Robot manipulator applied to bottle filling processes: an approach in the teaching-learning process

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Latacunga

Robot Manipulator Applied to Bottle Filling Processes: An Approach in the Teaching-Learning Process

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Abstract. In this paper, a position-based visual servo control scheme for a bottle packaging process using the ScorBot-ER-4U robot manipulator is proposed. The control scheme considers the eye-to-hand configuration and is based on the kinematic model of the manipulator robot and the perspective projection model of the vision camera (Pinhole Model). The proposed scheme was evaluated on a virtual environment developed in the Unity3D graphics engine; and experimentally with the ScorBot-ER-4U manipulator robot and the ZED 2 stereo vision camera. Finally, it is concluded that the results obtained by simulation and experimentally show that the control errors converge to zero asymptotically.

Keywords: Virtual reality, robot manipulator, visual servo control, ScorBot-ER-4U

1 Introduction

The world has gone through various challenges, such as wars, natural disasters and pandemics [1]. The covid-19 pandemic was declared in March 2020 by the World Health Organization (WHO), initiating mandatory isolation due to the significant increase in infections and its high risk of mortality, causing the closure of schools [2]. As a result, the educational system has evolved significantly by leaps and bounds due to the crisis that has arisen, providing various alternatives by developing multiple methodologies that contributed to the teaching-learning process through the use of simulators as training systems and preparation of previous knowledge [3][1]. Therefore, the scientific community has developed different technological alternatives focused on minimizing the effects produced by isolation between students and teachers at different levels of education. Among the most representative advances is the design of educational applications in virtual reality environments, using the Unreal Engine and Unity3D graphics engines. The Unity 3D graphics engine created by the company Unity Technologies was originally created for the development of video games [4][2]; however, it is currently used for the development of new applications with focus on the area of education and robotics [5].

From the area of industrial automation, the implementation of robotic systems in the manufacture of different processes is essential, by virtue of the significant increase in production and minimizing the cost, thus achieving a more competitive industry

[6]. For the execution of a robotic system in industrial processes, it is necessary to implement advanced control algorithms. Among the different control techniques can be classified into: *(i) Control based on proprioceptive sensors*, are based on control algorithms that consider the feedback of the position and velocity of each of the joints of the robotic system [7][3]; *(ii) Exteroceptive sensor-based control*, is based on the implementation of sensors that perceive the environment in which the robotic system is executing a task. Among the most commonly used are the force-torque sensor, and vision sensors [7]. Among the control techniques that consider the incorporation of a vision sensor are: *(a) Handheld camera:* this consists of positioning the camera in the final link of the robot in such a way that it maintains the visibility of the target, avoiding obstructions of the object receiving the direct information of the image, it must be considered that this methodology will depend on the movements made by the robot [8]; *(b) Handheld camera:* it is based on the placement of the camera at a fixed point allowing to obtain a better visibility of both the object, robot and the working space [9].

As described in previous paragraphs, this work proposes a virtual training system focused on providing methodologies and educational alternatives in the teaching-learning process in the area of industrial robotics. The system consists of a virtual industrial work environment and the Scorbot-ER-4U robot that simulates a bottle packaging process. Therefore, it requires the digitalization of the elements that are part of the system, being developed through the use of CAD software. The dimensioning of the robot and its joints refers to the real one developed in SolidWorks and then exported to the Unity3D graphic engine. Therefore, by obtaining mathematical models that determine the characteristics and restrictions of movement of the articulated robot and the implementation of control algorithms within a virtual process. The implementation of position-based control is based on vision sensors at a fixed point, capturing greater visibility of the work area (handheld camera). Finally, the results obtained from the simulation and experimental phases are analyzed in order to validate the proposed control scheme.

The following document consists of five sections including the Introduction. Section 2 details the methodology implemented for the bottle packaging process. The methodology contemplates the development of a simulation environment and the experimental implementation of the proposed control scheme. Section 3 describes the modeling of the ScorBot-ER-4U manipulator robot and the Pinhole Model. In addition, the proposed position-based visual servo control scheme is presented. Section 4 presents the results obtained from both the simulation in the Unity3D graphics engine and the experimental tests performed with the ScorBot-ER-4U manipulator robot. Finally, conclusions are presented in Section 5.

2 Methodology

This section presents the virtualization of the industrial process, which is divided into four main stages, as shown in Figure 1: *(i) Virtual Environment*, this stage is in charge of digitizing the real resources, robot, user and industrial environment, in order to interact in a virtual scenario that simulates the bottle filling process; *(ii) Graphics engine*, responsible for generating an interactive and immersive virtual environment, in order to "trick" the user's senses for a better teaching-learning process; *(iii) Controller*, through the mathematical model and the implementation of a closed-loop control algorithm, it will be possible to execute autonomous bottle packaging tasks. Finally, *(iv) Experimentation*, this stage allows experimental evaluation of the proposed control scheme.

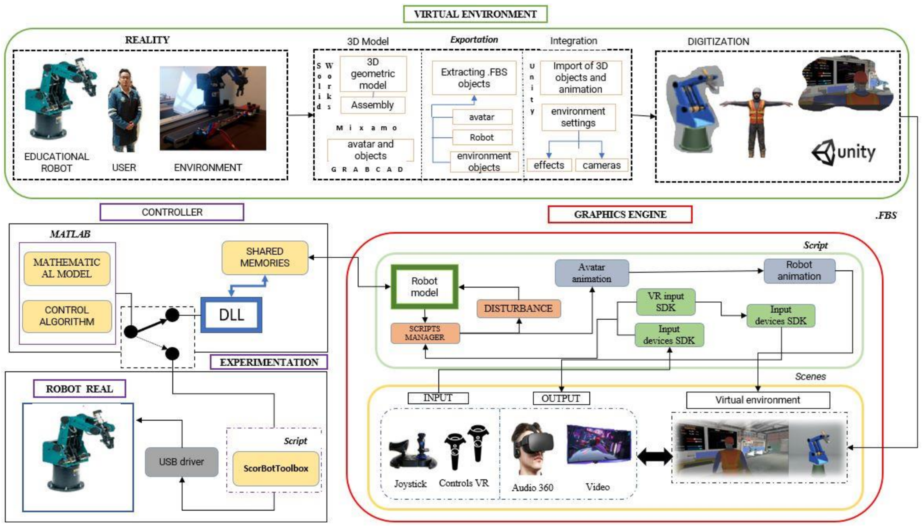


Figure 1: Digitization Scheme

A. Digital Resources

This stage considers the digitization of the external resources, in order to be incorporated into the 3D virtual scene. Three relevant resources are considered for digitization: *(i) Virtualized robot*, is associated with the 3D geometric model which is assembled in SolidWorks. The digitization takes into account the actual dimensions and motion characteristics of the ScorBot-ER-4U [4]. The virtualized robot must be exported as a file. FBS, extension compatible with the libraries of the Unity 3D graphics engine; *(ii) Virtualized scenario*, is related to the digitalization of industrial environments related to bottle packaging. For the digitization, photography, videos and other resources that allow the development of a realistic environment are considered; *(iii) User*, can be represented as a person or operator depending on the virtual environment, taking into account the anthropomorphic aspect of the human being (gender), who will be contributing to the virtualized scenario. The avatar can be acquired by the support platforms (Mixano, GrabCad) having a wide variety of designs for its corresponding scene.

B. Graphics engine

The main contribution of this subsection is the interaction between human-machine, since having a digitized environment can be easily and intuitively interconnected with the simulator; allowing the user to visualize the evolution of the program. The graphics engine is divided into two groups: *(i) Scenes*, is represented by an environment developed with 3D scenes intended to have certain proposed applications to be simulated such as robotic assistance. In addition, a user interface is incorporated for the avatar to interact with the robot when implementing the control algorithms. To give greater realism and interaction with the virtual environment, the incorporation of virtual input and output devices is considered, in order to manage the parts that make up the scene, effects, animation, lighting, movement of the robotic system and user interface; *(ii) Scripts,* it is the main part because without its interaction it will not be able to give functionality to the developed virtual environment. Through the scripts it is possible to emulate the behavior of the robotic system and avatars, as well as to manage the input and output SDK libraries of the virtual devices. In addition, it manages the bidirectional communication between the virtual environment and the mathematical software, through a dynamic link (DLL) allowing to generate a shared memory in RAM, thus having a data exchange.

C. Controller

At this stage, the implementation of a Position-based visual servo control scheme for bottle filling is considered. The handheld camera technique is considered, whereby the vision sensor is placed in a fixed position and orientation, capturing the working area where the bottles and the robot gripper are located. To determine the proper characteristics of the objects (bottle and clamp), image processing techniques are considered, in order to define the position of the objects in the image plane; for this purpose, the perspective projection model of a vision camera is considered. The control scheme is implemented in MATLAB software, which communicates in real time with the Unity3D software through the use of shared memories.

D. Experimentation

This section details the real experimentation that the robot will have once validated the correct operation of simulated form is considered that, to have real interaction with the robot, you need the toolbox libraries for movement of each joint of the robot, which through the mathematical model and the controller can perform autonomous tasks of packaging bottles.

3 Control Scheme

This section presents the constraints and motion characteristics of the Scorbot-ER-4U Robot (see Figure 2); and the perspective projection model of a vision sensor (see Figure 3). In addition, the proposed at this stage, the implementation of a position-based visual servo control scheme for bottle filling is considered scheme is described, in order to execute autonomous tasks for bottle packaging.

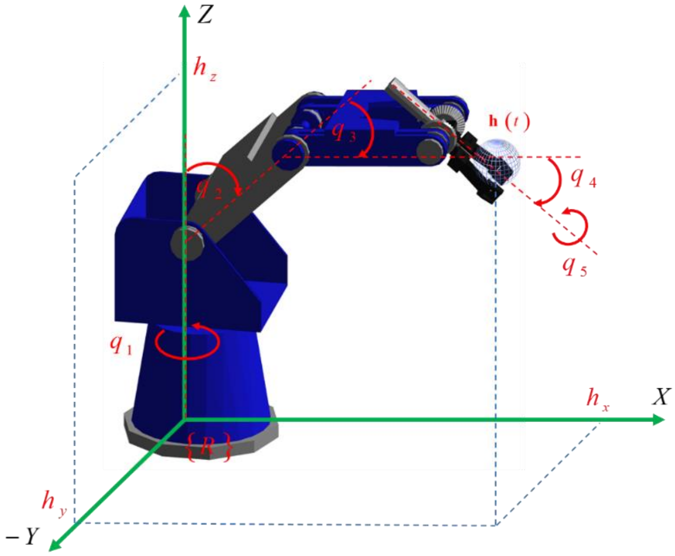


Figure 2: Robotic arm ScorBot-ER-4U

3.1. Kinematic model

The Scorbot-ER-4U robot is a 5DOF anthropomorphic robot plus gripper. Kinematic modeling allows the determination of the robot motion constraint and the location of the end effector $\mathbf{h}(t) = f(\mathbf{q})$ in reference to a static coordinate system $\{R\}$, located at the base of the robot [5]. The instantaneous kinematic model is determined by the derivative of the end-effector location with respect to the robot configuration.

$$\dot{\mathbf{h}}(t) = \frac{\partial f(\mathbf{q})}{\partial \mathbf{q}} \dot{\mathbf{q}}(t)$$

(1)

where $\dot{\mathbf{h}} = [\dot{h}_1 \ \ \dot{h}_2 \ \ .... \ \ \dot{h}_m]^T$ represents the velocity vector of the end effector; $\dot{\mathbf{q}} = [\dot{q}_1 \ \ \dot{q}_2 \ ......\dot{q}_n \ ]^T$ symbolizes the angular velocity vector of each joint. Considering $\mathbf{J}(\mathbf{q}) = \frac{\partial f}{\partial \mathbf{q}}(\mathbf{q})$ in (1), is held:

$$\dot{\mathbf{h}}(t) = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}(t) \tag{2}$$

where, $\mathbf{J}(\mathbf{q}) \in \Re^{m \times n}$ represents the Jacobian matrix of the manipulator robot [5].

3.2. Perspective Projection Model

To implement a position-based visual servo scheme, it is essential to know the geometric aspects by which the image is constituted, thus allowing the definition of the perspective projection model (Pinhole Model), to be implemented in a vision-based control scheme. [5].

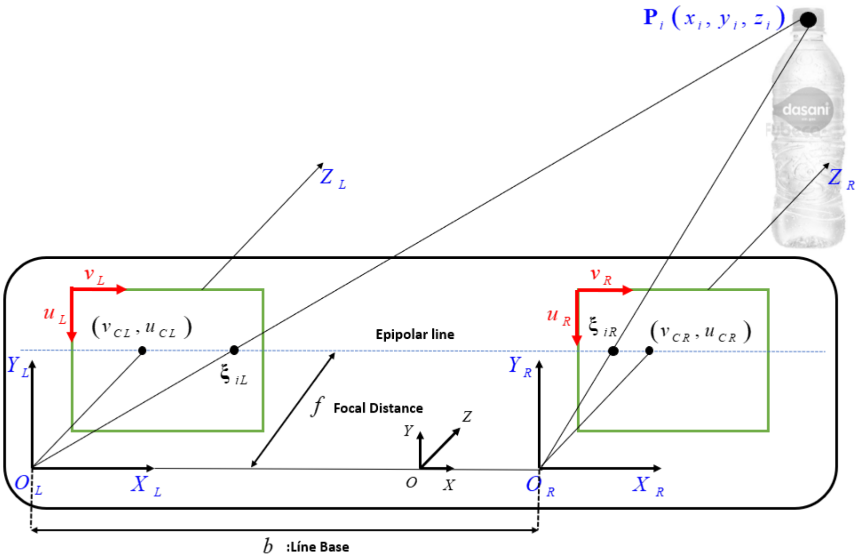


Figure 3: Perspective projection model (aligned cameras).

The Pinhole model is based on a point $\mathbf{P}_i = [x_i \;\; y_i \;\; z_i]^T$ and an optical center where the different projection rays converge. The image plane is located at a certain focal distance from the optical center, and is perpendicular to the axis Z [5].

The subscripts L and R refer to the definitions related to the camera located on the left and right side, respectively. The points $\xi_{iL}(v_{iL}, u_{iL})$ and $\xi_{iR}(v_{iR}, u_{iR})$ represent the projection of the object point $\mathbf{P}_i(x_i \;\; y_i \;\; z_i)$ on the image plane; $\xi_{CL}(v_{CL}, u_{CL})$ and $\xi_{CR}(v_{CR}, u_{CR})$, respectively, represents the pixel coordinates of the optical center of the image plane for the left and right side of each lens; b represents the distance between the right and left camera lenses, as shown in Figure 3. It is considered that the focal length f of each mink chamber are equal. Therefore, the following expressions are obtained:

$$\frac{f}{z_i} = \frac{(v_{iL} - v_{CL})}{x_i} = \frac{(v_{iR} - v_{CR})}{x_i - b} = \frac{(u_{CL} - u_{iL})}{y_i} = \frac{(u_{CR} - u_{iR})}{y_i} \tag{3}$$

To determine the coordinates of the point $\mathbf{P}_i(x_i \;\; y_i \;\; z_i)$ in Cartesian space is considered a geometric relation of similarity of triangles:

$$x_i = \frac{(v_{iL} - v_{CL})b}{d - (v_{CL} - v_{CR})} ; y_i = \frac{(u_{CL} - u_1)b}{d - (v_{CL} - v_{CR})} ; z_i = \frac{fb}{d - (v_{CL} - v_{CR})} ; d = v_{iL} - v_{iR}$$

(4)

where, the disparity between images is denoted as $d = (v_{iL} - v_{iR})$ which is inversely proportional to the depth Z .

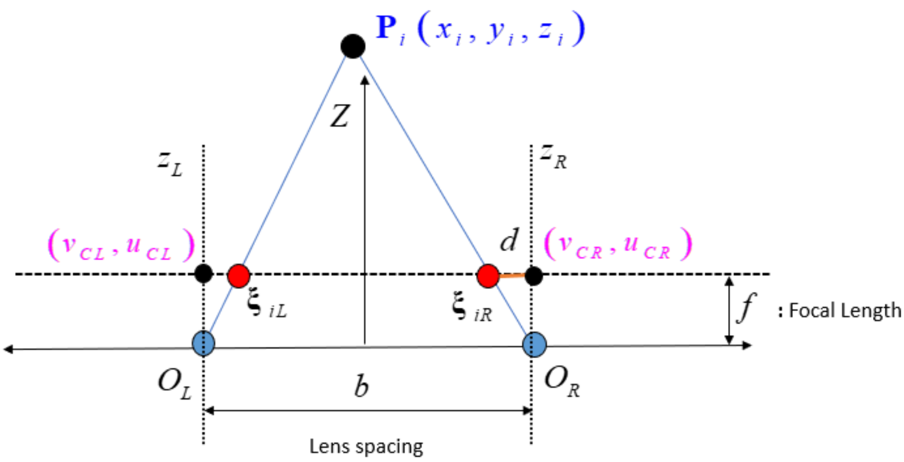


Figure 4: Representation of the stereo projection.

From Figure 4 it is possible to represent the relationship between distance and depth. To determine the position of the point $\mathbf{P}_i(x_i \;\; y_i \;\; z_i)$ in three-dimensional space. It is necessary to have the intrinsic and extrinsic parameters for the camera and identifying that same focused point in each image plane. It is worth mentioning that the point $\mathbf{P}_i(x_i \;\; y_i \;\; z_i)$ will focus at the same height on both image planes:

$$u_L - u_{CL} = u_R - u_{CR} \tag{5}$$

Therefore, it can be deduced that, if the cameras are aligned and the optical center is in the same position, it can be concluded that the coordinates in space of the point $\mathbf{P}_i(x_i \;\; y_i \;\; z_i)$ are:

$$\begin{cases} x_i = \frac{b}{d}\left(v_L - v_{CL}\right) \\ y_i = \frac{b}{d}\left(u_{CL} - u_L\right) \\ z_i = \frac{fb}{d} \end{cases} \quad (6)$$

3.3. Control Scheme

This section presents the design of the Position-based visual servo control algorithm based on the eye-to-hand configuration. The position and orientation of the camera is fixed, with respect to the reference system $\{R\}$, located at the base of the manipulator robot.

Image processing is used to extract the image characteristics of the objects and to obtain the position of the operating end of the manipulator robot and the position of the bottle with respect to the viewing camera, see Figure 5.

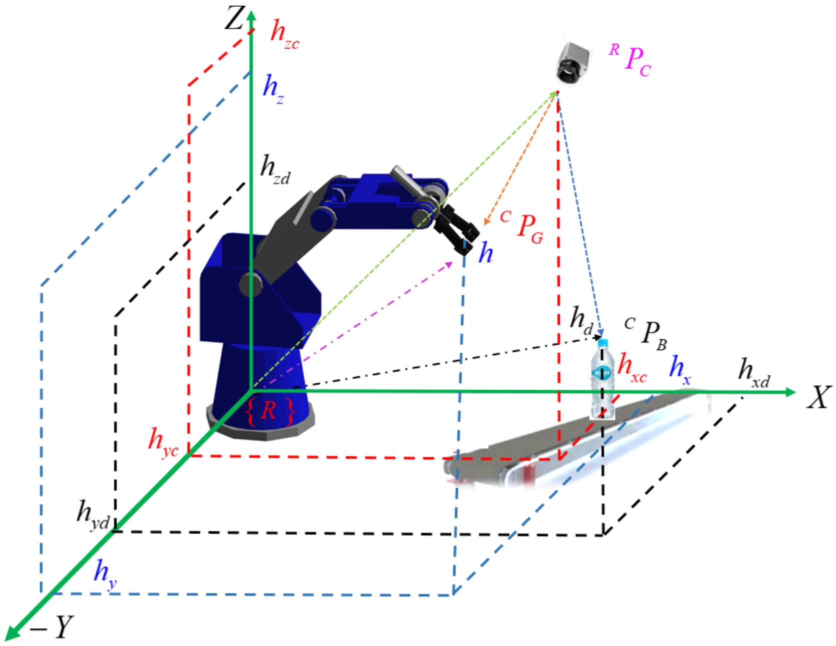


Figure 5: System of reference.

From Figure 5 we can determine the position of the operating end and the position of the bottle with respect to the reference system $\{R\}$.

$$\mathbf{h_d}(t) = {}^{\mathbf{R}}\mathbf{P_B}(t) = {}^{\mathbf{R}}\mathbf{P_C} + {}^{\mathbf{C}}\mathbf{P_B}(t) \quad (7)$$

$$\mathbf{h}(t) = {}^{\mathbf{R}}\mathbf{P_G}(t) = {}^{\mathbf{R}}\mathbf{P_C} + {}^{\mathbf{C}}\mathbf{P_G}(t) \quad (8)$$

The proposed Position-based visual servo control scheme for bottle packaging is presented in Figure 6.

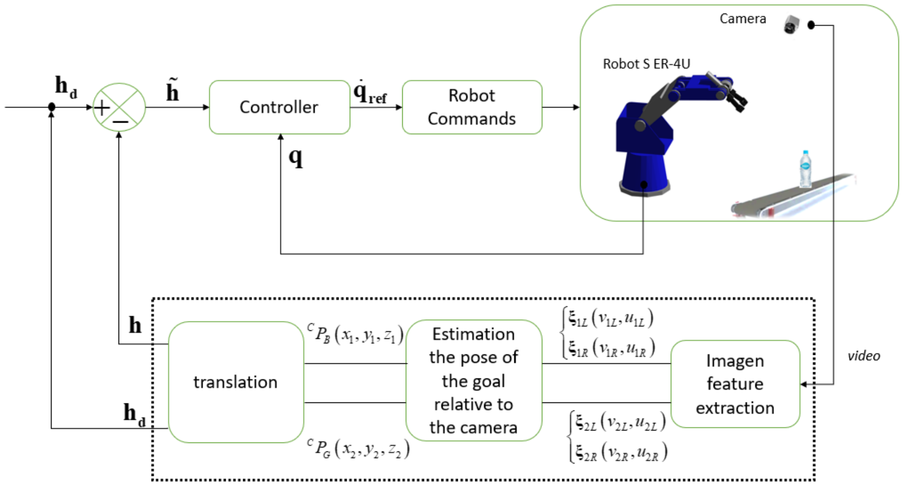


Figure 6: Position-based visual servo control: eye-to-hand configuration.

To obtain the solution of the position of the ScorBot-ER-4u robot to perform the task of the bottle packaging process, the following control law is proposed:

$$\dot{\mathbf{q}}_{\mathbf{ref}}(t) = \mathbf{J}^{\#}\left(\mathbf{\Gamma}\tanh\left(\mathbf{\kappa}\tilde{\mathbf{h}}\right)\right) + \left(\mathbf{I} - \mathbf{J}^{\#}\mathbf{J}\right)\mathbf{\Omega\eta} \tag{9}$$

where, $\mathbf{J}^{\#}$ represents the pseudo inverse matrix of $\mathbf{J}(\mathbf{q})$; $\mathbf{\Gamma} = diag\left(\Gamma_x, \Gamma_y, \Gamma_z\right)$ and $\mathbf{\kappa} = diag\left(\kappa_x, \kappa_y, \kappa_z\right)$ are positive definite matrices weighing the control errors; the control error is defined by $\tilde{\mathbf{h}}(t) = \mathbf{h_d} - \mathbf{h}$; $\mathbf{\Omega} = diag\left(\Omega_{q1}, \Omega_{q2}, \ldots \Omega_{q5}\right)$ is a positive definite matrix weighing the null space vector; $\mathbf{\eta}(t)$ represents the secondary control objective. The first term of equation (9) describes the main task of the operating end of the manipulator robot. The second term defines the proper motion of the manipulator robot in which the matrix $\left(\mathbf{I} - \mathbf{J}^{\#}\mathbf{J}\right)$ project an arbitrary vector $\mathbf{\eta}(t)$ in the null space of the Jacobian matrix $\mathbf{J}(\mathbf{q})$ of the robot manipulator, so that the secondary control objectives do not affect the main task of the robot manipulator. Therefore, any value given to $\mathbf{\eta}(t)$ will only affect the internal structure of the manipulator robot, but not the final control of the operating end. For this work, the internal configuration of the robot will be considered as secondary objectives; therefore,

$$\mathbf{\eta}(t) = [q_{1d} - q_1 \quad q_{2d} - q_2 \quad q_{3d} - q_3 \quad q_{4d} - q_4 \quad q_{5d} - q_5]^T \in R^5 \tag{10}$$

where q_{id} at $i = 1, 2, ..5$ represents the desired position of each joint of the robot manipulator; and q_i is the current position of each joint of the manipulator robot.

On the other hand, in order to determine the evolution of the control error $\tilde{\mathbf{h}}(t)$ stability is analyzed through the Lyapunov theory. We consider with Lyapunov candidate function $V(\tilde{\mathbf{h}}) = \frac{1}{2}\tilde{\mathbf{h}}^T\tilde{\mathbf{h}}$, where the first derivative is:

$$\dot{V}(\tilde{\mathbf{h}}) = \tilde{\mathbf{h}}^T\dot{\tilde{\mathbf{h}}}\,. \tag{11}$$

Consider perfect speed tracking, *i.e.*, $\dot{\mathbf{q}}_{\mathbf{ref}}(t) \equiv \dot{\mathbf{q}}(t)$, the closed-loop equation is obtained from (1) and (9)

$$\dot{\tilde{\mathbf{h}}}(t) = -\mathbf{\Gamma}\,\mathbf{tanh}(\boldsymbol{\kappa}\tilde{\mathbf{h}}) \tag{12}$$

Replacing (12) in (11) we have

$$\dot{V}(\tilde{\mathbf{h}}) = \tilde{\mathbf{h}}^T\mathbf{\Gamma}\,\mathbf{tanh}(\boldsymbol{\kappa}\tilde{\mathbf{h}}) < 0 \tag{13}$$

If $\mathbf{\Gamma}$ and $\boldsymbol{\kappa}$ are positive definite matrices; hence, the control error converges to zero asymptotically, *i.e.*, one has asymptotically stable stability when time tends to infinity.

4 Analysis and Results

This Section presents the results obtained from the Position-based visual servo control scheme with handheld camera configuration. The section is divided into three main parts: *i) Simulation*, the results obtained from the control algorithm proposed in section 3 are presented; *ii) Image processing*, details the processing of obtaining the image characteristics of the bottle and the manipulator robot; and *iii) Experimental tests*, the results of the bottle filling process using the Position-based visual servo control technique are shown.

4.1 Simulation - Virtual environment

This subsection emphasizes the simulation of a pot-pot packaging process through an immersive and interactive virtual environment. The design of the work scenario considers mainly the digitization of the industrial environment, bottles, conveyor belt and the Scorbot-ER-4U robot manipulator, among others. The packaging process is divided into three main stages, see Figure 7: *i) Transportation*, at this stage, the bottles are moved on a conveyor belt until they are positioned inside the working area of the manipulator robot; *ii) Manipulation*, this stage considers positioning the end effector (gripper) of the manipulator robot at a close distance to the bottle, in order to perform the task of gripping and transporting the bottle from a conveyor belt to the points established for packaging. Finally, *iii) Packaging,* at this stage packaging usually involves placing the 6 bottles in a carton, which is then sealed and placed on a pallet for transport. This ensures that the bottles are protected during transit and can be easily moved around the production plant.

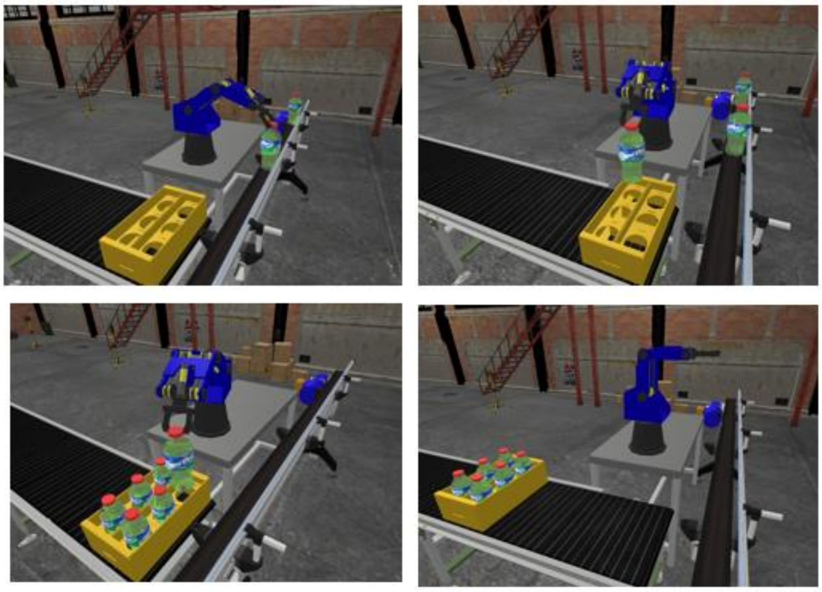


Figure 7: Virtual training system for a bottle filling process.

Figure 8 shows the results obtained from the behavior of the manipulator robot when performing bottle packaging tasks. The implemented control law is detailed in (9); for which, several desired end points of operation are considered according to the bottle packaging phase. The control error $\tilde{\mathbf{h}}(t) = \mathbf{h}_d - \mathbf{h}$ is defined as the difference between the desired positions of the operating endpoint $\mathbf{h_d} = [h_{xd} \quad h_{yd} \quad h_{zd}]$ and actual positions $\mathbf{h}(t) = [h_x \quad h_y \quad h_z]$. Figure 9 shows the control actions calculated by the control law (9), which allows describing the motion of the manipulator robot.

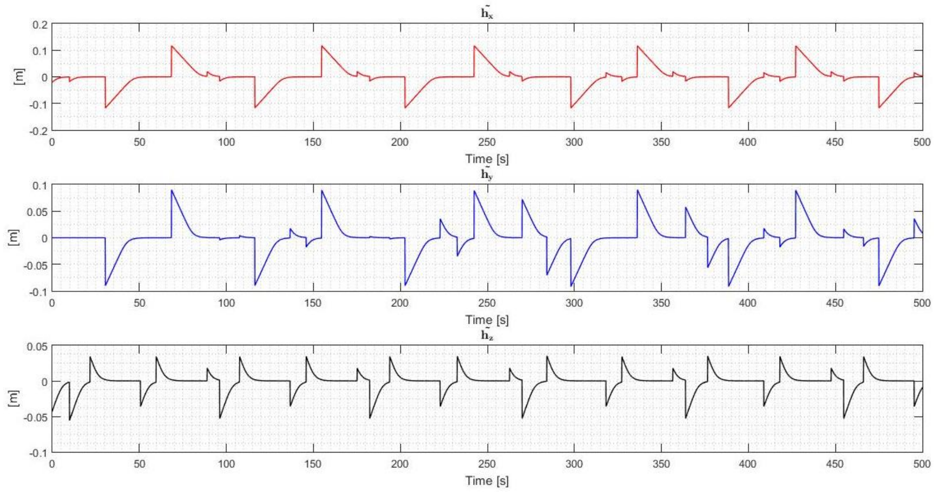


Figure 8: End-effector control errors of the manipulator robot

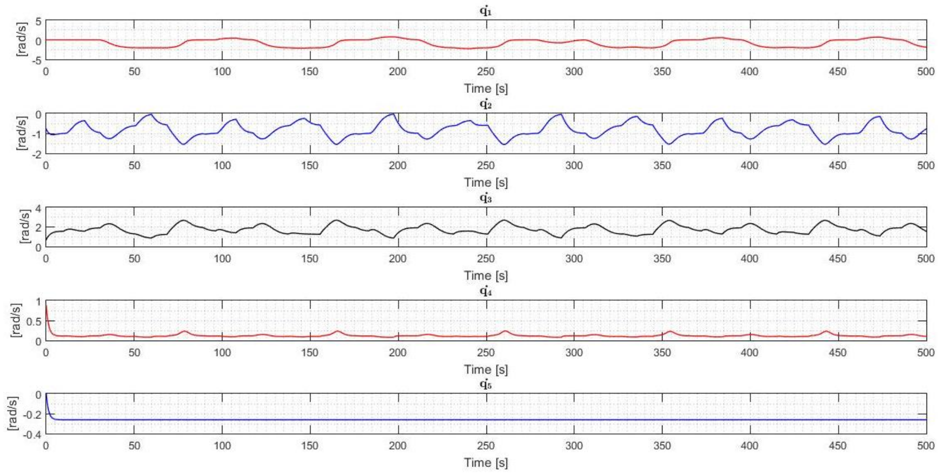


Figure 9: Control actions of the manipulator robot.

4.2 Image processing

The Position-based visual servo control process considers the ZED 2 camera, developed by STEREOLABS [6]. This camera uses two lenses to capture images from slightly different angles, which allows the creation of a 3D image, enabling the calculation of depth information. In this work, the Python programming language was considered for image processing. In the image processing is considered: *i)* object detection through neural networks; and *ii)* determination of the position of the detected objects with respect to the camera.

i) Object detection by neural networks

For the next item, the neural network SSD (Single Shot Detection) is a state-of-the-art object detection algorithm that uses an architecture based on Mobile Net. This architecture adds a few convolutional layers to extract as much information or features as possible from an image captured by a vision camera. The SSD network is capable of detecting objects in real time with high accuracy and speed, making it ideal for use in applications such as robotics. [7]. The Subsampling layers take all the information provided by the convolution by reducing the information they receive by taking the maximum or average value of the pixels in the region, generating a smaller area. Finally, the output layers link all the input neural networks with the outputs so that when image features are subtracted, they can be related to each other facilitating prediction, see Figure 10.

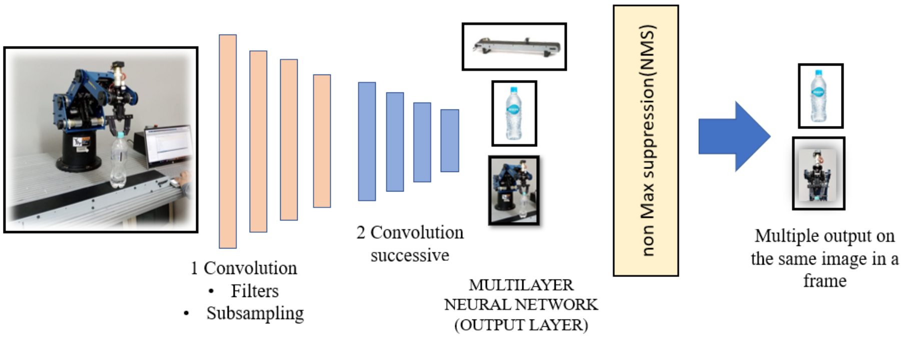


Figure 10: Neural network based on Mobile Net.

The NMS algorithm is a technique used in object detection to eliminate duplicate detections of the same object and obtain a single accurate bounding box. This algorithm works by comparing the confidence scores of the overlapping bounding boxes and suppressing those with lower scores, see Figure 11.

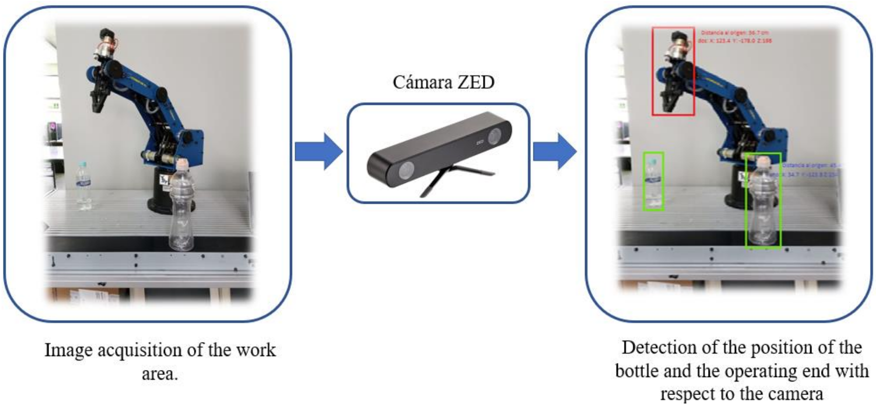


Figure 11: Detection of object position relative to the camera

ii) Position of detected objects with respect to the camera.

To determine the position of objects ${}^{C}P_{B}$ requires libraries that are included in the software development kit (SDK) specific to the ZED camera. The library (pyzed.sl) is included, in order to make use of the command (Point_Cloud_Value) that determines the position in the coordinates of the ZED camera. $\mathbf{P}_i\left(x_i, y_i, z_i\right)$ where the bottle is positioned with respect to the chamber ${}^{C}P_{B}\left(x_B, y_B, z_B\right)$ and the operating end with respect to the camera ${}^{C}P_{G}\left(x_G, y_G, z_G\right)$, see Figure 12,

a) Left lens b) Right lens

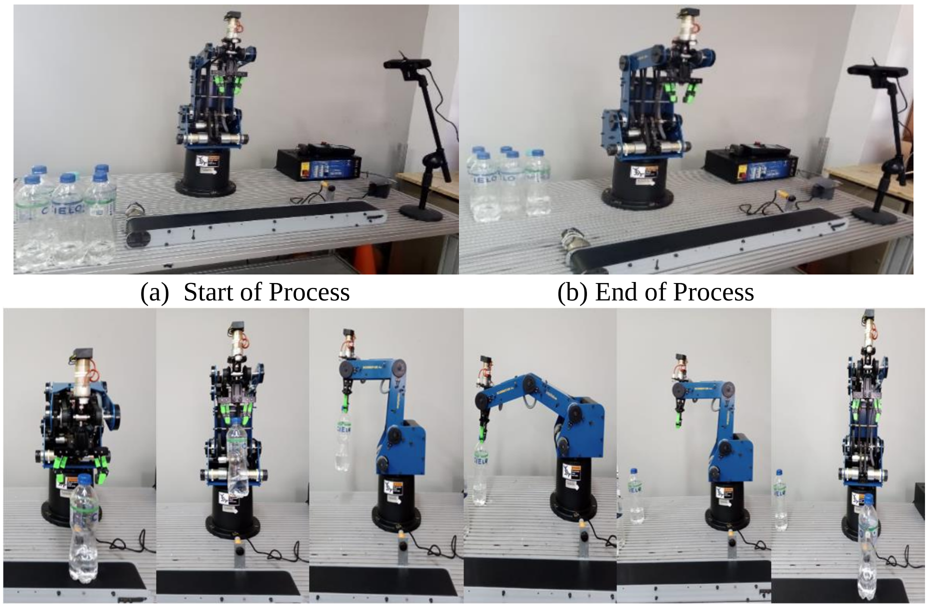
Figure 12: Object recognition through the ZED camera.

Finally, the position of the bottle and the operating end are sent to MATLAB via TCP/IP protocol; in order to implement the control algorithm for the autonomous bottle packing task.

4.3 Control Algorithm Implemented

This subsection considers the experimental implementation of the Position-based visual servo control scheme for the bottle packaging process using the ScorBot-ER-4U robot manipulator. For the implementation of the control scheme, the image processing of the previous subsection and the control law proposed in (9) are considered. The HOME configuration of the mobile manipulator robot is defined in $\mathbf{q} = [0,\ -0.785,\ 0.698,\ 0.873,\ 0]\left[\text{rad}\right]$; while the matrices weighing the control errors are: $\mathbf{\Gamma} = diag\left(0.8,\ 0.8,\ 0.8\right)$, $\mathbf{\kappa} = diag\left(0.5, 0.5, 0.5\right)$, $\mathbf{\Omega} = diag\left(0.95, 0.95, 0.95, 0.95, 0.95\right)$. While the null space vector is defined as: $\mathbf{\eta}\left(t\right) = \mathbf{\eta_d} - \mathbf{\eta}\left(t\right)$ with $\mathbf{\eta_d} = [0\ \ 1.047\ \ 0.524\ \ 0\ \ -0.262]^T\left[rad\right]$. A sampling period is considered for the execution of the task. $T_0 = 0.2[\text{s}]$.

Figure 13(a) represents the beginning of the process where the bottles are grouped at the end of the conveyor belt, to be later transported gradually until they are positioned in front of the operating end of the manipulator robot. Figure 13(b) shows the completion of the process, considering six-bottle packs for packaging. Finally, Figure 13(c) displays a sequence of images of the process.



(a) Start of Process (b) End of Process

$t = 10$ [s] $t = 20$ [s] $t = 30$[s] $t = 40$[s] $t = 55$[s] $t = 65$[s]

(c) Progressive process movements

Figure 13: ScorBot-ER-4U instant positions.

5 Conclusions

In this paper, a position-based visual servo control was implemented for a bottle packaging process using the Scorbot-ER-4U robot manipulator. The proposed control scheme considers the eye-to-hand configuration, in order to determine the position of the operating end of the manipulator robot and the position of the bottle to be manipulated. The control scheme was evaluated by simulation and experimentally. For the simulation tests, a virtual environment was developed in the UNITY3D graphics engine. Virtual environment that considered the digitization of a bottle packaging process. On the other hand, experimental laboratory tests were carried out with the Scorbot-ER-4U manipulator robot and the ZED 2 stereo vision camera. Finally, from the simulation and experimental tests, it was verified that the control errors converge to zero, according to the stability analysis performed with the Lyapunov theory.

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