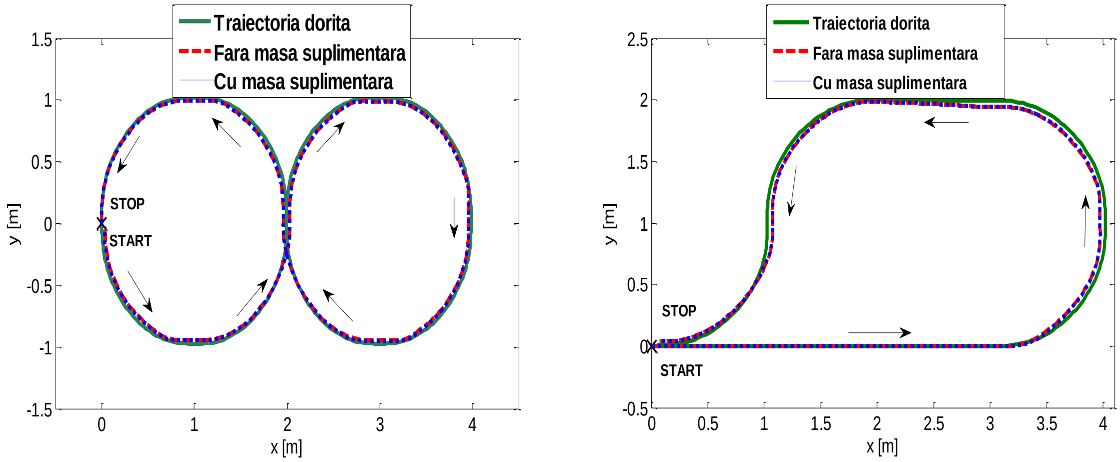


Fig.2.49. Real-time trajectory

In Fig. 2.50 it can be observed that the initial errors, lateral $x_e = 0.50$, longitudinal $y_e = 0.00$ and angular $\theta_e = 0.00$ tend to be zero in about 10s.

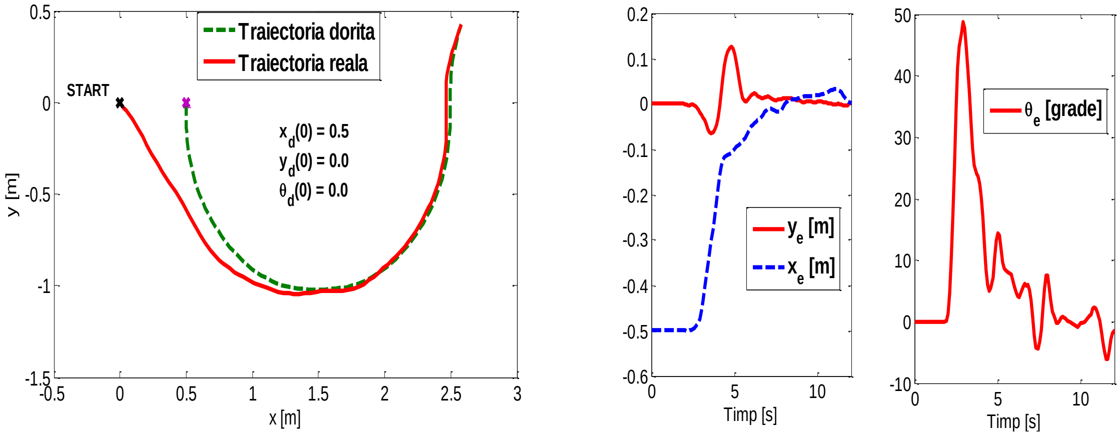


Fig.2.50. Real-time tracking errors, starting from the initial status error in absolute coordinates

2.6. Design and real-time implementation of STSMC structure for WMR

STSMC performs better in tracking the imposed trajectory than the SMC. This method has high convergence and stands on the slip surface. It reduces the phenomenon of chattering (high frequency oscillations superimposed on the order, status and/or output), phenomenon that occurred in the management of SMC.

Finally, the effectiveness of the proposed method is demonstrated by the simulation and real-time results. The comparative study between STSMC and SMC demonstrates the superiority of the proposed method.

2.6.1. Designing the STSMC structure

The block scheme for STSMC is presented in Fig. 2.51.

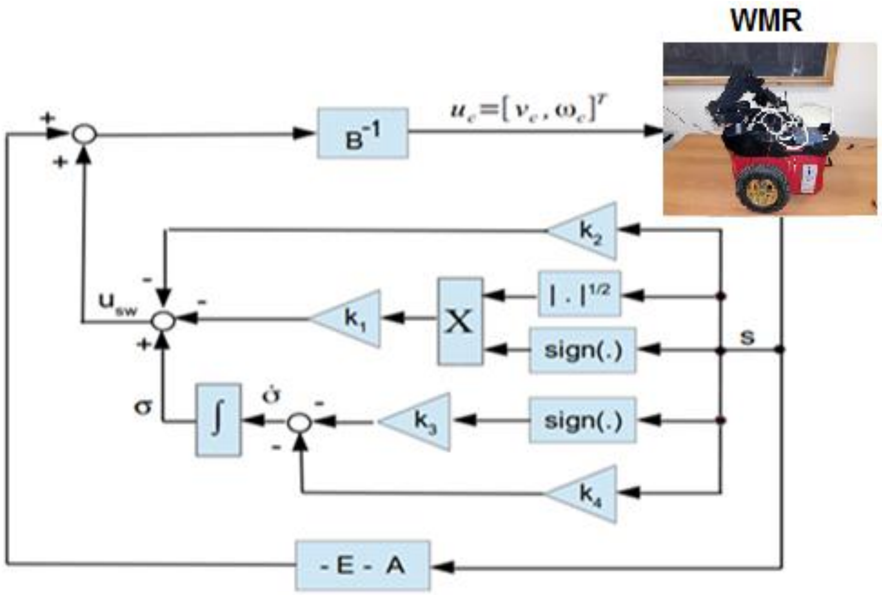


Fig.2.51. Block scheme for STSMC

2.6.2. Real-time implementation and testing of the STSMC structure

To make a comparative analysis of the two methods SMC and STSMC, two types of reference trajectories were used, one circular (case I) and the second linear (case II).

Analyzing case I, one can easily see from Fig.2.52 that the tracking errors at STSMC converge to 0 faster than at the SMC. It is found that the tracking performance is satisfactory.

Following the analysis of the sliding surfaces s1 and s2 of Fig.2.54 a) and b) it can be observed that the amplitude of the oscillations is higher in the SMC than in the STSMC. This leads to confirmation of expectations, namely that STSMC reduces the phenomenon of "chattering", occured due to delays in calculating the switching function argument.

In Fig.2.55 are represented both the calculated commands (linear velocity v_c, angular velocity ω_c, as well as the movement speed of the simulated robot $(v_r \quad \omega_r)$. In these figures it is easy to see the attenuation of the oscillations generated by the command for STSMC. The time interval in which the angular error, ϕ_e converges to 0, for the STSMC the command is 4-5 times shorter than for the SMC, Fig.2.52.

Analyzing case (II), it can be seen from Fig.2.57 that the tracking errors at STSMC converge to 0 faster than the SMC.

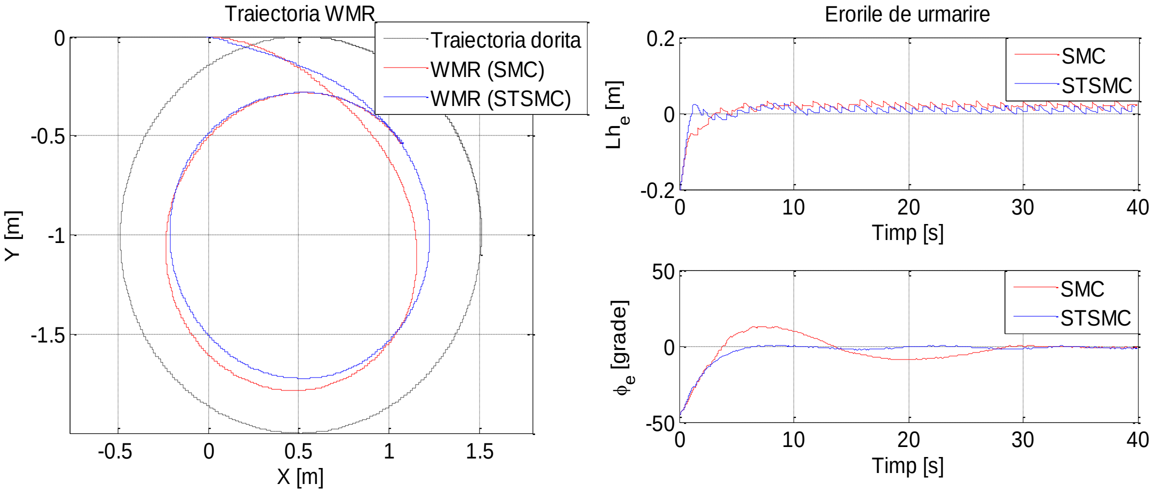


Fig.2.52. Trajectory and tracking errors in L_h coordinates for Case I, in simulation

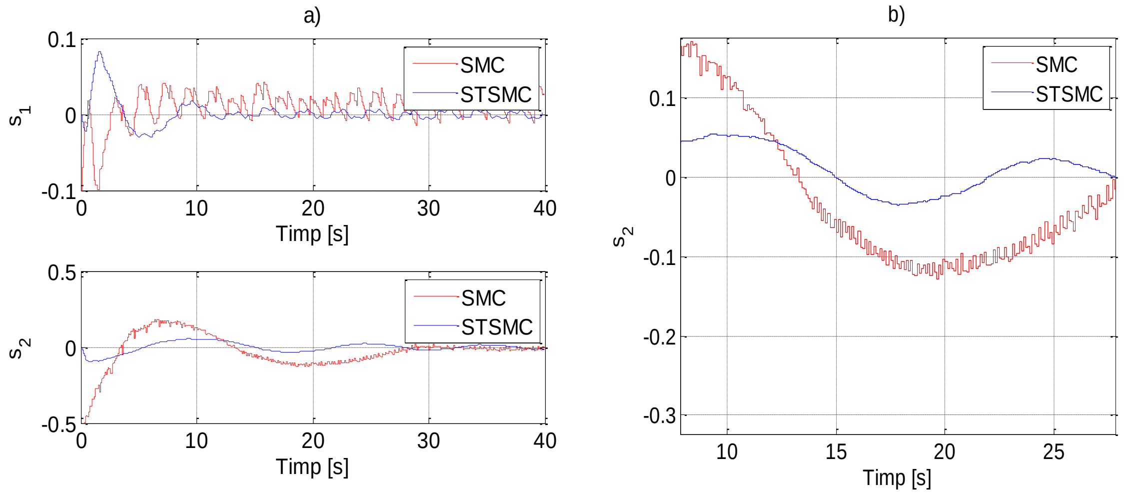


Fig.2.54. a) The sliding surfaces in L_h coordinates for Case I, in simulation b) zoom on the sliding surface s2

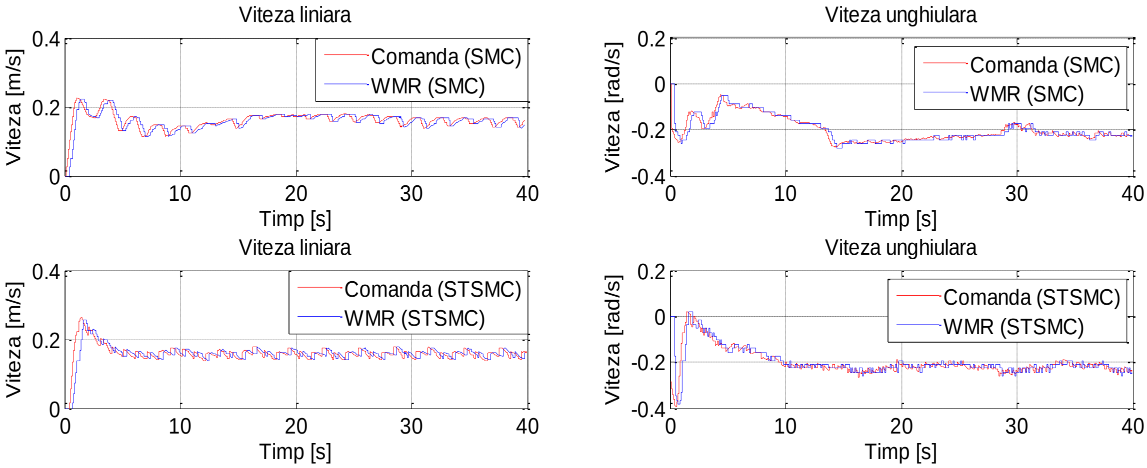


Fig.2.55. The linear and angular velocity in L_h coordinates for Case I in simulation

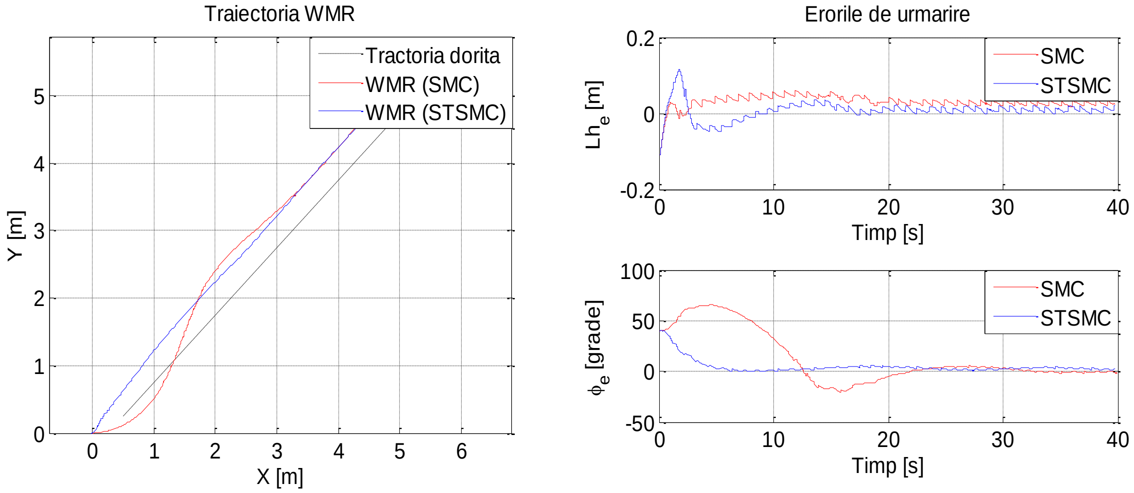


Fig.2.57. Trajectory and tracking errors in L_h coordinates for Case II, in simulation

The results from the simulation showed the advantages of STSMC and encouraged the real-time implementation. The WMR Pioneer P3-DX was used for real-time control. Real-time tests are represented only for the first case, which is sufficient to show the performance for both types of controls. The results of the real-time experiments are very similar to the results obtained from the simulations.

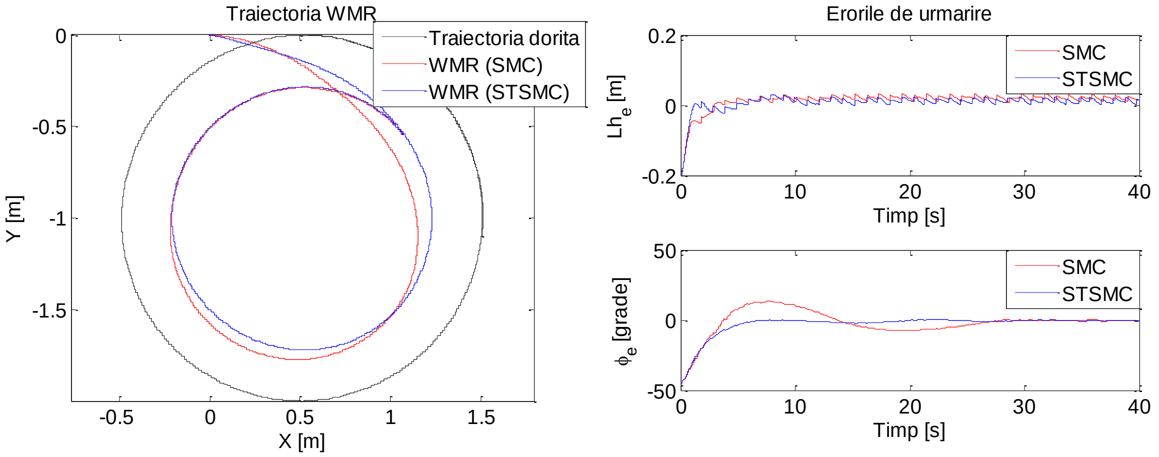


Fig.2.59. Trajectory and real-time tracking errors for Case I in L_h coordinates

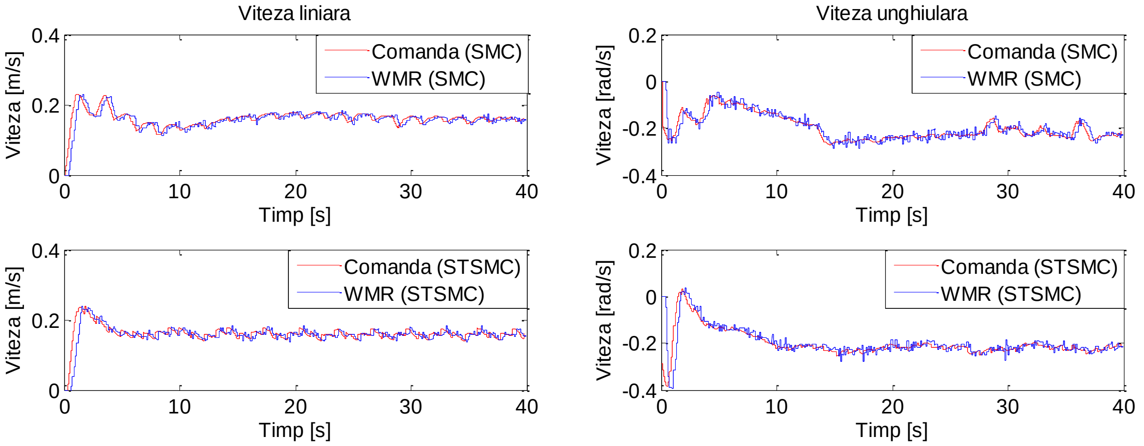


Fig.2.61. Real-time linear velocity and angular velocity for Case I in L_h coordinates

2.7. SMC structure of MAV 4DW/SW

The control architecture of the MAV Seekur is shown in Fig. 2.67. In the simulation, a path like the one in Fig.2.68 was imposed.

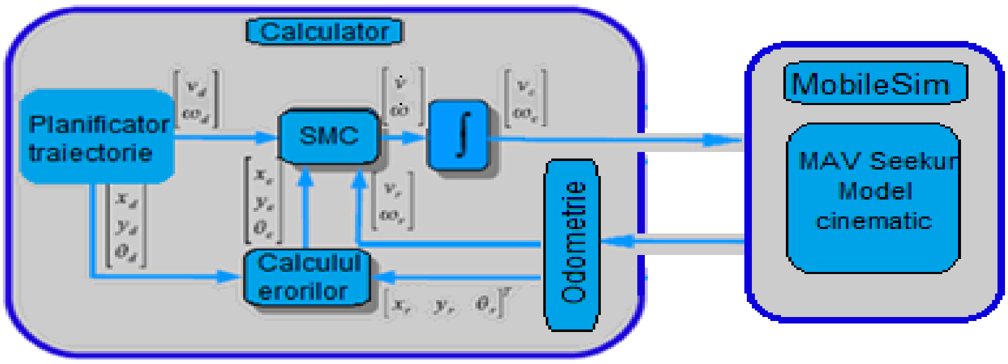


Fig.2.67. The control architecture of MAV Seekur

```
seekur: Ready for a dient to connect on TCP port 8101.
seekur: Client connected from raz-Lenovo (127.0.0.1)
seekur: Got CLOSE command, closing connection.
seekur: Client disconnected.
seekur: Port opened. Listering on TCP port 8101... [8]
seekur: Ready for a dlient to connect on TCP port 8101.
Time: 0:00:47.900 (avg sim/real time: 1.00) 0 active devices |MobileSim 0.7.5 (Stage v2.0.0a-amr11)
```

Fig.2.68. The trajectory in MobileSim of MAV Seekur

In Fig. 2.69 are presented: the desired trajectory, the obtained trajectory and zoom on the two, at the closed loop control, with data saved and represented in Matlab. Fig. 2.70 shows the tracking error when traveling on the X axis and the tracking error when traveling on the Y axis. In Fig. 2.71 the angular error is presented. In Fig. 2.72 the sliding surfaces s1 and s2 obtained in the trajectory tracking are shown.

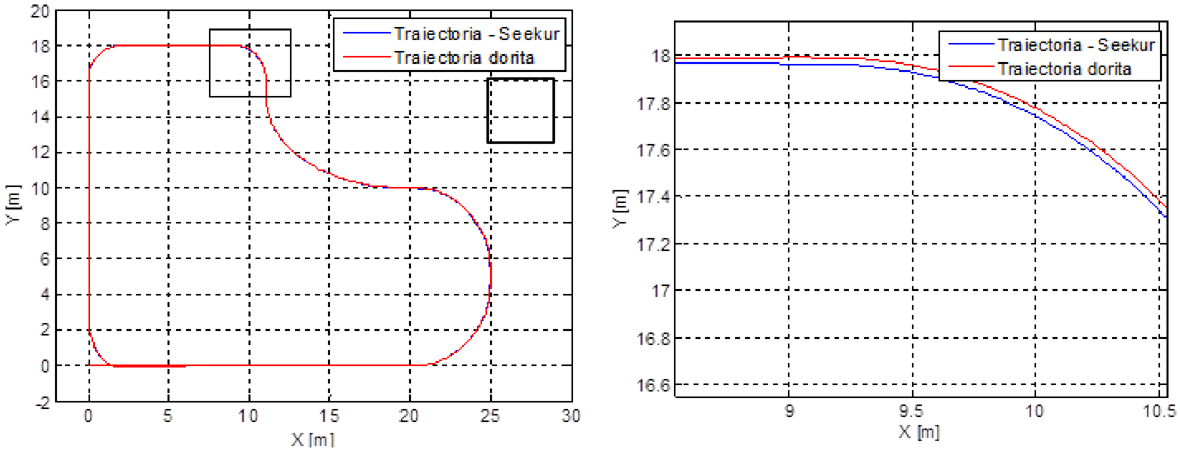


Fig.2.69. The desired trajectory and the MAV Seekur trajectory in MobileSim

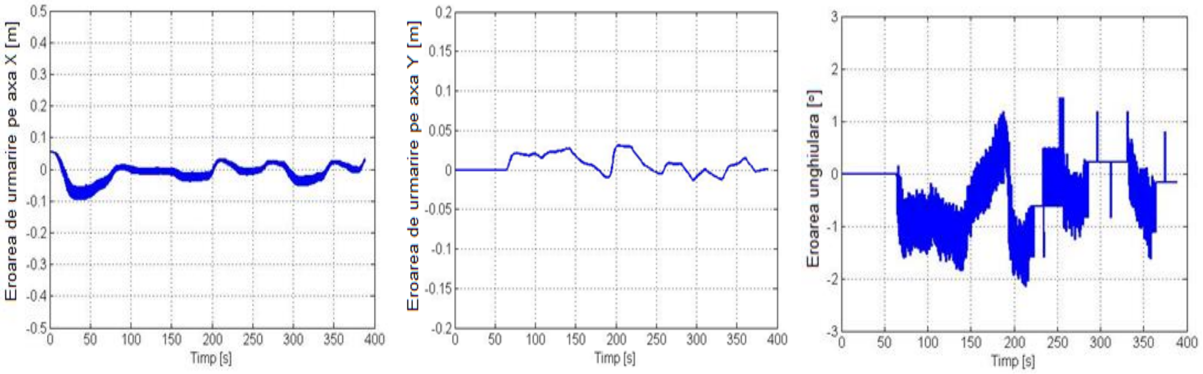


Fig.2.70. Tracking errors when traveling on X-axis and Y-axis and angular error for MAV Seekur in absolute coordinates

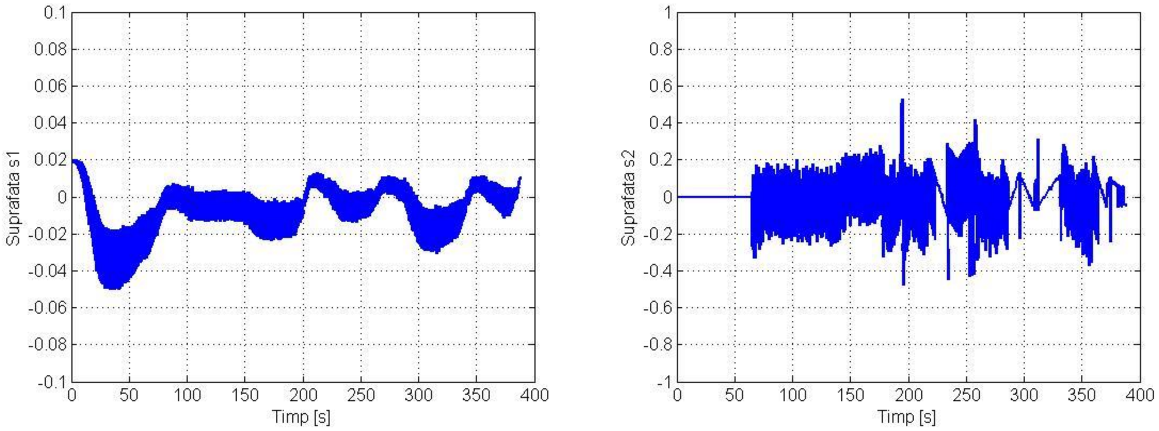


Fig.2.72. The sliding surfaces s1 and s2 for MAV Seekur, in absolute coordinates

Chapter 3. Navigation with obstacle avoidance of autonomous robotic systems

Avoiding obstacles during the movement along the trajectory, requires in the first phase their identification (static, mobile, dimensions), in the second phase elaboration of a bypass trajectory, and in the third phase re-inscription on the old trajectory.

In the thesis, obstacle avoidance navigation is presented step by step starting from the detection sensors with which autonomous systems are equipped, data acquisition and finally, the avoidance method. Two algorithms for avoiding obstacles are proposed, one for both outdoor and indoor navigation, the second for narrow space navigation.

3.1. Advanced navigation algorithms with obstacle avoidance

The reactive "bubble rebound" algorithm, presented in [73], was used to avoid obstacles. The algorithm defines a sensitivity bubble around the robot that is adjusted according to the speed of movement of the robot. Once the bubble is defined, it is checked if an obstacle has penetrated inside. If an obstacle is detected inside the bubble, a bypass trajectory is generated, given the minimum obstacle density, until the obstacle has been avoided or a new obstacle is detected.

Figure 3.6 shows the block diagram of the algorithm for avoiding obstacles.

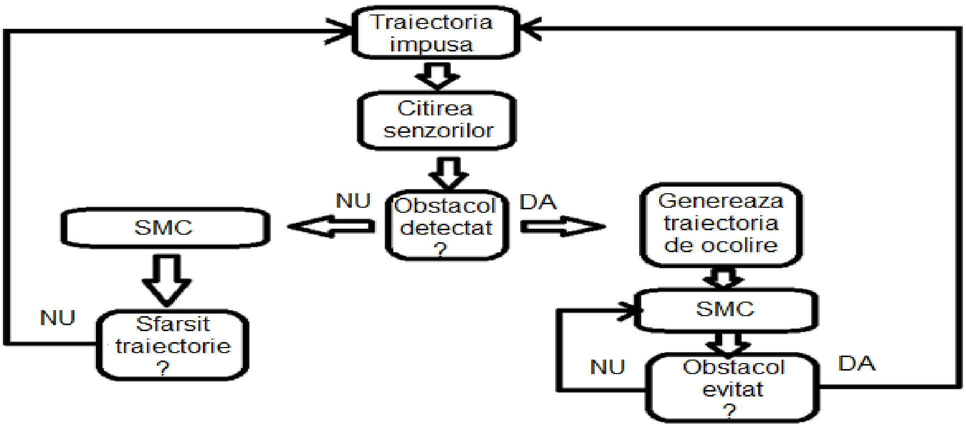


Fig.3.6. Block diagram of the algorithm for avoiding obstacles

It can be seen in Fig.3.8 that on the desired path (the black line) there is an obstacle and it is desired to find a point with the property that the robot can avoid the obstacle – that is the bypass trajectory (blue line). Knowing the width of the robot, it is checked whether the sonars/laser detects another obstacle close in the chosen circumvention direction.

Two experiments were performed in which the imposed trajectory is linear. This trajectory is in the first case blocked by a single obstacle, Fig.3.11, and in the second case the trajectory is blocked by two obstacles, Fig.3.12.

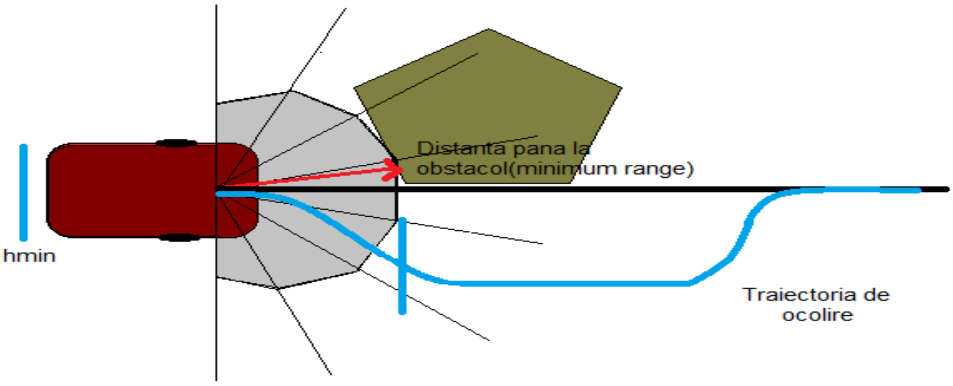
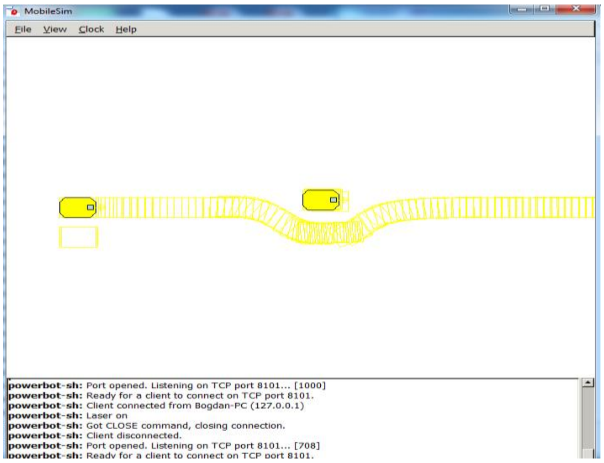
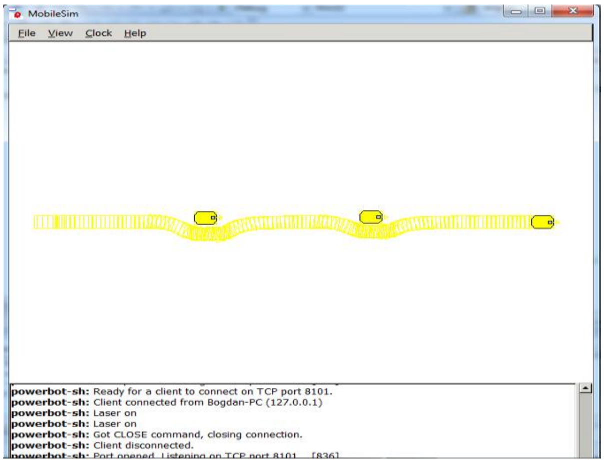


Fig.3.8. The bypass trajectory to avoid the obstacle



```
powerbot-sh: Port opened. Listening on TCP port 8101... [1000]
powerbot-sh: Ready for a client to connect on TCP port 8101.
powerbot-sh: Client connected from Bogdan-PC (127.0.0.1)
powerbot-sh: Laser on
powerbot-sh: Got CLOSE command, closing connection.
powerbot-sh: Client disconnected.
powerbot-sh: Port opened. Listening on TCP port 8101... [708]
powerbot-sh: Ready for a client to connect on TCP port 8101.
```

Fig.3.11. Avoiding a single obstacle



```
powerbot-sh: Ready for a client to connect on TCP port 8101.
powerbot-sh: Client connected from Bogdan-PC (127.0.0.1)
powerbot-sh: Laser on
powerbot-sh: Laser on
powerbot-sh: Got CLOSE command, closing connection.
powerbot-sh: Client disconnected.
powerbot-sh: Port opened. Listening on TCP port 8101... [836]
```

Fig.3.12. Avoiding two obstacles

The data from the closed loop simulation obtained in MobilSim were entered in Matlab for graphical representation - Fig.3.13, in which the desired trajectory is red and the trajectory of the mobile robot obtained in the simulation is blue.

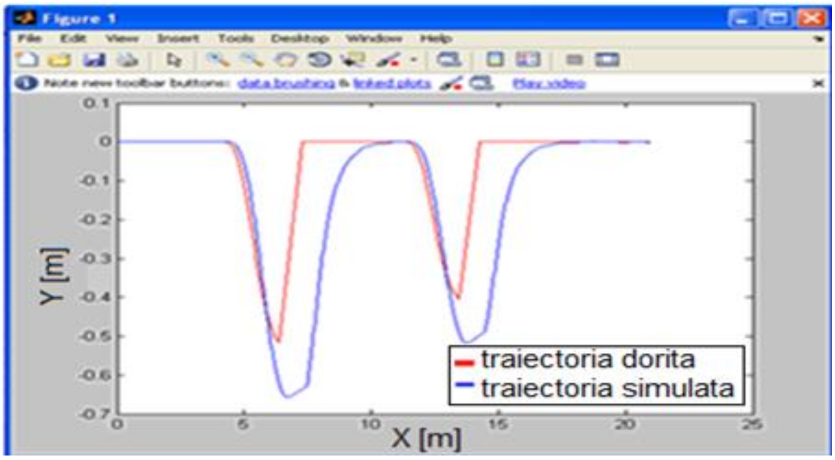


Fig.3.13. Calculated command and trajectory of the mobile robot in simulation

3.2. Indoor navigation based on laser system for access through narrow spaces

Below are presented three different cases of detection of the midpoints using the laser sensor, when the free space is detected on the left, right and in the middle, relative to the wheelchair position, Fig.3.21.

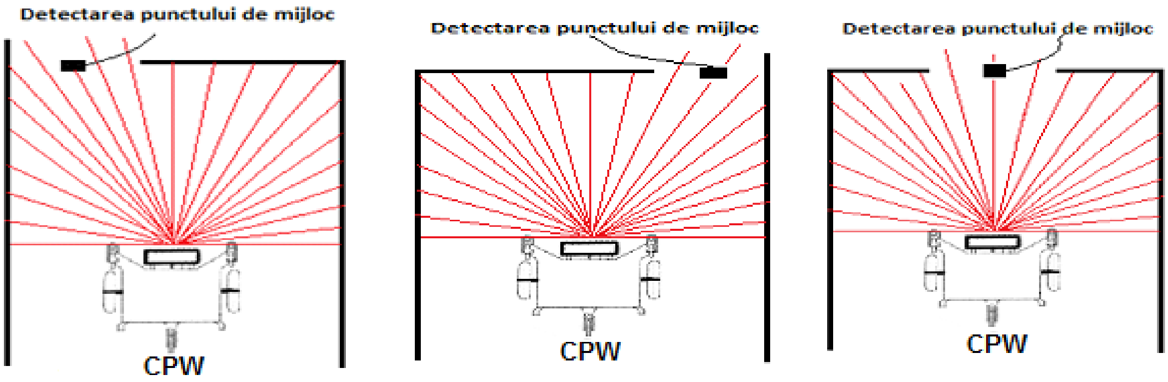


Fig.3.21. Free space detected on the left, right and middle of the CPW

3.3. Real-time navigation using the narrow space algorithm

The path taken by CPW is represented by the median points, calculated according to the number of free windows. The algorithm runs in real time. After completing the first midpoints, other midpoints will be recalculated, once the CPW position is changed.

Case 1 - CPW positioning near the narrow space that allows the passage. Following the graphical representation of the trajectory obtained with the help of Matlab, one can observe the trajectory that it establishes, Fig.3.25.

Case 2 - CPW positioning in relation to two narrow spaces, positioning that allows only one of them to pass. The trajectory that it establishes can be seen in Fig. 3.26.

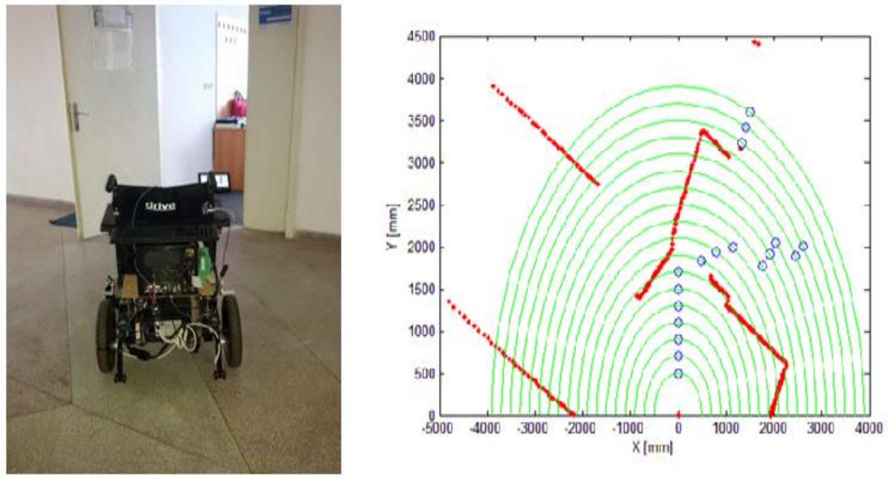


Fig.3.25. The real image of the CPW and the graph obtained for Case 1

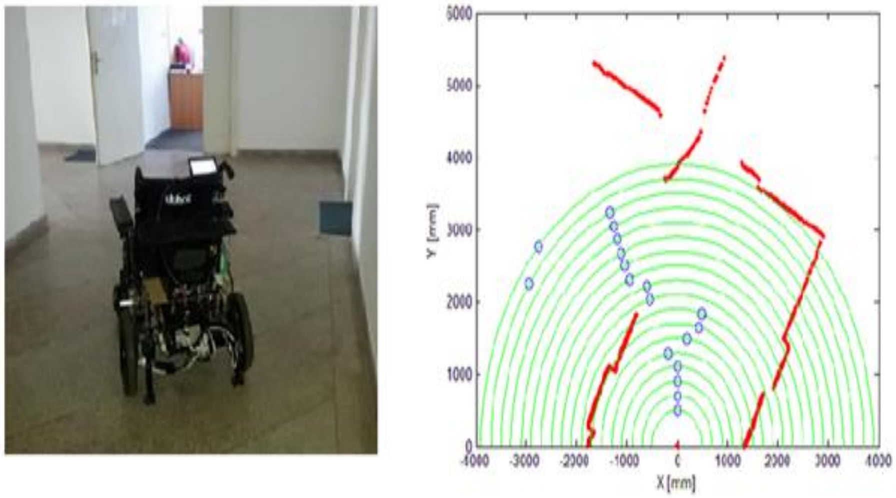


Fig.3.26. The real image of the CPW and the graph obtained for Case 2

Chapter 4. Control and navigation of autonomous robotic systems involved in personal assistance technologies and service for precision manufacturing lines

In this chapter an algorithm is proposed for the real-time implementation and testing of the CPW control and navigation structure, specifically intended for the assistance of people with disabilities. Also, a control structure of a processing/reprocessing mechatronics line served by mobile robotic platforms, robotic manipulators and visual servoing systems is implemented.

The approach proposed in this thesis satisfies the new control concepts of flexible manufacturing processes of processing/reprocessing (P/R), [82], [83], [84], on laboratory systems (mechatronics lines) served by autonomous robotic systems equipped with manipulators and visual servoing systems. The purpose is to increase productivity and the degree of automation. Also, the proposed approach responds to the new requirements – recovery and reuse of parts or components that do not correspond qualitatively – following a technological process.

4.1. Design of a control and navigation structure for people with severe neurolocomotor disabilities

In order to better identify the movements of the eye and for the best detection of the iris, a data acquisition system was created, consisting of a pair of eyeglasses that had attached a video camera with an adjustable clamping system for focusing, Fig.4.2.

Fig. 4.8 shows the logic scheme of the realized algorithm for image processing and direction identification.

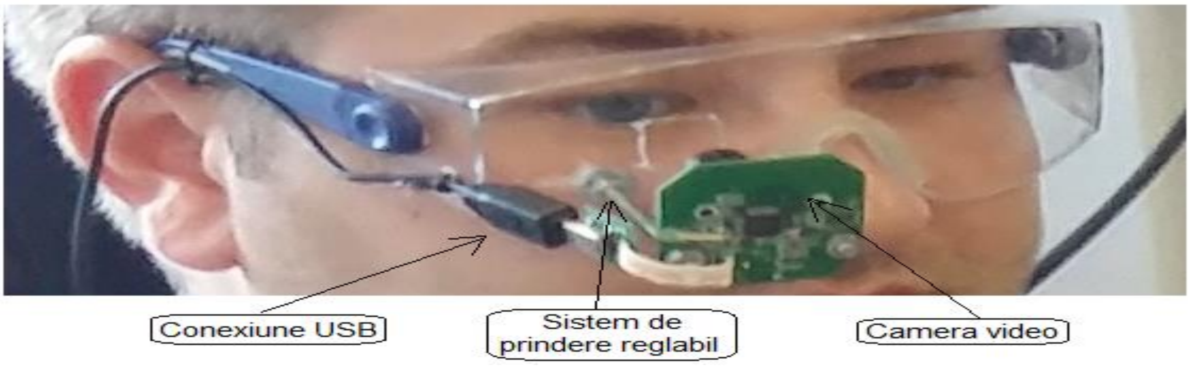


Fig.4.2. Video camera attached on a pair of glasses

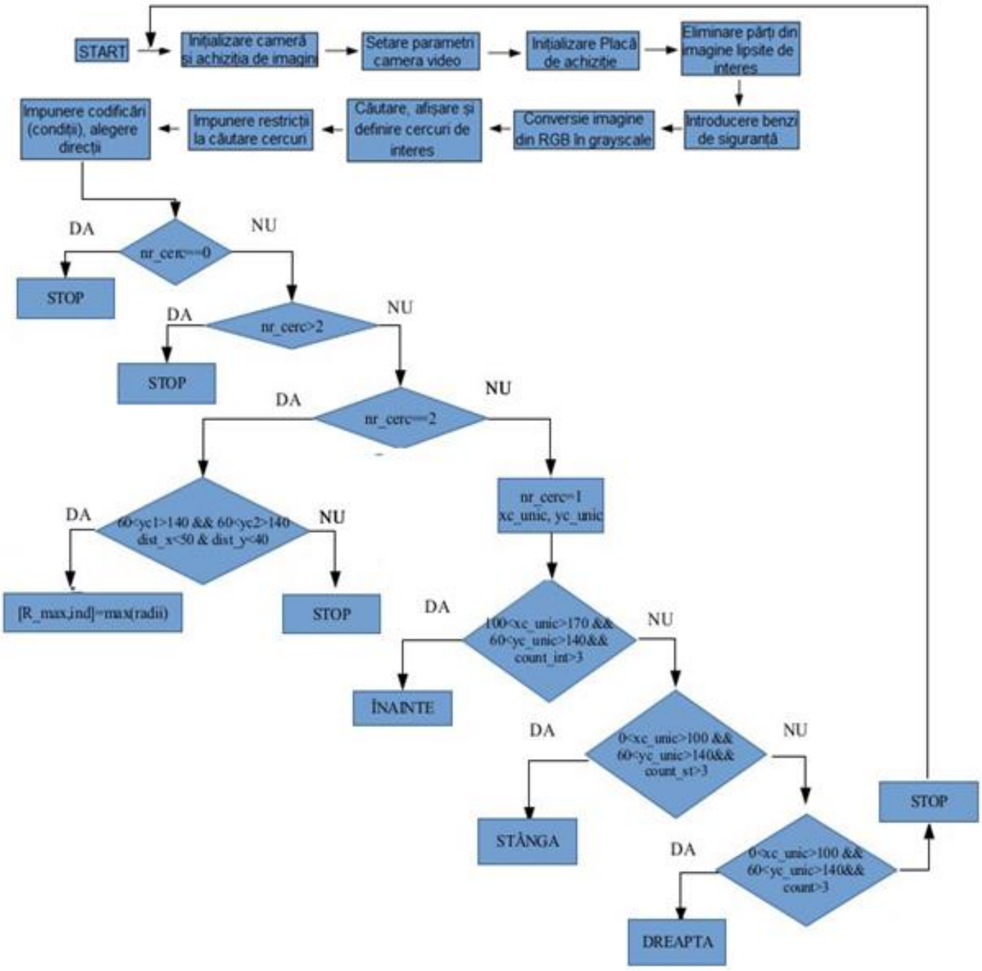
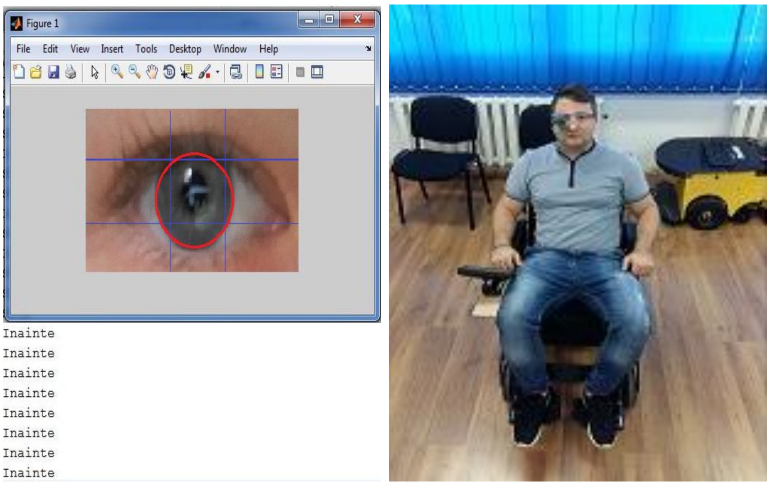


Fig.4.8. Logic scheme of the realized algorithm

4.2. Implementation and real-time testing of control and navigation structure for people with severe neurolocomotor disabilities

The results of the tests performed in real-time for the commands for moving in three directions and stopping, based on the identification of the valid circles: FORWARD, Fig. 4.12; LEFT, Fig. 4.13; RIGHT, Fig. 4.14; STOP, Fig. 4.15.



```
Inainte
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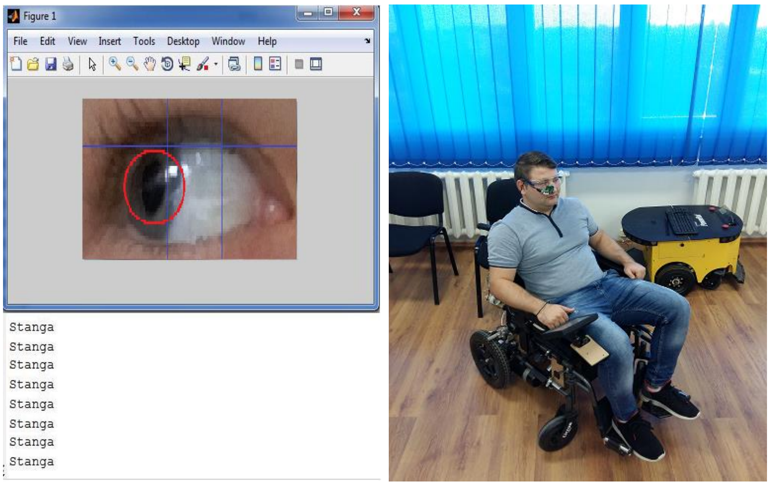
Fig.4.12. Fig.4.12. FORWARD, valid circle: red outline



```
Stanga
Stanga
Stanga
Stanga
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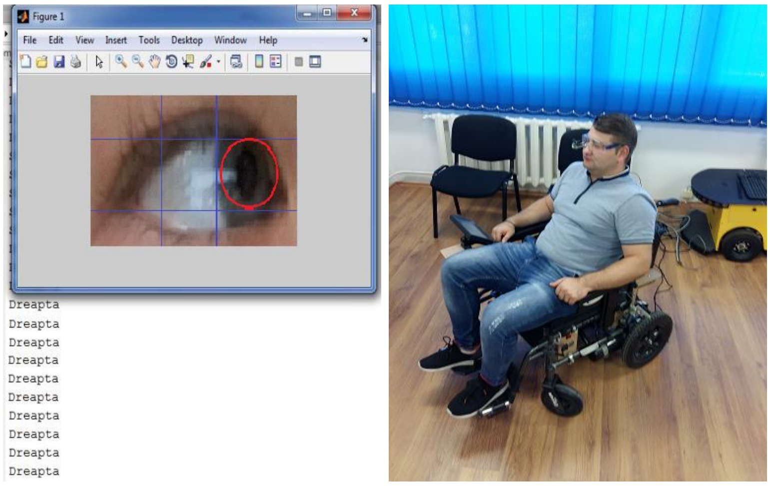
Stanga
Stanga
Stanga
```

Fig.4.13. LEFT, valid circle: red outline



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Dreapta
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Dreapta
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Dreapta
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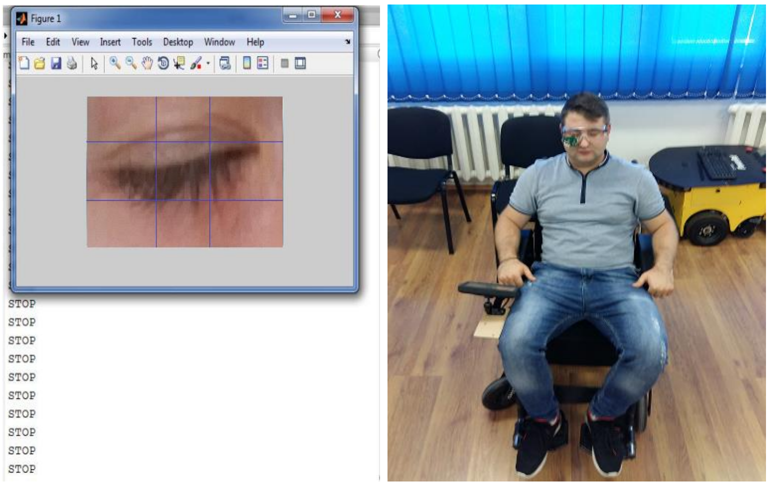
Fig.4.14. RIGHT, valid circle: red outline



```
STOP
STOP
STOP
STOP
STOP
STOP
STOP
STOP
STOP
STOP
```

Fig.4.15. STOP

4.3. Mobile platforms, robotic manipulators and visual servoing systems integrated into a precision manufacturing line assist technology

The VSS eye to hand architecture is defined by mounting the visual sensor in a fixed position relative to the working environment, Fig. 4.16 a) and the VSS eye in hand architecture is defined by mounting the visual sensor on the Cyton RM EOF 1500, Fig. 4.16 b).

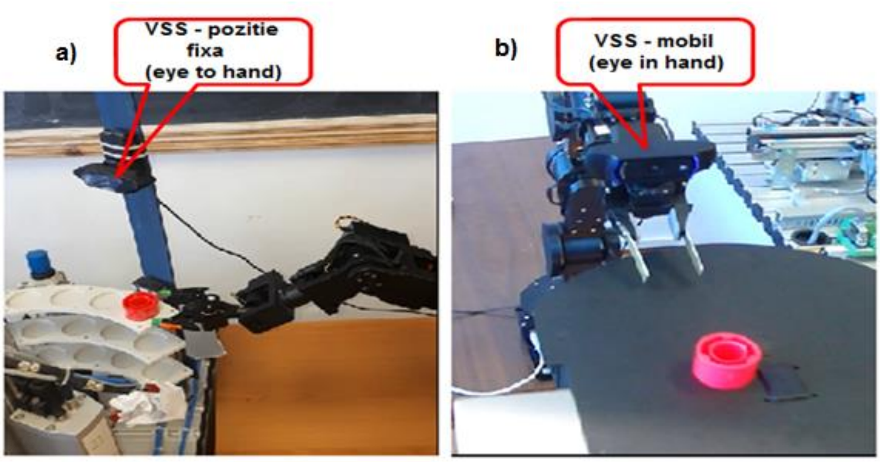


Fig.4.16. Types of VSS

The VSS structure is based on an autonomous system composed of a mobile robot equipped with a manipulator, a regulator and a visual sensor. The main idea for VSS modeling is to minimize the error between the real features, extracted by the visual sensor and the desired features. The main control structures of the VSS are shown in Fig. 4.17 and Fig. 4.18.

The precision manufacturing line, in this case, is the FESTO MPS-200 mechatronic system, Fig. 4.19. It consists of 4 workstations, being serviced by two mobile robots (WMR), two robotic manipulators (RM) and two types of visual servoing systems (VSS) for pick-up, transporting and handing over the work piece.

Figure 4.22 shows the block diagram that defines the processing and reprocessing cycle of the FESTO MPS-200 mechatronic system. This diagram is based on a graph of representation, highlighting the cycle of processing and reprocessing of the piece, according to its color, [82], [83].

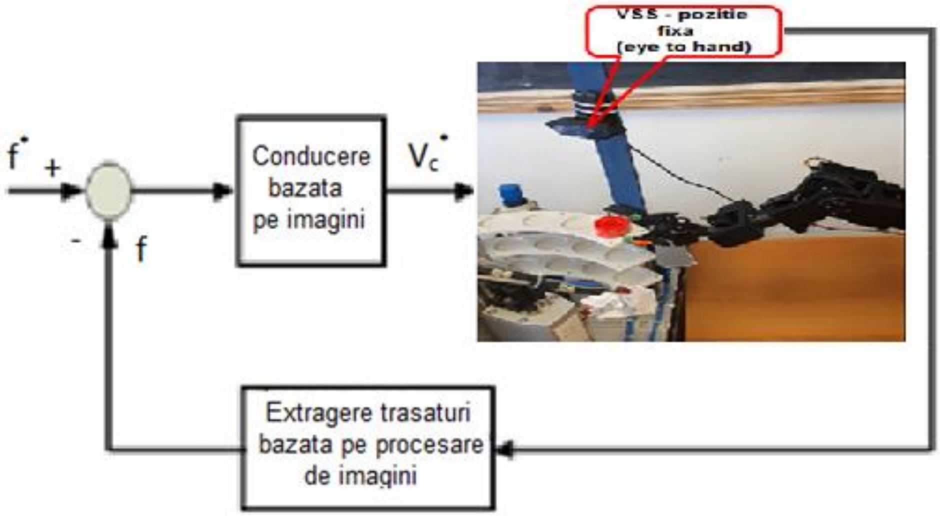


Fig.4.17. WMR Pioneer P3-DX equipped with RM Pioneer 5-DOF Arm closed loop control VSS eye to hand

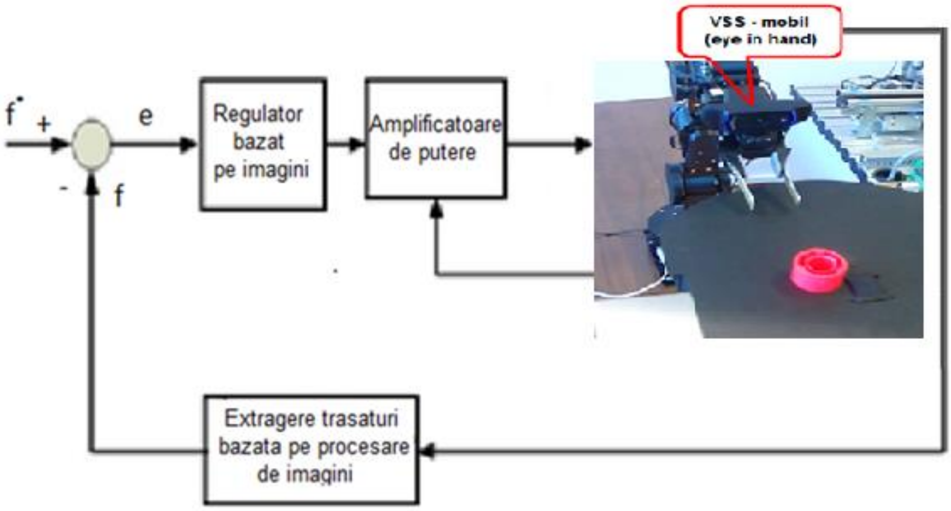


Fig.4.18. Closed loop control based on VSS eye in hand of RM Cyton 1500

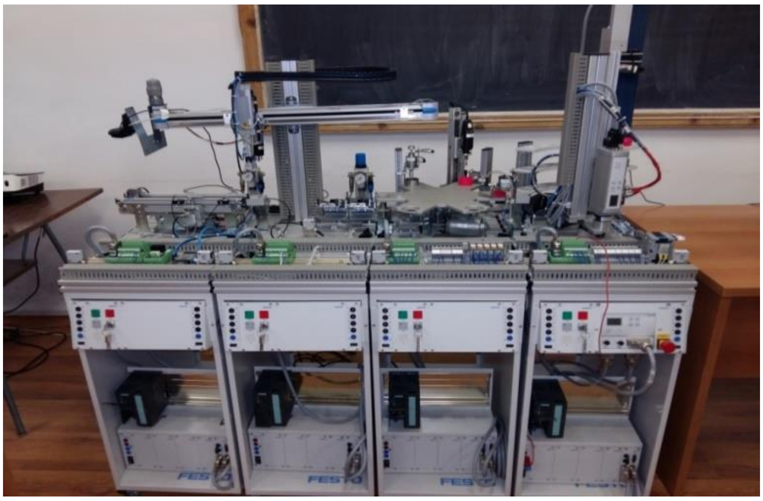


Fig.4.19. Flexible manufacturing system FESTO MPS-200

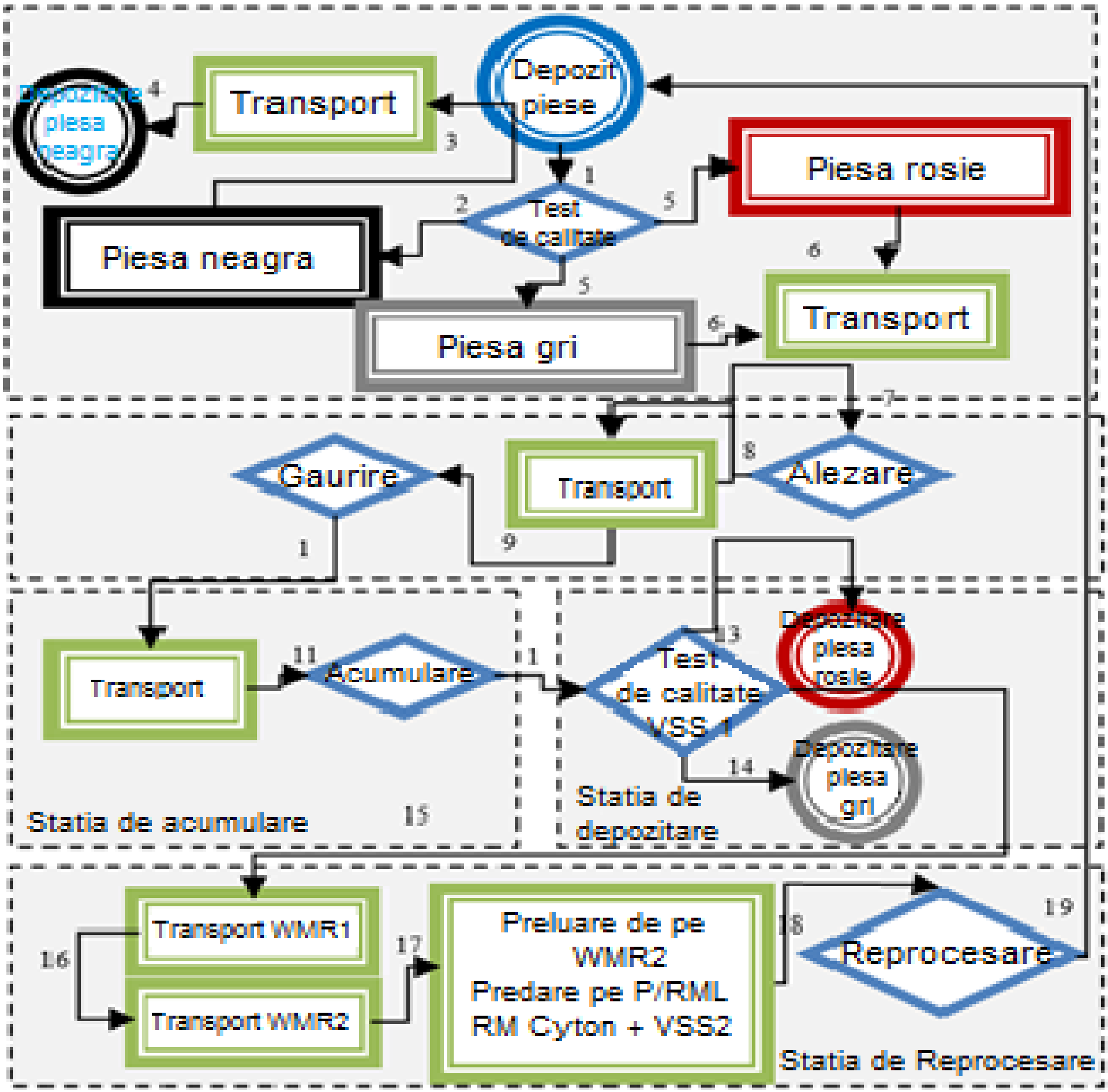


Fig.4.22. Block diagram defining the processing/reprocessing cycle of the FESTO MPS-200 mechatronic system

In Fig.4.23 It can be seen the trajectory in MobileSim of the WMR PeopleBot when it encounters an obstacle.

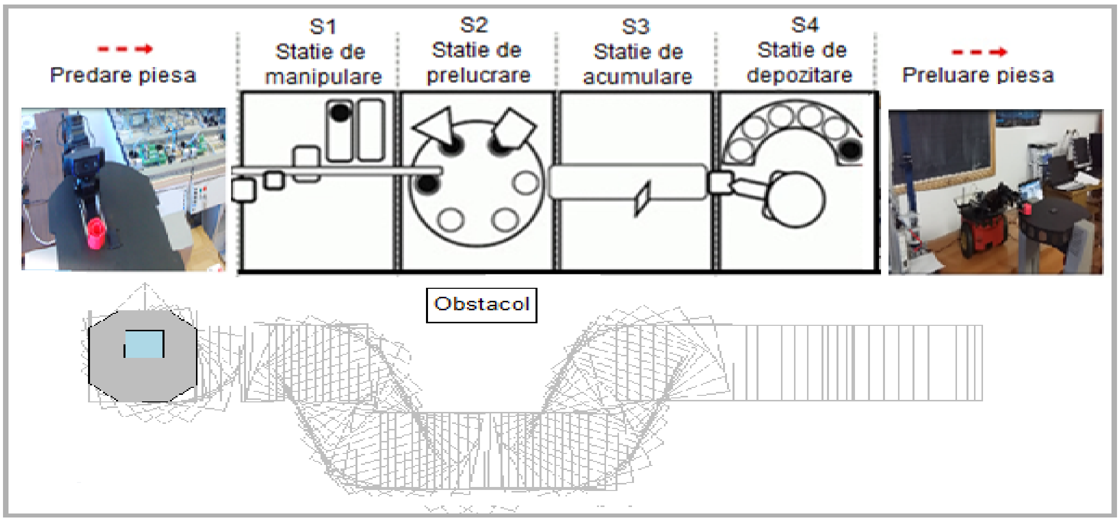


Fig.4.23. The trajectory in MobileSim of WMR PeopleBot in absolute coordinates

In Fig. 4.24 the types of used parts and some stages of the precision manufacturing line cycle based on mobile platforms, robotic manipulators and visual servoing systems are presented.

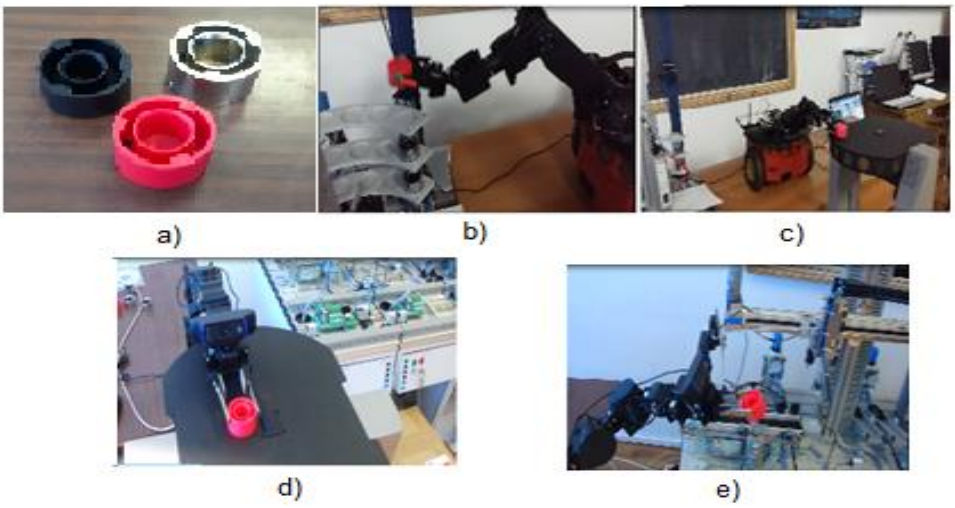


Fig.4.24. a) types of used; parts b) WMR Pioneer P3-DX with RM Pioneer 5-DOF picks up the piece from P/RML; c) WMR Pioneer P3-DX place the piece on WMR PeopleBot; d) RM Cyton 1500 picks up the piece from PeopleBot; e) RM Cyton 1500 place the piece on P/RML for reprocessing

4.4. Real-time control of the precision manufacturing line served by robotic and visual servoing systems

The communication structure of the whole system – Fig. 4.25 – is based on a TCP/IP protocol. Three HD webcams are connected to the PC, two of them are mounted on P/RML and one on the EOF of the Cyton 1500 robotic arm.

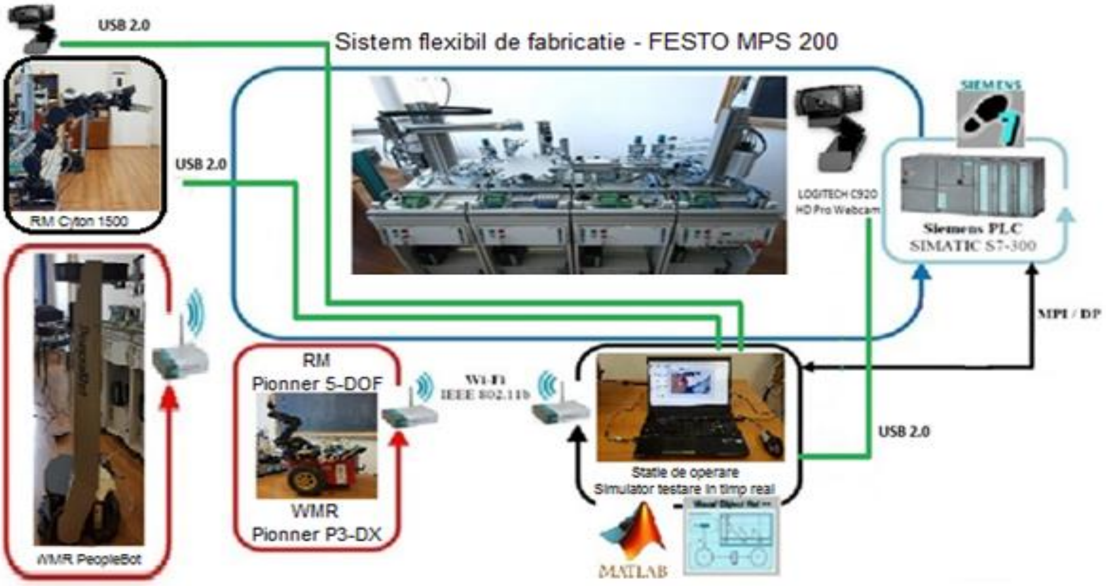


Fig.4.25. Communication structure of the precision manufacturing line

Fig. 4.27 shows the real-time steps with the precise positioning based on the fixed VSS of the Pioneer 5-DOF Arm robotic manipulator: a) moving the WMR Pioneer P3-DX and positioning to retrieve the part from the P/RML, b) picks up the piece, c) moves the WMR Pioneer P3-DX to the WMR PeopleBot, d) hands over to the WMR PeopleBot, e) returns to the initial position of the WMR Pioneer P3-DX

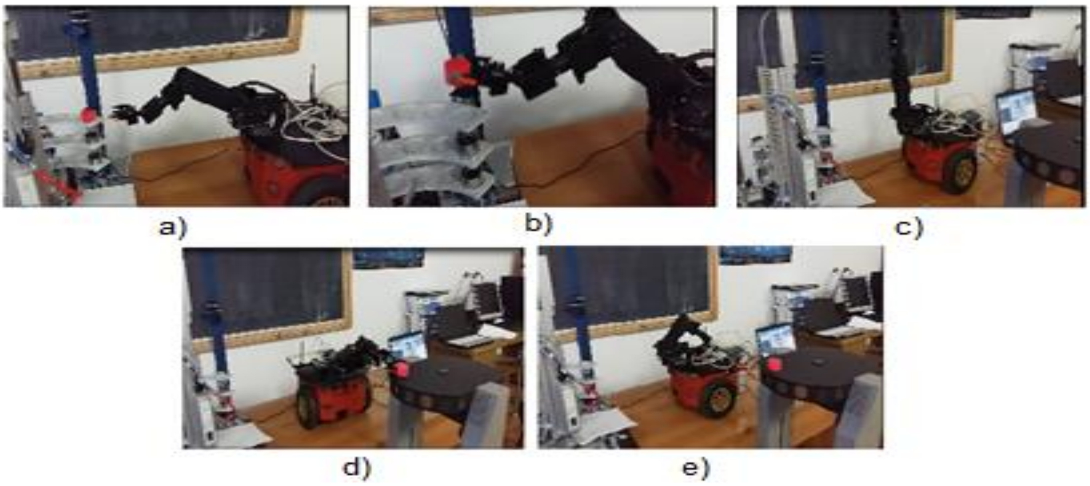


Fig.4.27. Real – time images where WMR Pioneer equipped with RM Pioneer 5-DOF picks up the piece from P/RML and hands it over to WMR PeopleBot

In Fig. 4.28 are presented: the desired trajectory, the real trajectory and the angular error (in absolute coordinates) of the WMR PeopleBot when controlling the SMC in a closed loop. You can see a slight deviation of the trajectory when WMR PeopleBot executes the return of 90° and that the maximum error is ±6°.

Fig. 4.29 shows the linear and angular speeds of the WMR Peoplebot as well as the desired ones. According to the results obtained from the presented graphs, the time required to complete the route from taking over the piece to place the piece was 60s.

Fig. 4.30 shows the tracking error when moving along the X-axis and the tracking error when moving along the Y-axis. It can be seen that in Fig. 4.30 in the case of the error when moving along the X-axis, there are two deviations present due to the connection loss, but it tends immediately to 0.

Fig. 4.32 shows the slip surfaces s1 and s2 obtained in the trajectory tracking.

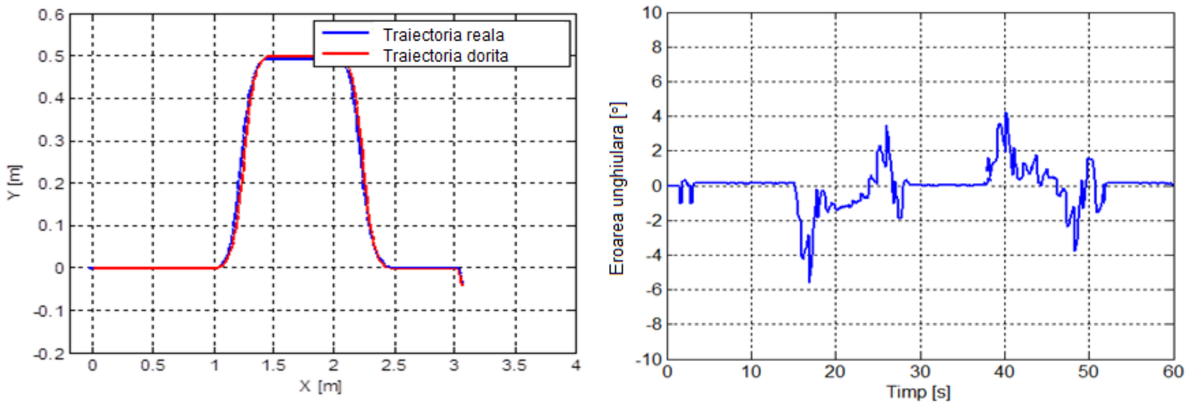


Fig.4.28. The desired trajectory, the real trajectory and the angular error (in absolute coordinates) of WMR PeopleBot at SMC control in real – time

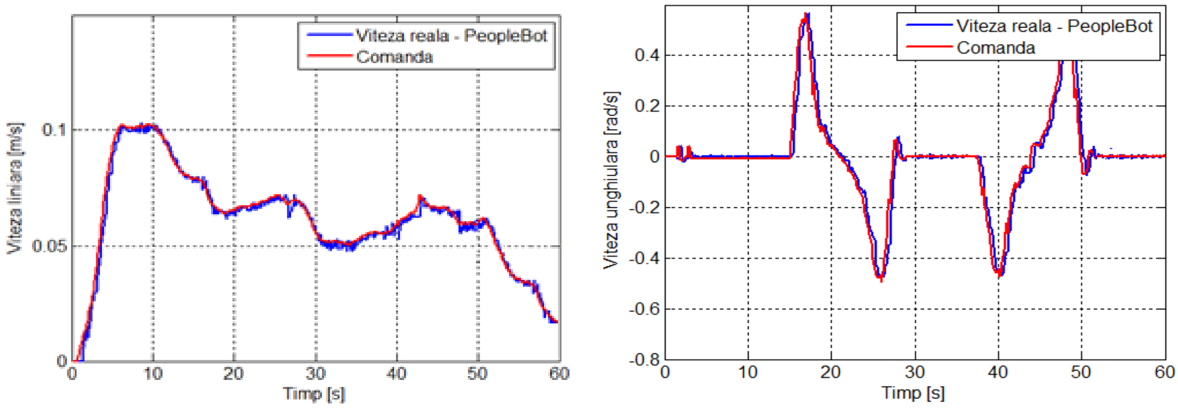


Fig.4.29. The linear and angular speed of the WMR Peoplebot and the command required in absolute coordinates

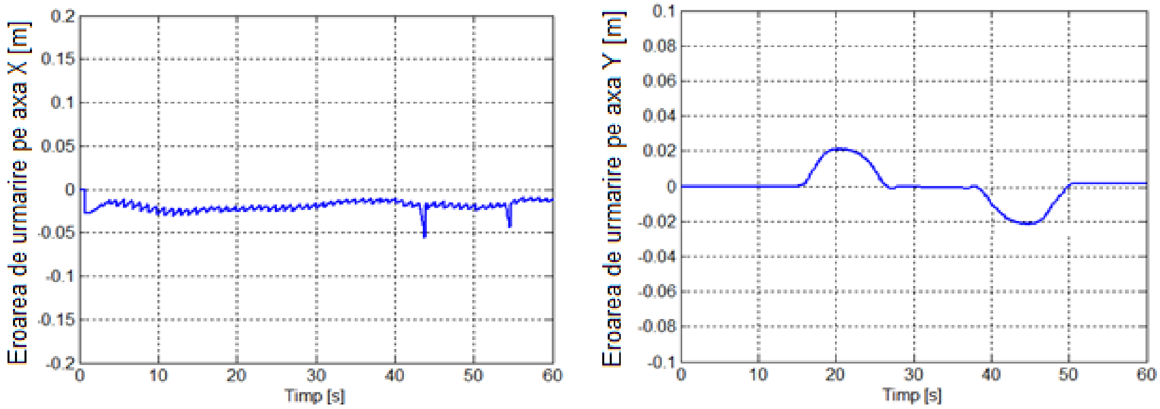


Fig.4.30. Tracking errors when moving on X-axis and Y-axis for WMR PeopleBot in absolute coordinates

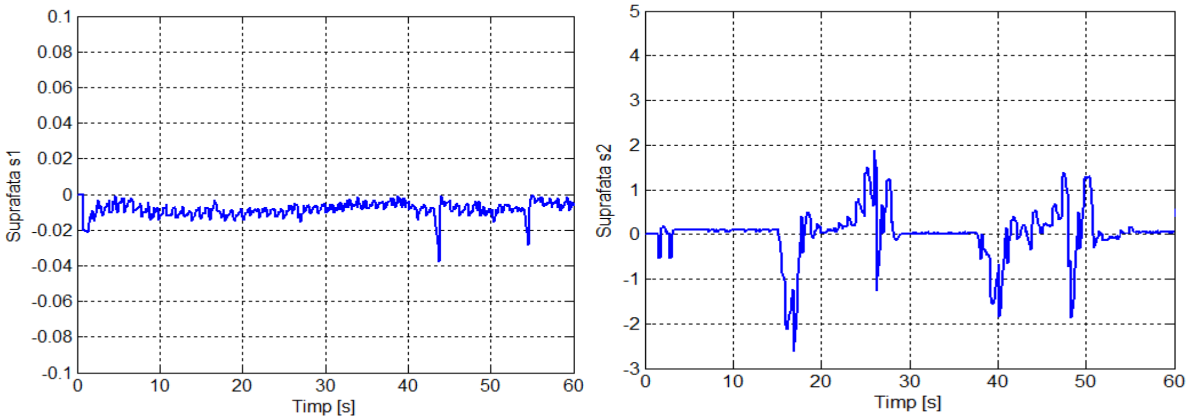


Fig.4.32. Sliding surface s1 and s2 for WMR PeopleBot in absolute coordinates

In Fig.4.34 and Fig.4.35 there are presented frames, during real-time experiments of the two fixed VSS mounted on P/RML, in order to pick up/hand over the reprocessing piece. Fig. 4.36 shows real-time frames of the mobile VSS mounted on the EOF of the Cyton 1500 robotic arm, in order to retrieve the piece from the WMR PeopleBot.

Fig. 4.37 shows the real-time steps with the precision positioning based on the mobile VSS, of the Cyton 1500 robotic manipulator: a) positioning to retrieve the piece from the WMR PeopleBot, b) pick up the piece, c) moving to the P/RML, d) handing the piece on P/RML, e) return to the initial position.

Fig.4.34. Real-time image in which RM Pioneer 5-DOF Arm picks up over the reprocessing piece

Fig.4.35. Real-time image in which the RM Cyton 1500 hand over the piece on P/RML for reprocessing

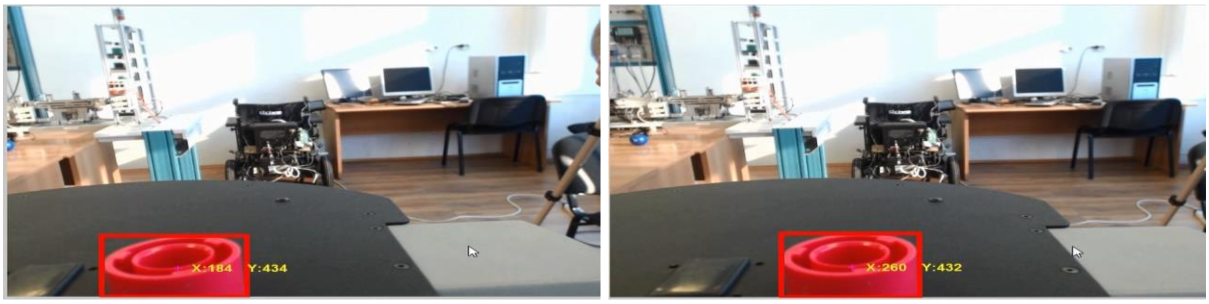


Fig.4.36. Real-time image where RM Cyton 1500 is positioned to retrieve the piece from WMR PeopleBot

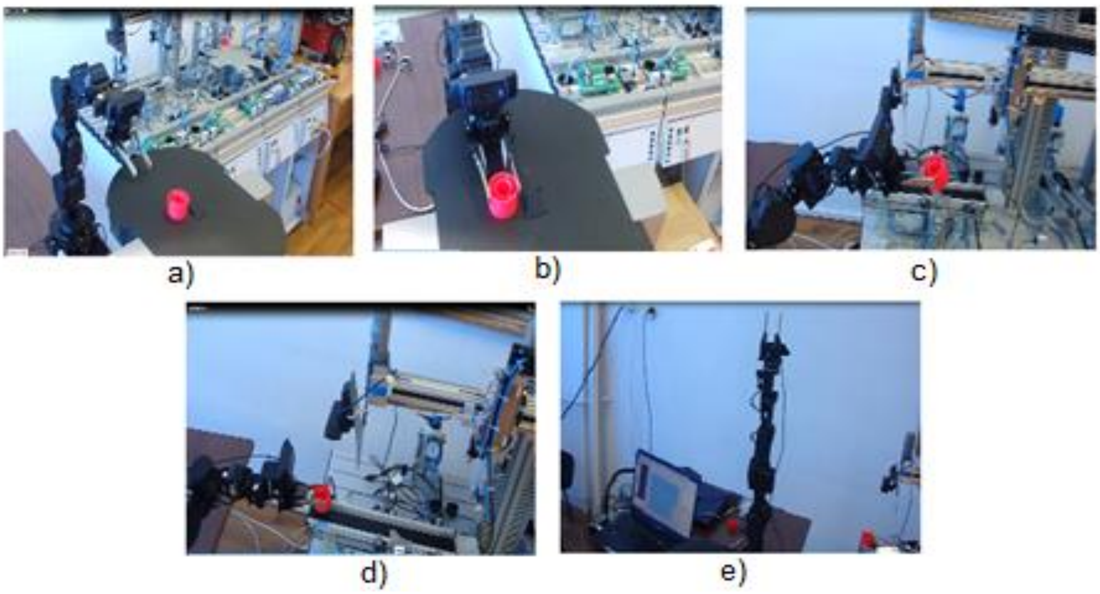


Fig.4.37. Real-time image in which RM Cyton pick up and hand over the piece

Chapter 5. Final conclusions, contributions, future research directions, dissemination of results

The development of new assistance systems for people with disabilities has led to a multidisciplinary approach based on new control and navigation technologies that meet the restrictions and needs of the assisted person.

The development of new control systems for the flexible precision manufacturing, processing/reprocessing line can lead to increased productivity and automation. The proposed approach responds to the new requirements of recovery and reuse of parts or components that do not correspond qualitatively, following a technological process.

5.1. Final conclusions

I believe that the objectives of the thesis were achieved by going through all the stages related to the implementation of a control and navigation structure: process analysis, modeling, identification, design, simulation testing and real-time testing. Starting from the current stage in the control and navigation of autonomous robotic systems involved in assistive technologies, the thesis mainly contributes to the implementation and testing in simulation and real-time regime.

The set of results and conclusions confirms that the techniques addressed in this doctoral thesis ensure the good performance of the wheelchair system for the assistance of people with severe neurolocomotor disabilities, both for inside/outside hospital and at home. Also, the techniques addressed for the control of autonomous robotic systems integrated in precision manufacturing technologies ensure the increase of productivity, quality and the minimization of costs of the delivered products.

5.2. Contributions

The contributions claimed in this thesis, disseminated and certified by the published papers, are the following:

- Modeling, identification and simulation of the drive system of the drive wheels at CPW, [CG6];
- Design, simulation and real-time testing of the driving structure of the motor wheels with PI controller, from CPW, [CG6];
- Modelling, simulation and real-time testing of the RM Cyton 1500, control based on the inverse kinematic model, [CG4], (program Annex 8);
- Real-time design, simulation and testing of the SMC structure, control based on the WMR Pioneer P3-DX kinematic model, [CG1], [CG2], [CG5], (program Annex 1);
- Real-time design, simulation and testing of the SMC structure, based on the dynamic model of the WMR PatrolBot, [CG5], (program Annex 2);
- Design, simulation, real-time testing of the STSMC structure, control based on the WMR Pioneer P3-DX kinematic model, [CG4], (program Annex 3);
- Comparative study of the two control methods, SMC and STSMC, for WMR Pioneer P3-DX, [CG1], [CG2], [CG3], [CG5], [CG6];
    - Comparative study on navigation performance, based on ultrasound and laser, [CG1], [CG2];

- Algorithm and navigation program for detecting and bypassing obstacles (fixed or mobile) encountered based on ultrasound and laser, [CG1], [CG2], [CG3], [CG5];
- The algorithm and program for real-time CPW access through narrow spaces, based on information received from the Hokuyo URG-04LX-UG01 laser, [CG5], (Annex 5);
- Designing navigation structure based on image processing of eye movement for CPW assistance for people with severe neurolocomotor disabilities, [CG6], [CG7];
- Implementation and testing real-time navigation structure based on image processing of eye movement for CPW assistance for people with severe neurolocomotor disabilities, [CG6], (program Annex 6);
- Design of the integrated system for the service of precision manufacturing lines (mechatronics lines) by autonomous robotic systems equipped with manipulators and visual servoing systems, [CG3],[CG4];
- Real-time testing and implementation of a precision manufacturing line assisted by autonomous robotic systems equipped with manipulators and visual servoing systems,[CG3], [CG4], (program Annex 7).

5.3. Results Dissemination

The results of the obtained research were published as follows:

- 6 papers in international conferences, indexed WoS, Scopus and IEEE, of which 2 papers as first author and as co-author of 4 papers;
- 1 journal work, as first author.

Papers published in proceedings (ISI indexed)

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