Visual servoing systems based control of complex autonomous systems serving a P/RML

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***Abstract*— The appearance of random event in autonomous processing systems is the main concern in this paper. The main scope is to embed different visual servoing systems (VSSs) with a processing/reprocessing mechatronics line (P/RML) in order to control different complex autonomous systems (CASs) while servicing the line in the operation of recovery of the pieces that did not pass the quality test. For achieving this objective, two different visual servoing systems are designed, tested and implemented for controlling different wheeled mobile robots (WMRs) equipped with robotic manipulators (RMs). To the first one, called *eye in hand*, the camcorder is located on the last link of the manipulator, thus the visual servoing system is mobile. To the second one, called *eye to hand*, the camcorder has a fixed position, usually positioned on a P/RML workstation. This paper is focused on video processing and control of different WMRs equipped with RM while serving the P/RML based on fixed or mobile VSSs.**

***Keywords* — CAS, VSS, WMR, RM, P/RML.**

I. INTRODUCTION

Lately, technological progress has led to industry to a global evolution. All the industry domains are concerned about this improvement and had triggered the appearance and development of new types of flexible production facilities, controlled by new methods of supervised or distributed management. Another aspect is regarding the development of new robot types, tools for processing machines and systems capable of efficient manipulation / transport [2], [4]. The flexible manufacturing systems that involve processing/reprocessing should be complex and real-time control systems, in order to facilitate the execution of multiple operations and tasks. In the background of this complex control is the off-line task planning, which refers to a large area of planning methodologies that can provide a detailed operation plan. This plan should include sensory action, rough motion planning, mobile robots trajectory planning, [10], fine motion planning and other kinds of planning, depending on the application [8]. On-line planning, on the other hand, refers to execution and reaction issues about how to execute and supervise an off-line plan, how to develop on-line plans and also how to manage the reaction while the plan is executed and various situations appear [1] and [9]. These presented issues can be easily classified, as if follows: behaviour-based action, reactive scheduling, and plan monitoring. Regarding the processing /reprocessing process, it has a lot more of complex requirements, which refers to system planning, geometric relationships, kinematics control, resource scheduling and performance measurement and evaluation, [17]. This kind of requirements will be a difficult task for in the new flexible and concurrent environment of the processing lines. Taking into account these combined factors and difficulties the real time processing will require a great knowledge and experience of the engineers in charge of designing and production.

On the other hand, for a mobile robot or a manipulator, the techniques relative to domain-independent methods are less effective for developing a planning strategy, and more useful is a strategy that is oriented to the system’s characteristics. Feasible plans could have big search space if the system model is represented conventionally, without constraints. By using this kind of model, it is much easier for the task planner to decide which component or sequence has to be removed to obtain specific tasks sequence. Also the planner will provide the best reprocessing sequence, in case the processed product will fail the quality test.

In this paper are presented two visual servoing models for controlling a P/RML while being serviced by a WMR which has mounted a RM or while being serviced by 2 mobile robots and a fixed manipulator. The issue of reprocessing is critical for minimizing the waste of resources (time, money) and for maximizing the automation level of the process [7],

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[14]. The main scope is to design and implement a visual servoing system, capable of synchronizing the P/RML with the WMR and to manage the recovery and the transport for reprocessing of the scrap pieces by controlling the RM. The same line is capable of doing both the processing and the reprocessing operations. The RM servicing the P/RML is mounted on the WMR. The dynamics of the line are determined by events, by the interaction with the robot and by the logic sequences developed for the system.

The paper has the following development: Section 2 gives preliminary hypothesis about different types of visual servoing systems; Section 3 shows the modelling of a visual servoing system; Section 4 is used for determining the interaction matrix for image moments features; in Section 5 is determined the control law for WMR with RM; result of testing and implementing the obtained visual servoing systems are shown in Section 6 along with the real time control of the P/RML and in Section 7 are presented the final remarks.

II. PRELIMINARIES ABOUT VISUAL SERVOING SYSTEMS

The main idea in using visual feedback for obtaining high quality results is to have features that can provide well defined properties like accuracy, robustness and stability. Meeting these expectations will provide the ability to obtain good control laws for the application.

In [3], [12] and [13] are presented the principal types of features that are usually employed for assuring maximum efficiency of tasks accordingly to the evolution of the environment as it is seen by the video sensor. Some specific features are discussed such as, moments of the image, orientation of lines that are joining 2 points, line parameters, point features (centres, corners), areas of the projected regions, edge lengths. The best of these features that can be used for implementing effective control laws are moments of the image and point features.

In the common practice are defined two visual servoing architectures, depending of the video sensor positioning and are presented in an extensive way in [6] and [19]. First, the eye-in-hand architecture is defined by the mounting of the video sensor in a seated position relative to the work space and the eye-to-hand architecture will refer to a system were the video sensor is applied to the effectors of the RM. Also in the mentioned articles are presented advantages and disadvantages for each of the architectures creating an idea about how each configuration can be used, depending on the desired application. The general representations of the two architectures are presented in Fig. 1 and Fig. 2.

The most common used features in object classification and forms recognition are the features called moments of the image and because of their benefits are also used for robotic and artificial intelligence purposes [11]. Depending on the types of applications different types of moments have been developed lately, also due to the evolution of image processing, [15], [16].

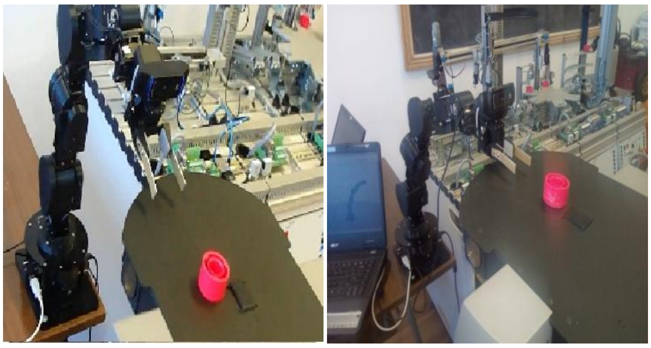
Fig. 1. Mobile visual servoing system (eye-in-hand)

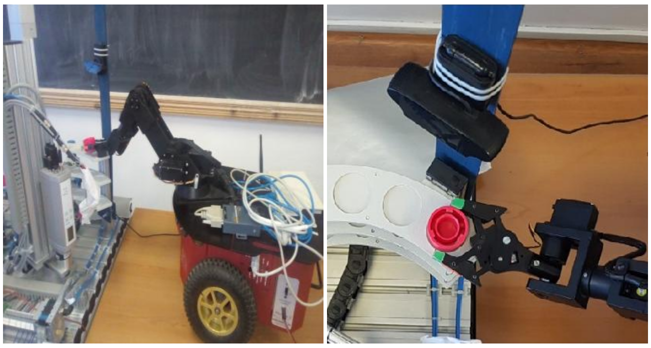
Fig. 2. Fixed visual servoing system (eye-to-hand)

For representing a digital image is used a distribution of intensity matrix that is bi-dimensional and the features will refer to the data about some specific properties of the interested objects, such as: area, center of gravity, orientation. The use of moments of the image determines the defining of the visual features vector [5].

Let $I(x,y)$ be an image that is defined as a density of probability of a random bi-dimensional variable. The assumption is that 0 values will represent the background of the environment and the other values different than 0 will represent objects. The moments m_{ij} of (i+j) order can be defined using the equation below:

$$m_{ij} = \int_0^{\infty} \int_0^{\infty} x^i y^j I(x,y) dxdy \qquad (1)$$

After customizing this equation, different object properties may be obtained, as it follows:

- For $i = 0$ and $j = 0$, is obtained the area of the object, corresponding to the moment m_{00};
- For $i = 1$ and $j = 0$ or $i = 0$and $j = 0$ the centre of gravity of the object (x_g, y_g), is obtained, corresponding to the 1st order moments, where:

$$x_g = \frac{m_{10}}{m_{00}}, y_g = \frac{m_{01}}{m_{00}} \qquad (2)$$

Usually in image processing the object will be defined as a set of pixels with (x,y) coordinates, for which $I(x,y) = 1$. Using this, the bi-dimensional moments m_{ij} of order $(i+j)$ can be defined as:

$$m_{ij} = \iint_O x^i y^j \, dxdy \tag{3}$$

III. MODELLING A VISUAL SERVOING SYSTEM

The structure of a visual servoing control system is based on several parts, such as: an autonomous system composed by a mobile robot with a 6-DOF manipulator, a regulator and a video sensor. The main idea for modelling such a system is to reach the minimum error between the real and desired features extracted from the video sensor. The main structure and components of a visual servoing system are shown in Fig. 3.

A separate analysis has to be made for the robotic structure and for the video sensor. v_c^* is the signal associated to the command given to the robotic assembly, having the form $v_c^* = (v^*, \omega^*)^T$, with $v^* = [v_x^*, v_{y,}^* v_z^*]^T$ and $\omega^* = [\omega_x^*, \omega_y^*, \omega_z^*]^T$ defined as the linear and respectively the angular components of the speed refference that will be applied to the complex robotic system.

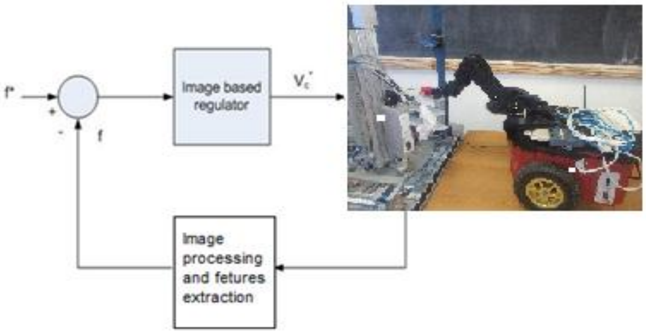

Fig. 3. Visual servoing system based closed loop control of the WMR with RM

Having into consideration the 6-dimensional vector that will define the robot's gripper positioning in the Cartesian coordinate system $s = [s_1, s_2, s_3, s_4, s_5, s_{6,}]^T$ and the current states of the joints of the manipulator, the Jacobian matrix will be defined as:

$$J_r = \begin{bmatrix} \frac{\delta s_1}{\delta q_1} & \frac{\delta s_1}{\delta q_6} \\ \cdot & \\ \cdot & \\ \cdot & \\ \frac{\delta s_6}{\delta q_1} & \frac{\delta s_6}{\delta q_6} \end{bmatrix}, \tag{4}$$

For applying the defined v_c^* signal to the joint of the robotic system it has to be transposed from the Cartesian space into the space of the joints of the robot. This transformation will be made using the Jacobian inverse matrix, J_r^{-1}.

IV. INTERACTION MATRIX COMPUTATION FOR MOMENTS OF THE IMAGE

In order to generate the control law for a visual servoing system there is used a specific mathematical analysis tool known as the interaction matrix or Jacobian matrix. This matrix needs to fulfil a series of properties in order to obtain the optimal behaviour for a visual servoing system, and these main features are described in [18]. There is a direct dependency between the performance of the matrix and the choosing of the visual features that are to be used in the application. First the interaction matrix should be non-singular and also, for disconnecting the components of the robot joint's velocities, the matrix should be diagonal.

Using the definition for image moments of $i + j$ order described in (3) the analytical form for time variation, $\dot{m}_{ij}$, cand be writen, which depends on the video sensor's speed:

$$\dot{m}_{ij} = L_{m_{ij}} v_c \tag{5}$$

Next equation (1) is used, by applying Green's theorem, and noting $h(x, y) = x^i y^j I(x, y)$, the time variation of m_{ij}, moments will have the following analytical form:

$$\dot{m}_{ij} = \iint_D \left[\frac{\partial h}{\partial x}\dot{x} + \frac{\partial h}{\partial y}\dot{y} + h(x, y)\left(\frac{\partial \dot{x}}{\partial x} + \frac{\partial \dot{y}}{\partial y}\right)\right] dxdy, \tag{6}$$

Assuming that the object is plane, the position of the object relatively to the coordinate system of the video sensor will be described using the following 1st order equation:

$$Z = \alpha X + \beta Y + Z_0 \tag{7}$$

where Z_0 will represent the distance between the object of interest and the video sensor.

Next, using the equations for perspective projection $x = \frac{X}{Z}$ and $y = \frac{Y}{Z}$, equation (7) will have the next form:

$$\frac{1}{Z} = Ax + By + C \tag{8}$$

with parameters: $A = -\frac{\alpha}{Z_0}$, $B = -\frac{\beta}{Z_0}$ and $C = \frac{1}{Z_0}$.

According to the velocity, $v_c = [v_x, v_y, v_z, \omega_x, \omega_y, \omega_z]^T$, can be deduced an analytical form for a point feature of coordinates (x, y) time variation:

$$\begin{cases} \dot{x} = -\frac{v_x}{Z} + x\frac{v_z}{Z} + xy\omega_x \\ \quad -(1 + x^2)\omega_y + y\omega_z \\ \dot{y} = -\frac{v_y}{Z} + \frac{yv_z}{Z} + (1 + y^2)\omega_x \\ \quad -xy\omega_y - x\omega_z \end{cases} \tag{9}$$

The next step is to replace (8) in (9) and the system resulting is described in (10):

$$\begin{cases} \dot{x} = -(Ax + By + C)v_x + x(Ax + By + C)v_z \\ \quad +xy\omega_x - (1 + x^2)\omega_y + y\omega_z \\ \dot{y} = -(Ax + By + C)v_y + y(Ax + By + C)v_z \\ \quad +(1 + y^2)\omega_x - xy\omega_y - x\omega_z \end{cases} \tag{10}$$

After deriving the two equations relative to x and y will result:

$$\begin{cases} \frac{\partial \dot{x}}{\partial x} = -Av_x + (2Ax + By + C)v_z \\ \qquad +y\omega_x - 2x\omega_y \\ \frac{\partial \dot{y}}{\partial y} = -Bv_y + (Ax + 2By + C)v_z \\ \qquad +2y\omega_x - x\omega_y \end{cases} \tag{11}$$

Next, after computing the partial derivatives relative to x and y for the function $h(x,y)$, $\frac{\partial h}{\partial x} = ix^{i-1}y^j I(x,y)$ and $\frac{\partial h}{\partial y} = jx^i y^{j-1} I(x,y)$ and by replacing (10) and (11) in (6), the time variation of the (i+j) order moments $\dot{m}_{ij}$ is obtained:

$$\dot{m}_{ij} = \iint_D \left\{ ix^{i-1}y^j \begin{bmatrix} -(Ax + By + C)v_x \\ +x(Ax + By + C)v_z \\ +xy\omega_x - (1 + x^2)\omega_y \\ +y\omega_z \end{bmatrix} + jx^i y^{j-1} \begin{bmatrix} -(Ax + By + C)v_y \\ +y(Ax + By + C)v_z \\ +(1 + y^2)\omega_x \\ -xy\omega_y - x\omega_z \end{bmatrix} + x^i y^j \left[-Av_x - Bv_y + (3Ax + 3By + 2C)v_z + 3y\omega_x - 3x\omega_y \right] \right\} I(x,y)dxdy \tag{12}$$

Following equation (12) will result the analytical form of the interaction matrix $L_{m_{ij}} = \left[m_{v_x}, m_{v_y}, m_{v_z}, m_{\omega_x}, m_{\omega_y}, m_{\omega_z} \right]$ for the m_{ij} moments:

$$\begin{cases} m_{v_x} = -i\left(Am_{ij} + Bm_{i-1,j+1} + Cm_{i-1,j}\right) \\ \qquad -Am_{ij} \\ m_{v_y} = -j\left(Am_{i+1,j-1} + Bm_{ij} + Cm_{i,j-1}\right) \\ \qquad -Bm_{ij} \\ m_{v_z} = (i + j + 3) \\ \quad * \left(Am_{i+1,j} + Bm_{i,j+1} + Cm_{ij}\right) - Cm_{ij} \\ m_{\omega_x} = (i + j + 3)m_{i,j+1} + jm_{i,j-1} \\ m_{\omega_y} = -(i + j + 3)m_{i+1,j} - im_{i-1,j} \\ m_{\omega_z} = im_{i-1,j+1} - jm_{i+1,j-1} \end{cases} \tag{13}$$

Next, after assuming a set of moments for the image having the form $f = [x_n, y_n, a_n, \tau, \xi, \alpha]^T$ and processing equation (13), will result the interaction matrix for the moments of the image defined by n points:

$$L_f = \begin{bmatrix} -1 & 0 & 0 & a_n e_{11} & -a_n(1 + e_{12}) & y_n \\ 0 & -1 & 0 & a_n(1 + e_{21}) & -a_n e_{11} & -x_n \\ 0 & 0 & -1 & -e_{31} & e_{32} & 0 \\ 0 & 0 & 0 & \tau_{\omega_x} & \tau_{\omega_y} & 0 \\ 0 & 0 & 0 & \xi_{\omega_x} & \xi_{\omega_y} & 0 \\ 0 & 0 & 0 & \alpha_{\omega_x} & \alpha_{\omega_y} & -1 \end{bmatrix} \tag{14}$$

V. PROPORTIONAL CONTROL LAW

Assuming f a set of visual features and the associated vector $r(t)$ defining the state at time t regarding the video sensor relative to the workspace, equation (15) will define the features variation $f(r(t))$, reported on the relative movement between the workspace and the video camera:

$$\dot{f} = \frac{\partial f}{\partial r}\frac{\partial r}{\partial t} + \frac{\partial f}{\partial t} = L_f v_c + \frac{\partial f}{\partial t} \tag{15}$$

Next, if the object will be static, $\frac{\partial f}{\partial t} = 0$, because the time variation of the features reporting to the object's motion is 0 and the next form of equation (15) is obtained:

$$\dot{f} = L_f v_c \tag{16}$$

where L_f represents the interaction matrix and has the form described in equation (14) and v_c is the vector describing the relative speed between the object and the video sensor.

For describing the control law, is needed to define an error function between the target features f* and the current features f:

$$e = f - f^* \tag{17}$$

After that, while ignoring the dynamics of the manipulator, v_c^*, which is the control signal applied to the manipulator's controller will be equal to v_c:

$$\dot{f} = L_f v_c^* \tag{18}$$

Next, combining equations (17) and (18) the time variation of the error will have the following analytical form:

$$\dot{e} = L_f v_c^* \tag{19}$$

The variance of the error should be exponentially negative decreasing in order to obtain good results for controlling the manipulator. Thus, $\dot{e} = -\lambda e$, so $\dot{e} = L_f v_c^* = -\lambda e$, and equation (19) becomes:

$$v_c^* = -\lambda L_f^+ e \tag{20}$$

L_f^+ cand be defined as the generalized inverse of the interaction matrix and can be computed by the equation: $L_f^+ = \left(L_f^T L_f\right)^{-1} L_f^T$. But, because of the uncertainties of the distances regarding the video sensor and the objects in the workspace in the Z-axis, it is very hard to determine this matrix and it has to be estimated, becoming $\widehat{L_f^+}$. The estimation of this matrix can be done using different methods. One of this methods is shown in [12] and it is estimated by the pseudo inverse of the target features interaction matrix $\widehat{L_f^+} = {L_f^*}^+$,because this matrix will remain constant during the entire control algorithm. Also in [19] there is an approach on estimating the matrix and $\widehat{L_f^+} = \frac{1}{2}(\mathrm{L_f} + \mathrm{L_f^*})^+$. In this case the control lay will be:

$$v_c^* = -\frac{1}{2}\lambda(\mathrm{L_f} + \mathrm{L_f^*})^+ e \qquad (21)$$

VI. REAL TIME CONTROL OF A COMPLEX AUTONOMOUS SYSTEM SERVICING A P/RML

The complex autonomous system will be composed by the flexible mechatronic line Festo MPS200, serviced by the Pioneer 3-DX autonomous robot which has mounted a RM. As shown in [8], the real time control of this system is based on two loops: one is the control loop writen in S7-300 PLC's for controling the mechatronic line and the second one is the control loop for the autonomous robotic system, using the control law by visual servoing defined above.

These two loops are communicating through a process computer, following the block diagram shown in Fig. 4. By using some specific programming environments like Microsoft Visual Studio an Matlab, this compter controls the WMR and RM.

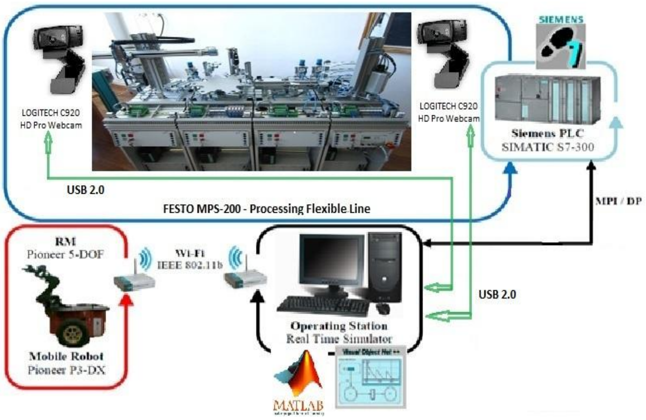

Fig. 4. Communication blockset for P/RML in real-time control using fixed visual servoing system

Fig. 4 shows the communication between the application used for the autonomous system control and the mobile robot which is done based on a TCP/IP protocol. On this process computer there also connected two HD fixed video cameras, one above the scrap pieces deposit and the other one at the beginning of the processing line.

Using the specialised image processing toolbox from Matlab and the control law defined above, is implemented the synchronizing between the two loops, and the control of the WMR with RM servicing the P/RML, in the case of recovering scrap pieces.

Fig. 5 and Fig. 6 show some results while executing the real time control loop of the visual servoing system, when servicing the mechatronics line.

For the next part, in order to improve the transport time and to be more efficient on using the existing resources, a new robot and a new fixed manipulator has been integrated with the P/RML in order to transport and return the scrap piece for reprocessing. The new idea here is to use the eye-in-hand configuration thus a mobile servoing system for recovering the piece from the transport robot PeopleBot.

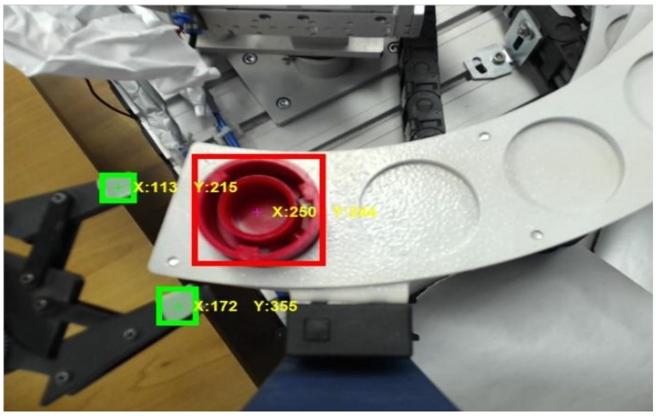

Fig. 5. Image from the real-time control of the WMR with RM during of caching the work piece for reprocessing or rebuting

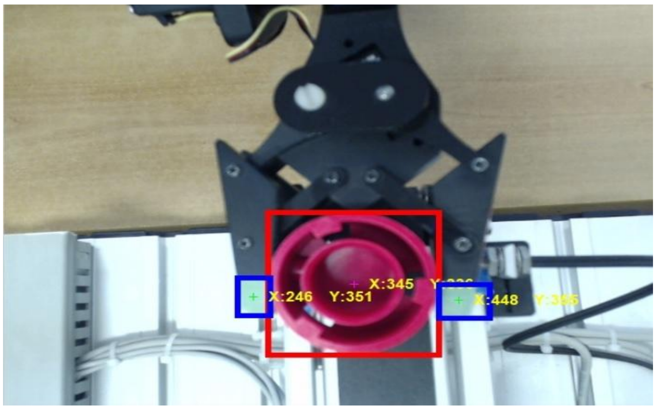

Fig. 6. Image from the real time control of the WMR with RM during of returning the work piece for reprocessing or rebuting.

The fixed manipulator used in this section is Cyton Gamma 1500 which has mounted on the effectors a web camera. Fig. 7 shows the communication block set of the concept.

The command of the manipulator is done using the inverse kinematic and the control law defined in (21), by analyzing the current and desired position of the manipulator regarding the target object. In Fig. 8 is shown an image while the visual servoing system is operating for recovering the piece.

VII. CONCLUSIONS

This paper presents a visual servoing system based on moments of image, which are the features that have been chosen after an analysis for an optimal control of the WMR with RM while servicing the P/RML. For fulfilling the task, the proportional control law has been computed, for both of the video sensors that are used in the application. The model of the processing line, which has been developed previously using Hybrid Petri Nets, has been tested in this paper using a real-time control implementation collaborating with the WMR.

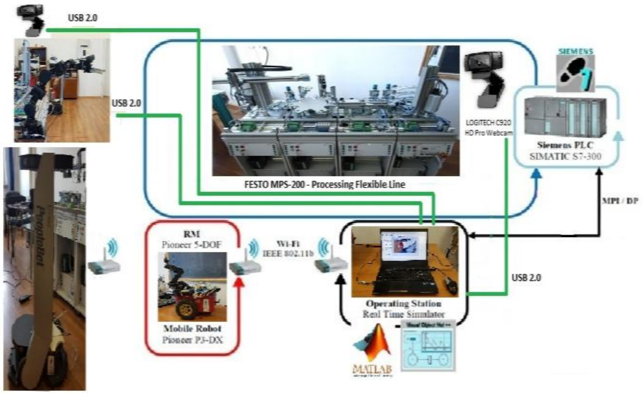

Fig. 7. Communication blockset for P/RML in real-time control using fixed and mobile visual servoing systems

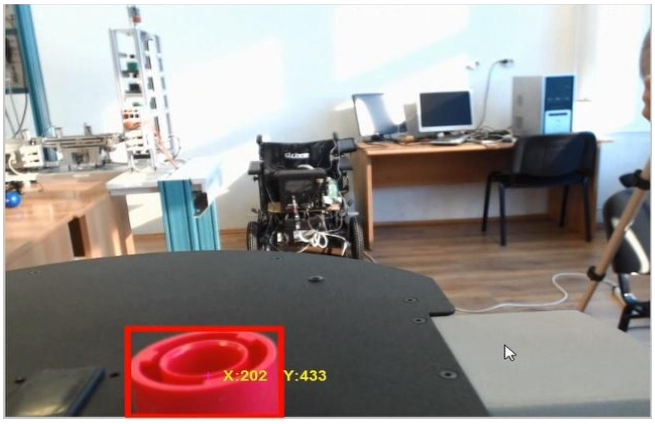

Fig. 8. Piece recovering using mobile visual servoing

This kind of applications fits very well and brings a big development to processes in metallurgy, car building industry, assembly of modular work pieces, etc. The most common applications are developed with fixed manipulators, positioned in a strategic place for servicing the lines. This study tries to extend the flexibility of this king of manufacturing lines by integrating complex autonomous systems.

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