



UNIVERSIDAD DE LAS FUERZAS ARMADAS ESPE

DEPARTAMENTO DE ELÉCTRICA, ELECTRÓNICA Y TELECOMUNICACIONES

CARRERA DE INGENIERÍA EN ELECTRÓNICA E INSTRUMENTACIÓN

**Artículo Académico Previo a la Obtención del Título de Ingeniero en
Electrónica e Instrumentación**

**CONTROL SERVO VISUAL DEL ROBOT SCORBOT-ER-4U PARA UN PROCESO DE
ENVASADO**

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Acceptance Letter - Future Technologies Conference 2023

Dear Jefferson S. Nuñez, Cristian P. Guilcazo, Jessica S. Ortiz, Víctor Hugo Andaluz Ortiz,

Congratulations! Your paper "Robot Manipulator Applied to Bottle Filling Processes. An Approach in the Teaching-Learning Process" has been accepted for oral presentation in the Future Technologies Conference 2023 to be held from 2-3 November 2023 in San Francisco, United States.

The Future Technologies Conference presents the best of current systems research and practice, emphasizing innovation and quantified experience. FTC has emerged as a renowned world-wide gathering of academic researchers, Ph.D. and graduate students, top research think tanks and industry technology developers.

Each of the manuscripts for this conference was reviewed based on the criteria of originality, significance, quality and clarity. We have followed double blind peer review process and each paper was reviewed by at least three regular PC members or two senior PC members.

Future Technologies Conference proceedings will be published in Springer series "Lecture Notes in Networks and Systems" (ISSN: 2367-3370) and submitted for consideration to Scopus, Web of Science, DBLP, INSPEC, WTI Frankfurt eG, zbMATH, SCImago.

You may now proceed with the registration process for publication and presentation of your paper at Future Technologies Conference 2023.

Online Registration: <https://saiconference.com/FTC>

Regards,
Supriya Kapoor
Conference Manager
Future Technologies Conference 2023
<https://saiconference.com/FTC>

Lecture Notes in Networks and Systems

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

Cristian P. Guilcazo, Jefferson S. Nuñez, Jessica S. Ortiz and Víctor H. Andaluz

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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

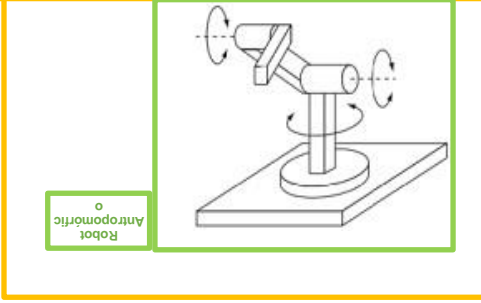
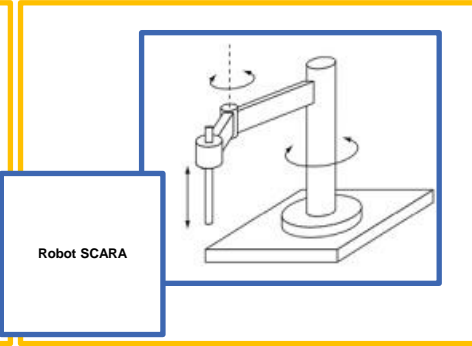
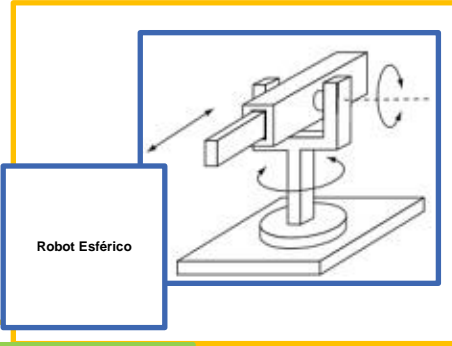
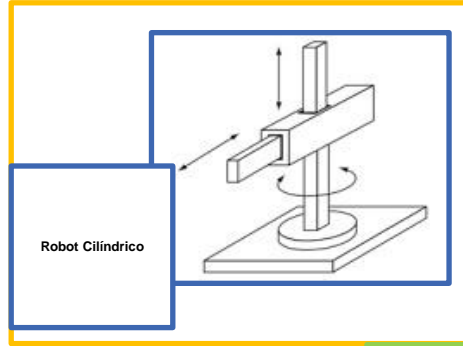
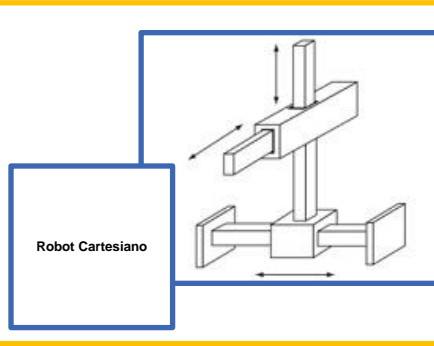
1 Introduction

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[1], [3]. 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[4]. The Unity 3D graphics engine created by the company Unity Technologies was originally created for the development of video games[2], [5]; however, it is currently used for the development of new applications with focus on the area of education and robotics[6].

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 [7].







Scorbot- ER-4U

OPERACIÓN CONTINUA Y TAREAS RIESGOSAS O DIFÍCILES

Maniobrabilidad



Se asemeja a un brazo humano (Tareas repetitivas y peso)



DIVERSIDAD DE APLICACIONES



Envasado de botellas

INDUSTRIA



Robótica inteligente

EDUCACIÓN



Hematología clínica

MEDICINA



Clasificación de Hortalizas

AGRICULTURA




Estación espacial

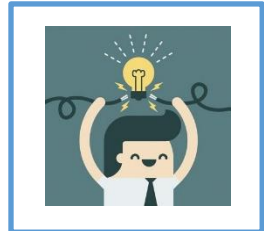
INVESTIGACIÓN

PLANTEAMIENTO DEL PROBLEMA


PROBLEMA



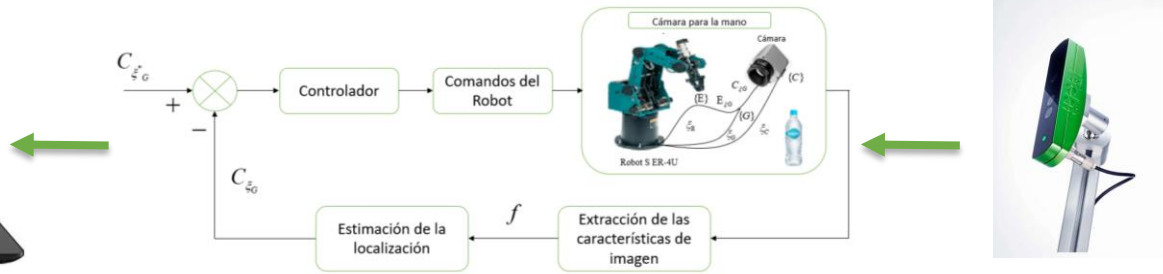
Año 2006



PROPUESTA



Año 2023

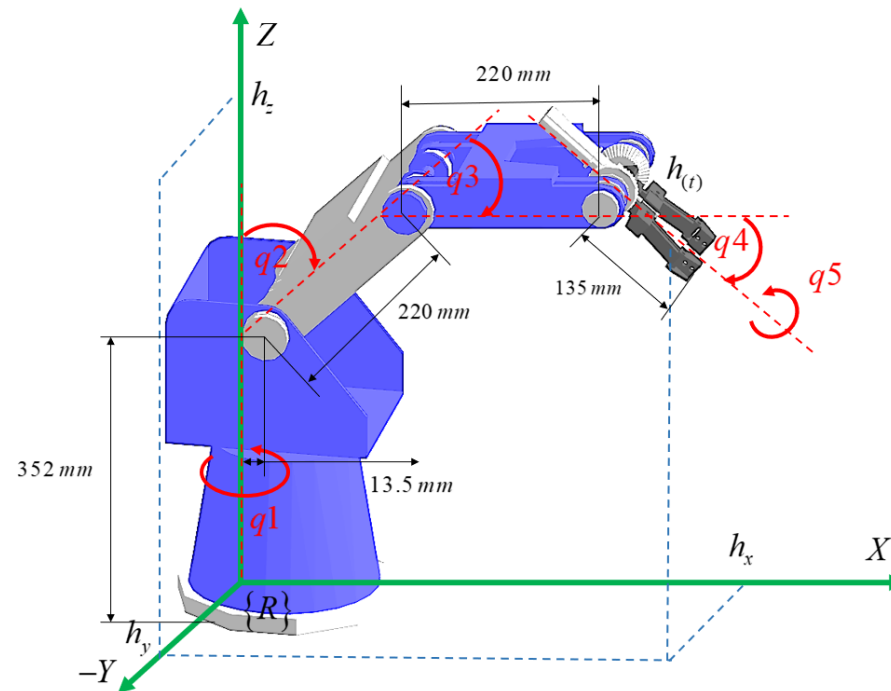


Implementar un esquema de control basado en **realimentación visual** y en la **cinemática de movimiento** del Robot ScorBot-ER-4U, a fin de ejecutar **tareas autónomas** orientadas al proceso de envasado..

- ✓ **Investigar la morfología y modos de control** del Robot ScorBot-ER-4U, con el propósito de ejecutar tareas industriales.
- ✓ **Modelar** las características **cinemáticas** y **restricciones de movimiento** del Robot ScorBot-ER-4U, a fin de implementar algoritmos de **control servo visual**.
- ✓ **Implementar estrategias de procesamiento** de imagen que permita **detectar y extraer** las características de **imagen** de un proceso de envasado.
- ✓ Determinar el **modelo de proyección de perspectiva (Pinhole Model)**, a fin de **mapear las características de imagen** del espacio de trabajo 3D al espacio de imagen 2D.
- ✓ **Desarrollar un simulador 3D** que permita implementar y evaluar **esquema de control** aplicadas a un Robot ScorBot-ER-4U.

- ✓ **Proponer** un esquema de **control servo visual** basado en la **cinemática** del robot manipulador, para ejecutar **tareas autónomas** en un proceso de envasado. El controlador propuesto deberá ser **implementado** en el Software de **Matlab**.
- ✓ **Implementar** el hardware necesario a fin de **evaluar experimentalmente** el **esquema de control propuesto**. Para la evaluación se considerará el robot SCORBOT-ER-4U disponible en el Laboratorio de **Investigación en Automatización, Robótica y Sistemas Inteligentes**.





$$\begin{cases} h_x(t) = \cos(q_1) [a_1 + a_2 \cos(q_2) + a_3 \cos(q_2 + q_3) + d_5 \cos(q_2 + q_3 + q_4)] \\ h_y(t) = \sin(q_1) [a_1 + a_2 \cos(q_2) + a_3 \cos(q_2 + q_3) + d_5 \cos(q_2 + q_3 + q_4)] \\ h_z(t) = d_1 + a_2 \sin(q_2) + a_3 \sin(q_2 + q_3) + d_5 \sin(q_2 + q_3 + q_4) \end{cases}$$

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

(1)

Cinemática Directa

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

Modelo Cinemático

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

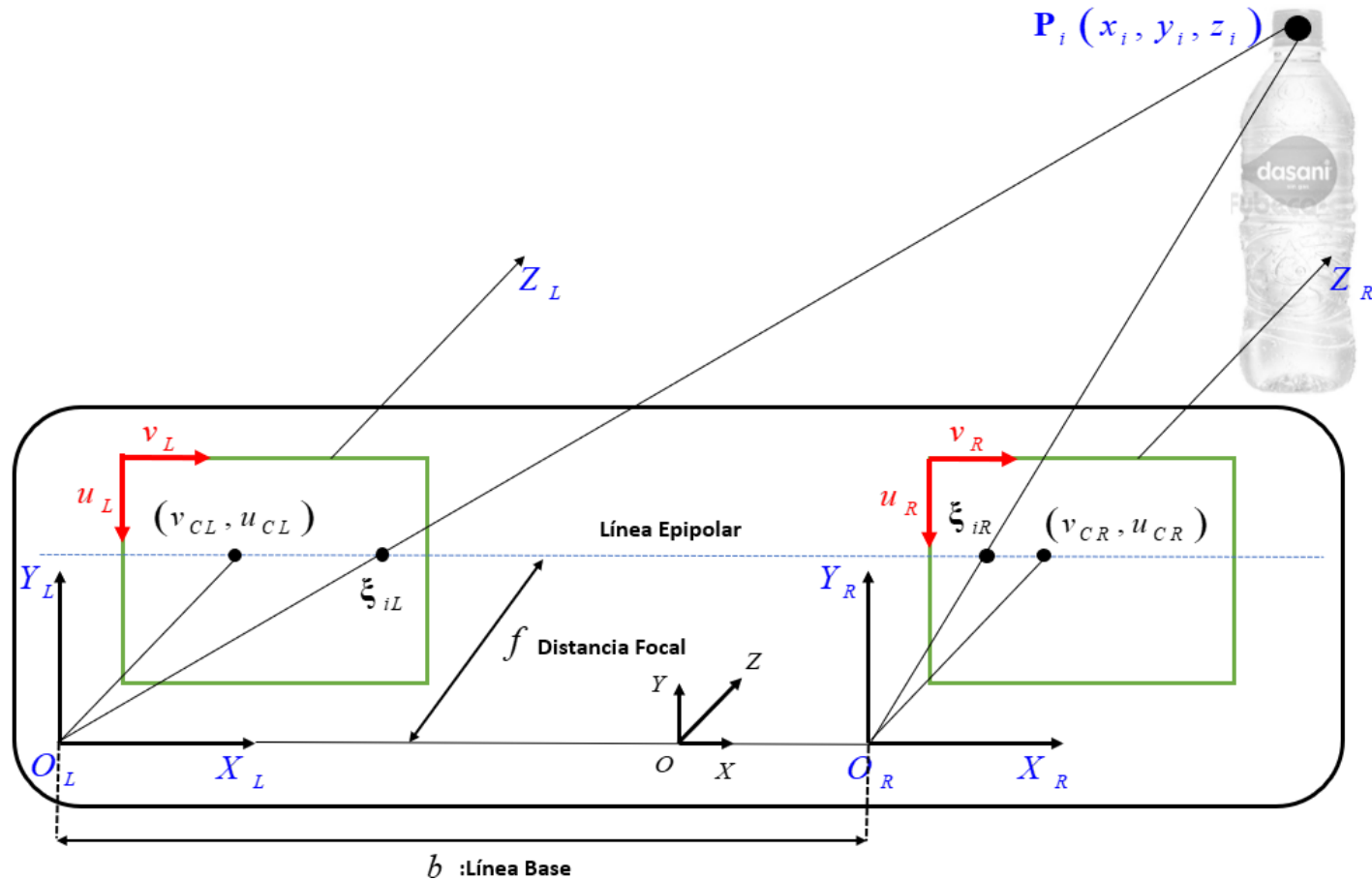
$$\begin{bmatrix} \dot{h}_x \\ \dot{h}_y \\ \dot{h}_z \end{bmatrix} = \begin{bmatrix} -S_1(a_1 + a_2C_2 + a_3C_{23} + d_5C_{234}) & -C_1(a_3S_{23} + a_2S_2 + d_5S_{234}) & -C_1(a_3S_{23} + d_5S_{234}) & -d_5S_{234}C_1 & 0 \\ C_1(a_1 + a_3C_{23} + a_2C_2 + d_5C_{234}) & -S_1(a_3S_{23} + a_2S_2 + d_5S_{234}) & -S_1(a_3S_{23} + d_5S_{234}) & -d_5S_{234}S_1 & 0 \\ 0 & a_3C_{23} + a_2C_2 + d_5C_{234} & a_3C_{23} + d_5C_{234} & d_5C_{234} & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \end{bmatrix}$$

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

(2)

$$\dot{\mathbf{h}} = [\dot{h}_1 \ \dot{h}_2 \ \dots \ \dot{h}_m]^T \quad = \text{Vector del Extremo Operativo}$$

$$\dot{\mathbf{q}} = [\dot{q}_1 \ \dot{q}_2 \ \dots \ \dot{q}_n]^T \quad = \text{Velocidad de las Articulaciones}$$



El método utilizado se basa en la triangulación;

$$\frac{f}{z_i} = \frac{(v_L - v_{CL})}{x_i} = \frac{(v_R - v_{CR})}{x_i - b} = \frac{(u_{CL} - u_L)}{y_i} = \frac{(u_{CR} - u_R)}{y_i} \quad (3)$$

En el espacio cartesiano se considera una relación geométrica de semejanza de triángulos donde se obtiene:

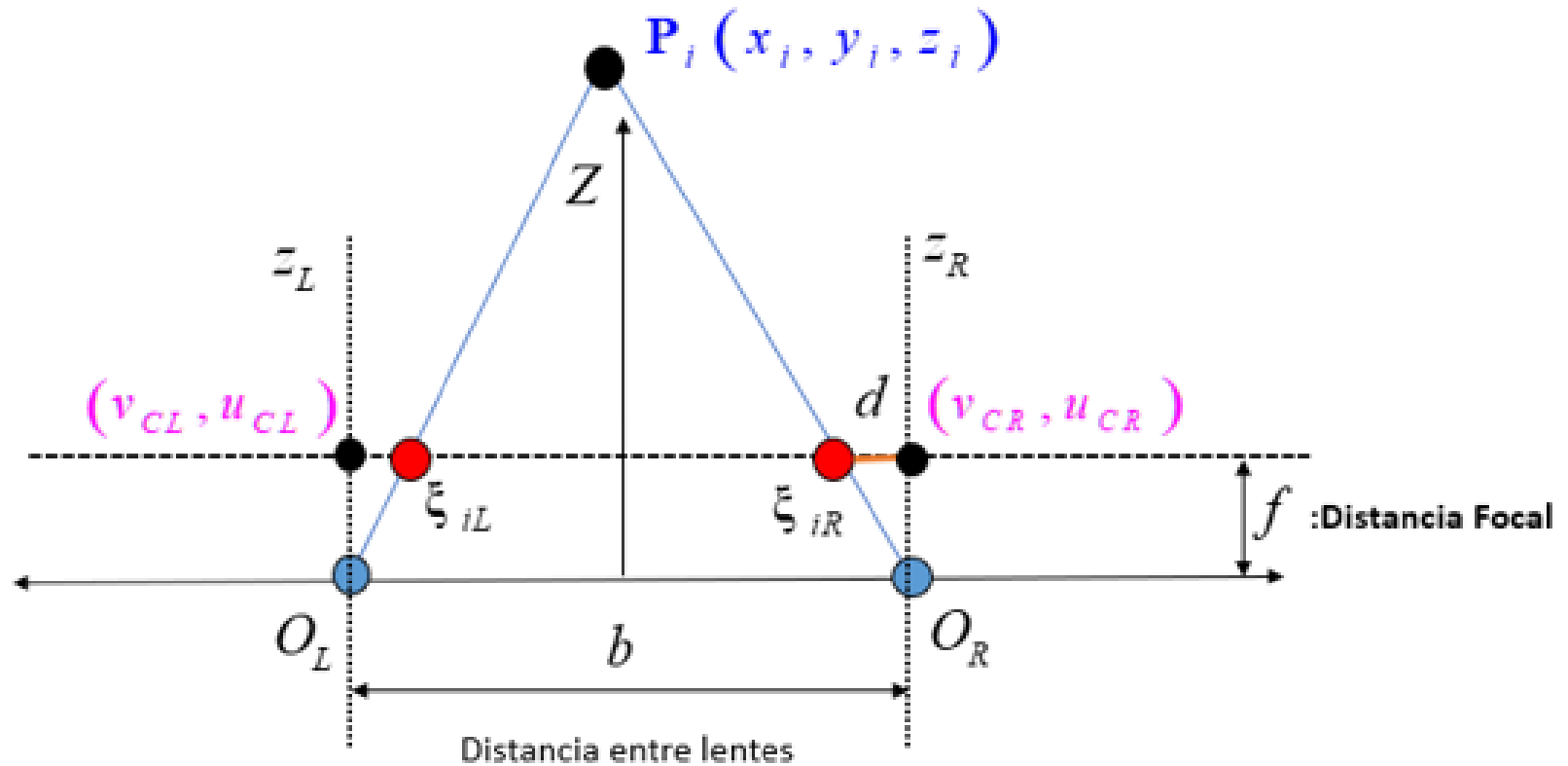
$$x_i = \frac{(v_L - v_{CL})b}{d - (v_{CL} - v_{CR})} \quad y_i = \frac{(u_{CL} - u_L)b}{d - (v_{CL} - v_{CR})} \quad (4)$$

Reduciendo términos en (3) se obtiene:

$$u_L - u_{CL} = u_R - u_{CR} \quad (5)$$

Si las cámaras se encuentran alineadas y el centro óptico en la misma posición se determina el punto **P** a través de:

$$x_i = \frac{b}{d}(v_L - v_{CL}); y_i = \frac{b}{d}(u_{CL} - u_L) \quad (6)$$



En base a las coordenadas del centro óptico del plano de imagen se determina la distancia focal y la profundidad

$$\left\{ O_L; \frac{\frac{b}{2} + v_{CL}}{Z} = \frac{V_{iL}}{f}; O_R; \frac{\frac{b}{2} + v_{CR}}{Z} = \frac{V_{iR}}{f} \right\} \quad (7)$$

se obtiene:

$$V_{iL} = \frac{f}{Z} \left(v_{CL} + \frac{b}{2} \right) \quad V_{iR} = \frac{f}{Z} \left(v_{CR} + \frac{b}{2} \right) \quad (8)$$

La disparidad entre imágenes se determina:

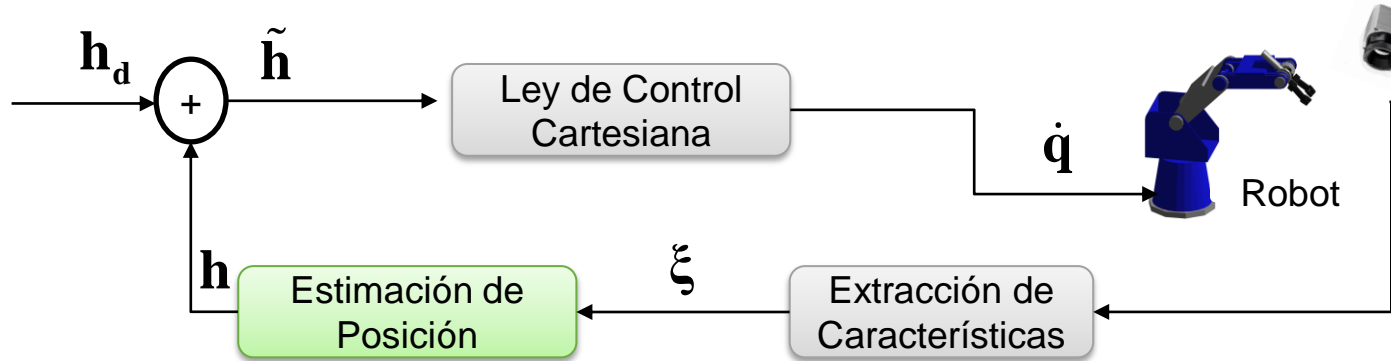
$$d = (v_{iL} - v_{iR}) \quad (9)$$

Se reemplaza (9) en (8) obteniendo la profundidad en función de la distancia focal:

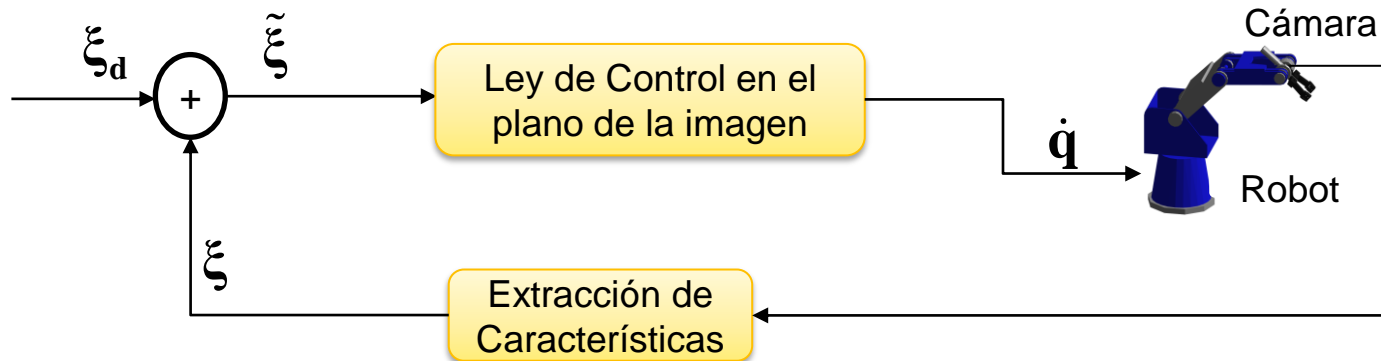
$$Z = \frac{fb}{d} \quad (10)$$



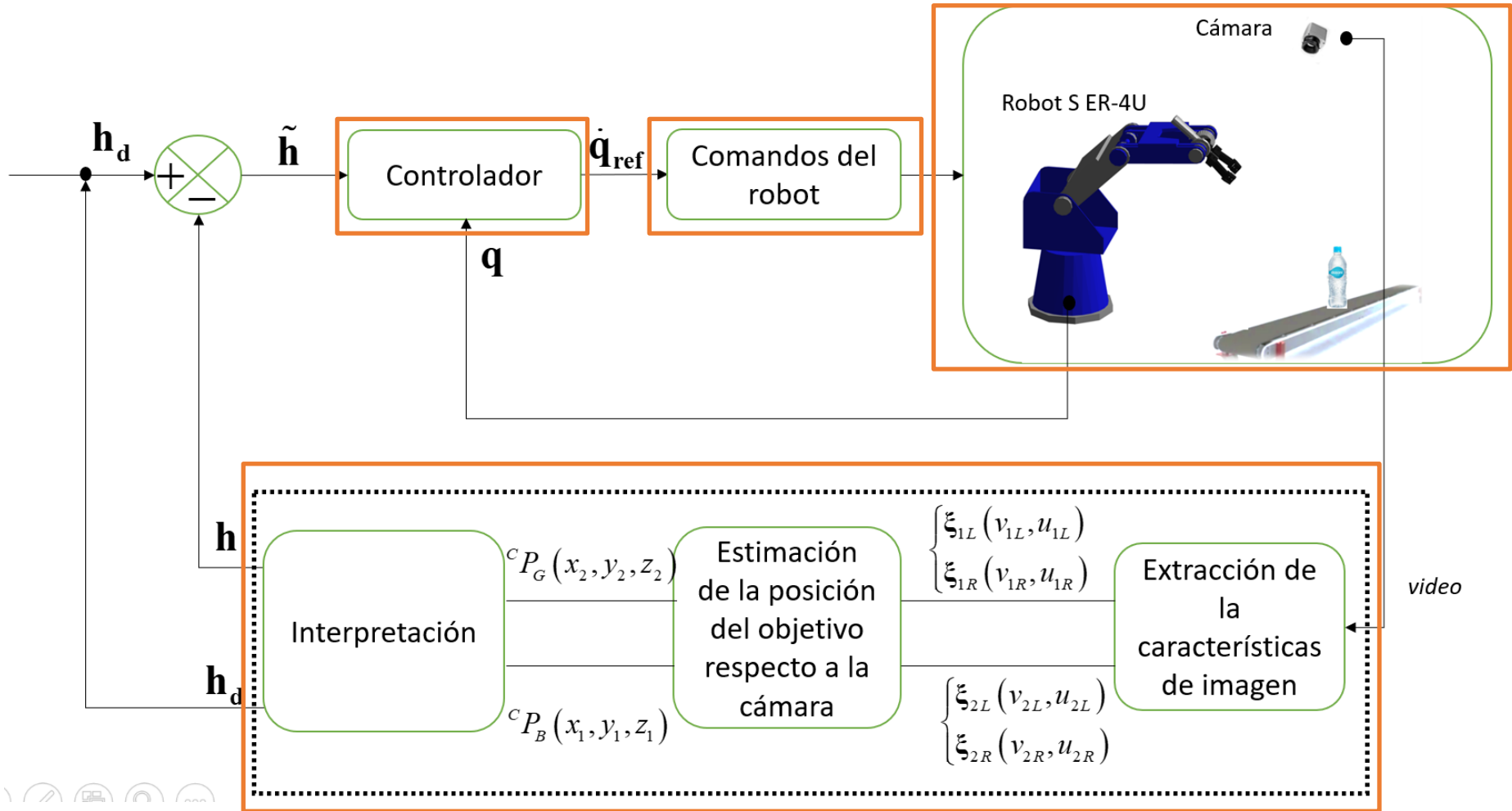
Control servo-visual basado en posición

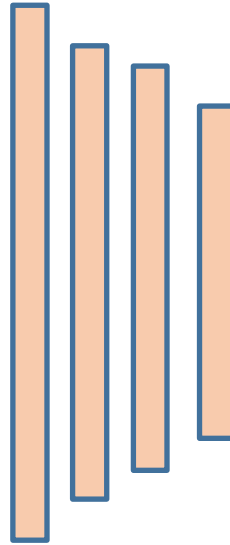


Control servo-visual basado en imagen



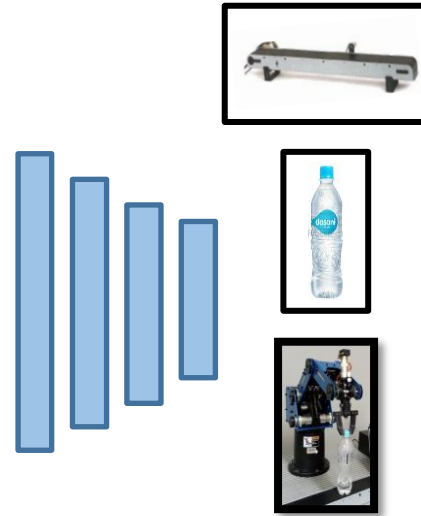
Control servo-visual basado en posición





1 Convolución

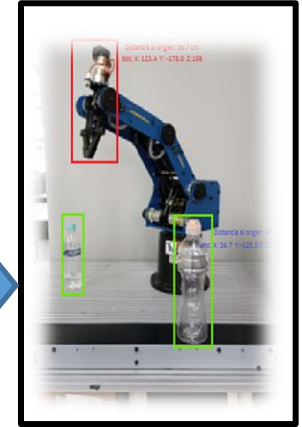
- Filtros
- Subsampling



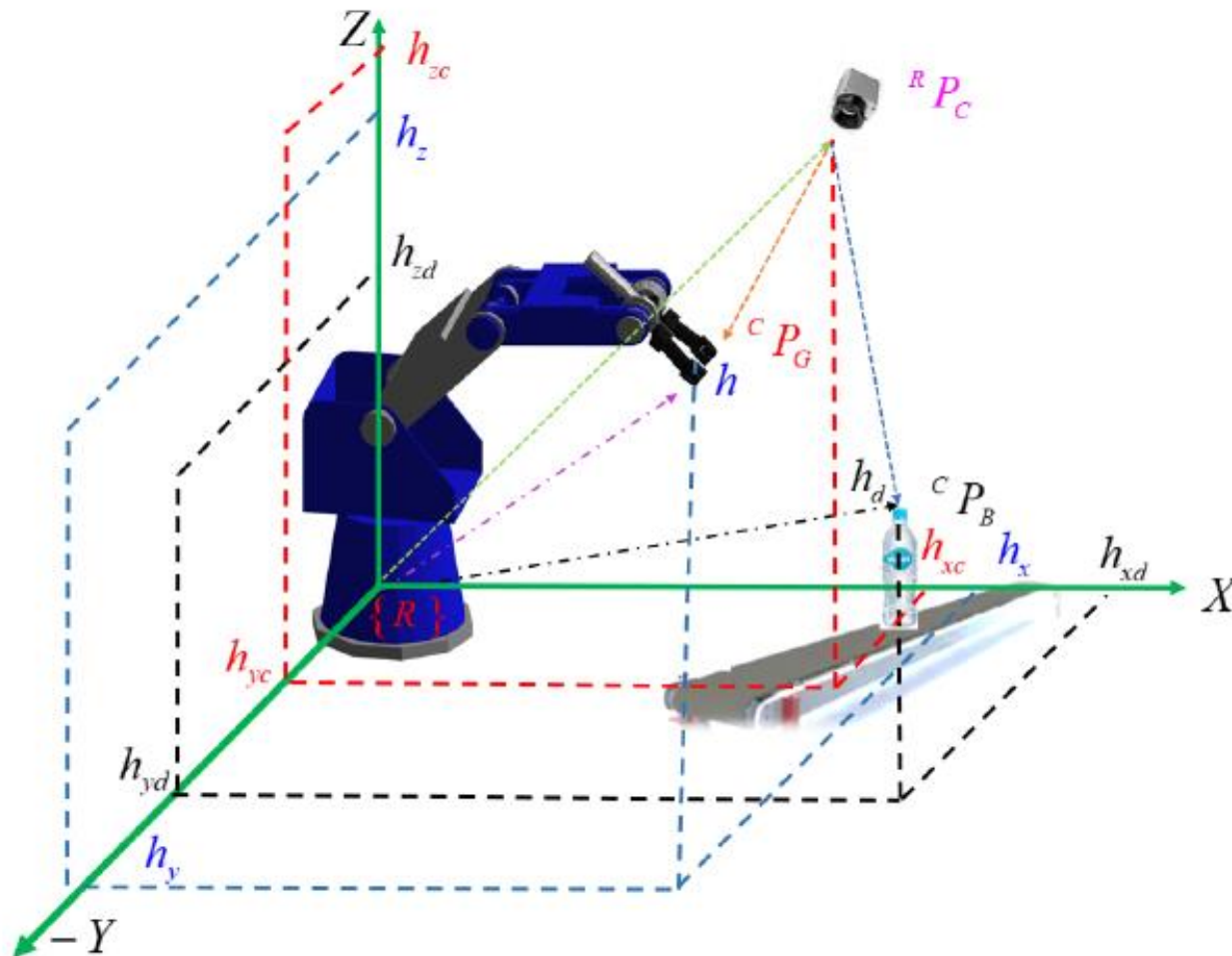
2 Convolución
successive

RED NEURONAL
MULTICAPA
(CAPA DE SALIDA)

non Max
suppression(NMS)



Salida múltiple en
la misma imagen en
un recuadro



$$\dot{\mathbf{q}}_{ref}(t) = \underbrace{\mathbf{J}^\# \left(\Gamma \tanh(\boldsymbol{\kappa} \tilde{\mathbf{h}}) \right)}_{\text{Objetivo Primario}} + \underbrace{\left(\mathbf{I} - \mathbf{J}^\# \mathbf{J} \right) \boldsymbol{\Omega} \tanh(\boldsymbol{\eta})}_{\text{Objetivo Secundario}} \quad (11)$$

$\mathbf{J}^\# \in \mathbb{R}^{3 \times 5}$ = Matriz pseudoinversa

$\Gamma = \text{diag}(\Gamma_x, \Gamma_y, \Gamma_z)$ = Matriz definida positiva de los errores de control

$\boldsymbol{\kappa} = \text{diag}(\kappa_x, \kappa_y, \kappa_z)$ = Matriz definida positiva de los errores de control

$\boldsymbol{\Omega} = \text{diag}(\Omega_1, \Omega_2, \dots, \Omega_5)$ = Matriz definida positiva del espacio nulo

$\tilde{\mathbf{h}}$ = Errores de control

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

Ecuación de Lazo Cerrado:

Robot:

$$\dot{\mathbf{h}}(t) = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}(t) \quad (12)$$

Ley de Control

$$\dot{\mathbf{q}}_{ref}(t) = \mathbf{J}^\# \left(\Gamma \tanh(\boldsymbol{\kappa}\tilde{\mathbf{h}}) \right) + \left(I - \mathbf{J}^\# \mathbf{J} \right) \boldsymbol{\Omega} \tanh(\boldsymbol{\eta}) \quad (13)$$

$$\text{con: } \dot{\tilde{\mathbf{h}}}(t) = \dot{\mathbf{h}}_d(t) - \dot{\mathbf{h}}(t)$$

Seguimiento perfecto de velocidad $\dot{\mathbf{q}}_{ref}(t) \equiv \dot{\mathbf{q}}(t)$

$$\dot{\tilde{\mathbf{h}}} = -\Gamma \tanh(\tilde{\mathbf{h}}) \quad (14)$$

Teoría de Lyapunov - Estabilidad

Candidata de Lyapunov:

$$\mathbf{V}(\tilde{\mathbf{h}}) = \frac{1}{2} \tilde{\mathbf{h}}^T(t) \tilde{\mathbf{h}}(t) \quad \longrightarrow \quad \dot{\mathbf{V}}(\tilde{\mathbf{h}}) = \tilde{\mathbf{h}}^T(t) \dot{\tilde{\mathbf{h}}}(t) \quad (15)$$

Ecuación de Lazo Cerrado (ELC)

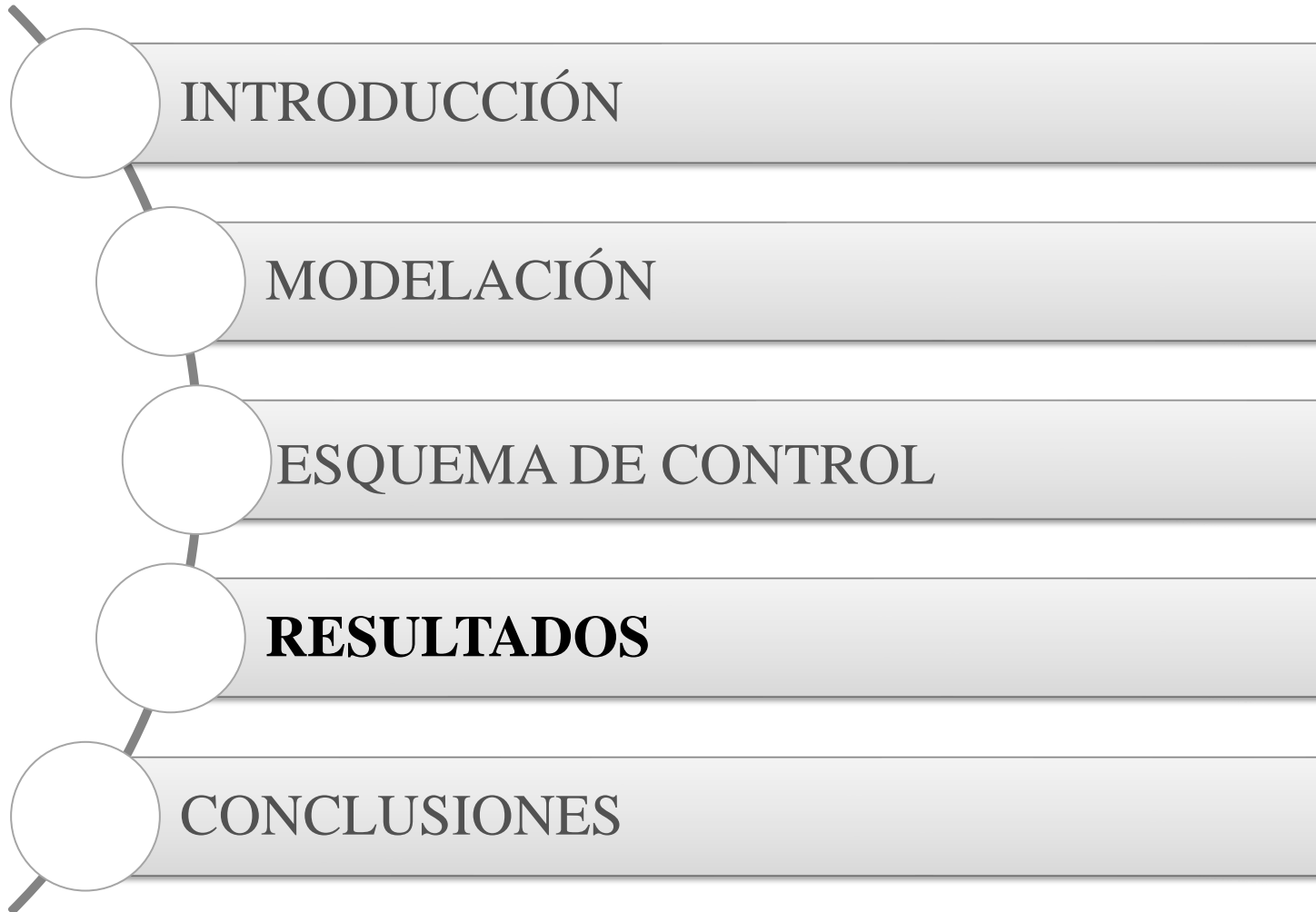
$$\dot{\tilde{\mathbf{h}}} = -\mathbf{\Gamma} \tanh(\tilde{\mathbf{h}}) \quad (16)$$

Relacionado la ELC con $\dot{\tilde{\mathbf{h}}}(t)$

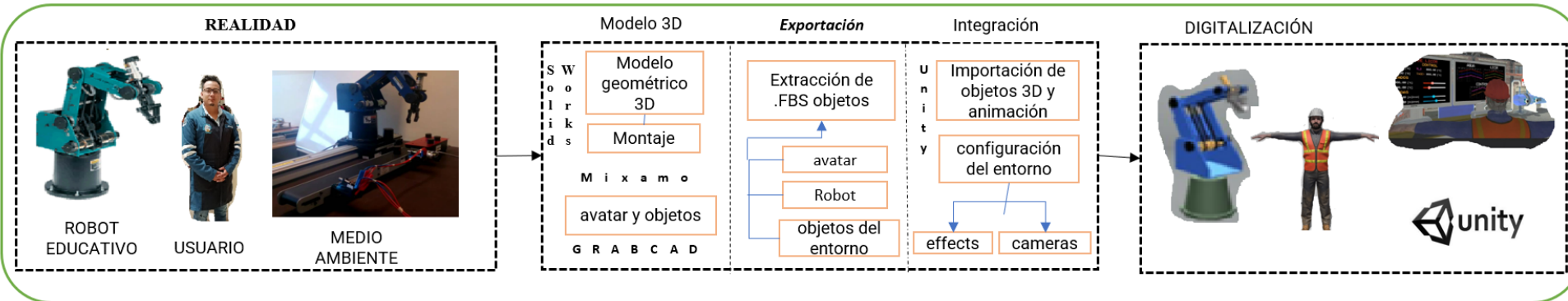
$$\dot{\mathbf{V}}(\tilde{\mathbf{h}}) = -\tilde{\mathbf{h}}^T \mathbf{\Gamma} \tanh(\kappa \tilde{\mathbf{h}}) < 0 \quad (17)$$

Por lo tanto si: $\mathbf{\Gamma} > 0$ y $\kappa > 0$

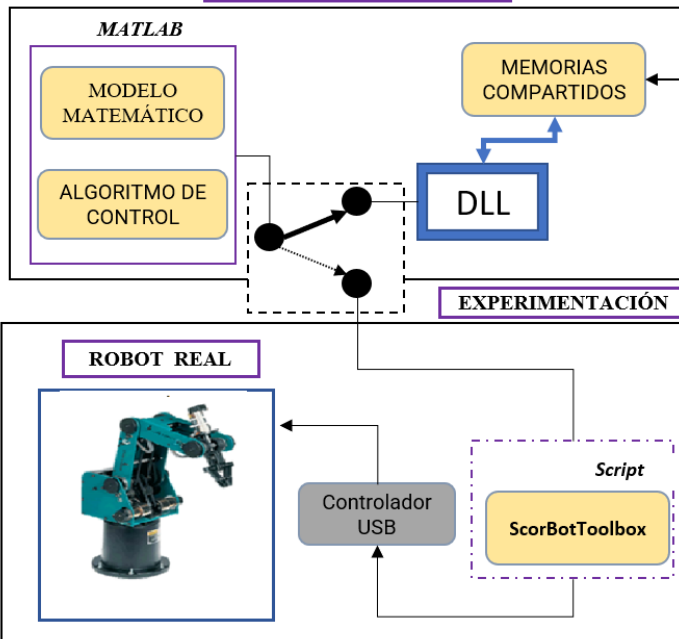
$$\lim_{t \rightarrow \infty} \tilde{\mathbf{h}}(t) = 0 \quad (18)$$



ENTORNO VIRTUAL

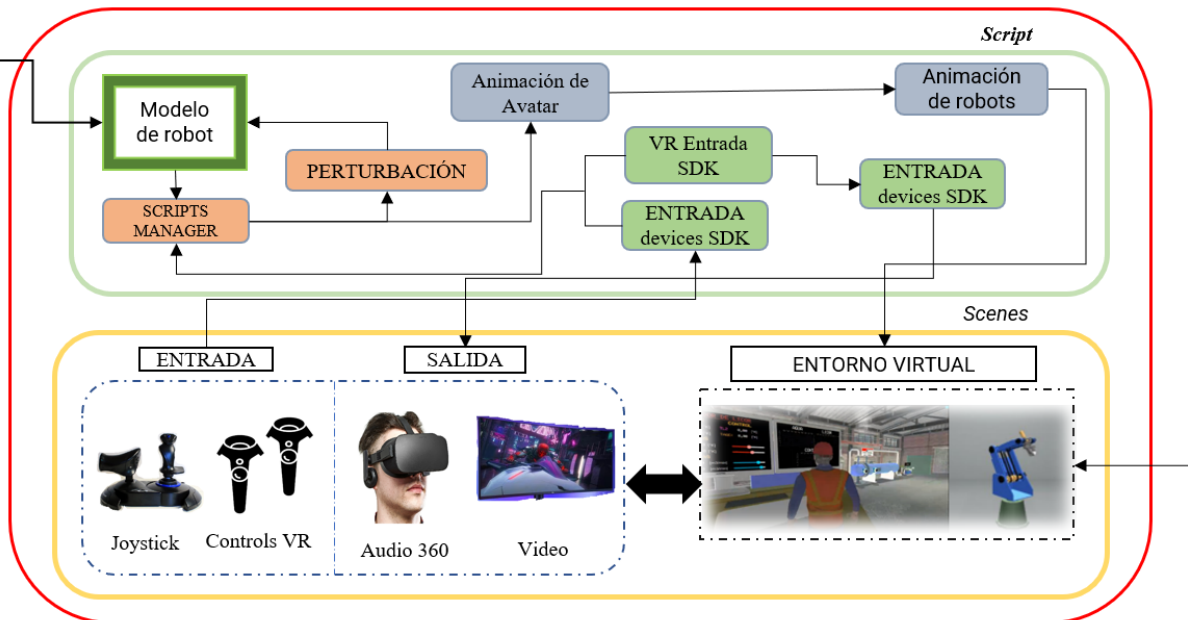


CONTROLADOR



GRAPHICS ENGINE

.FBS

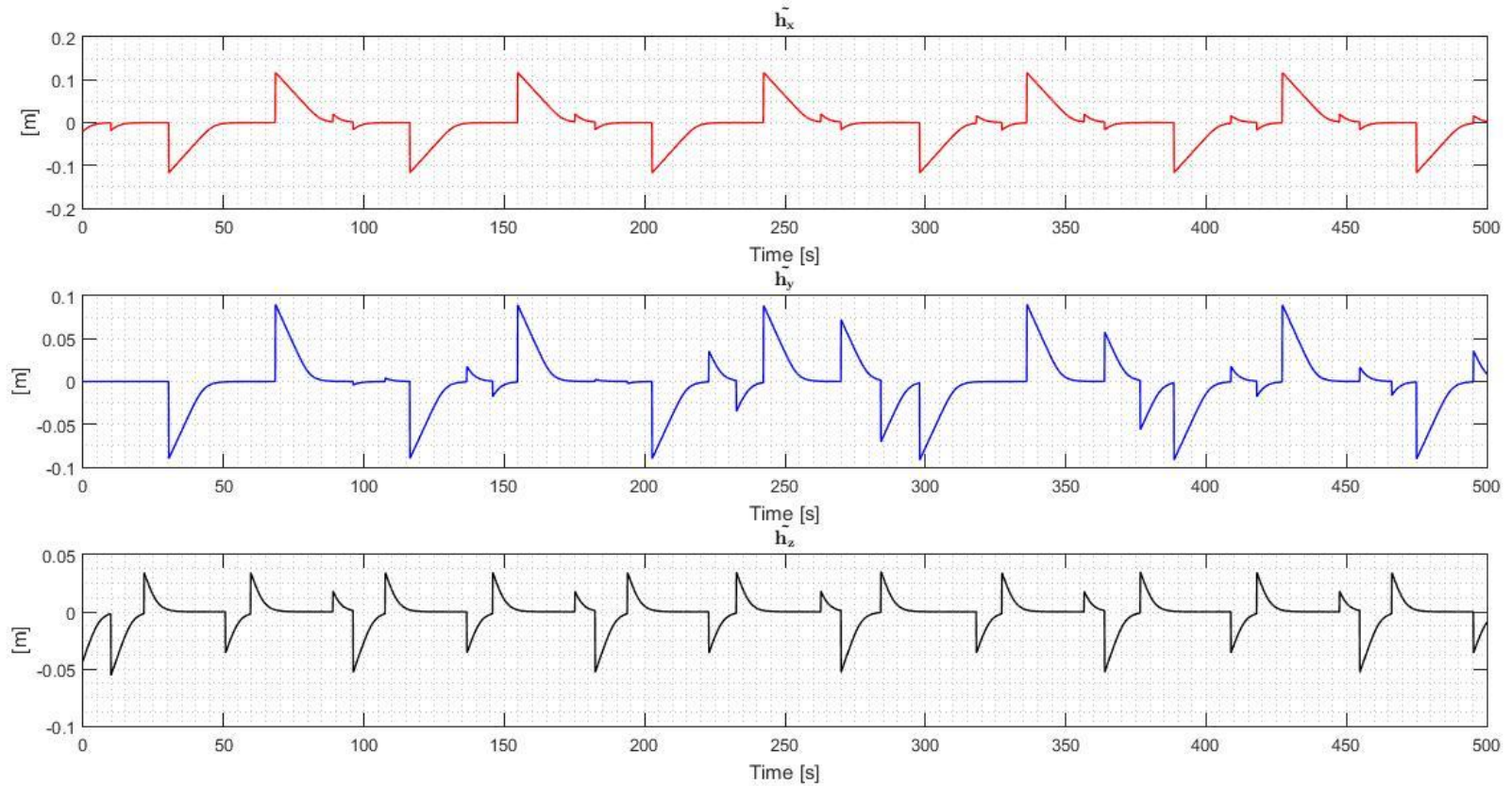


File Edit Assets GameObject Component Services Investor Mobile Input Tools Window Help

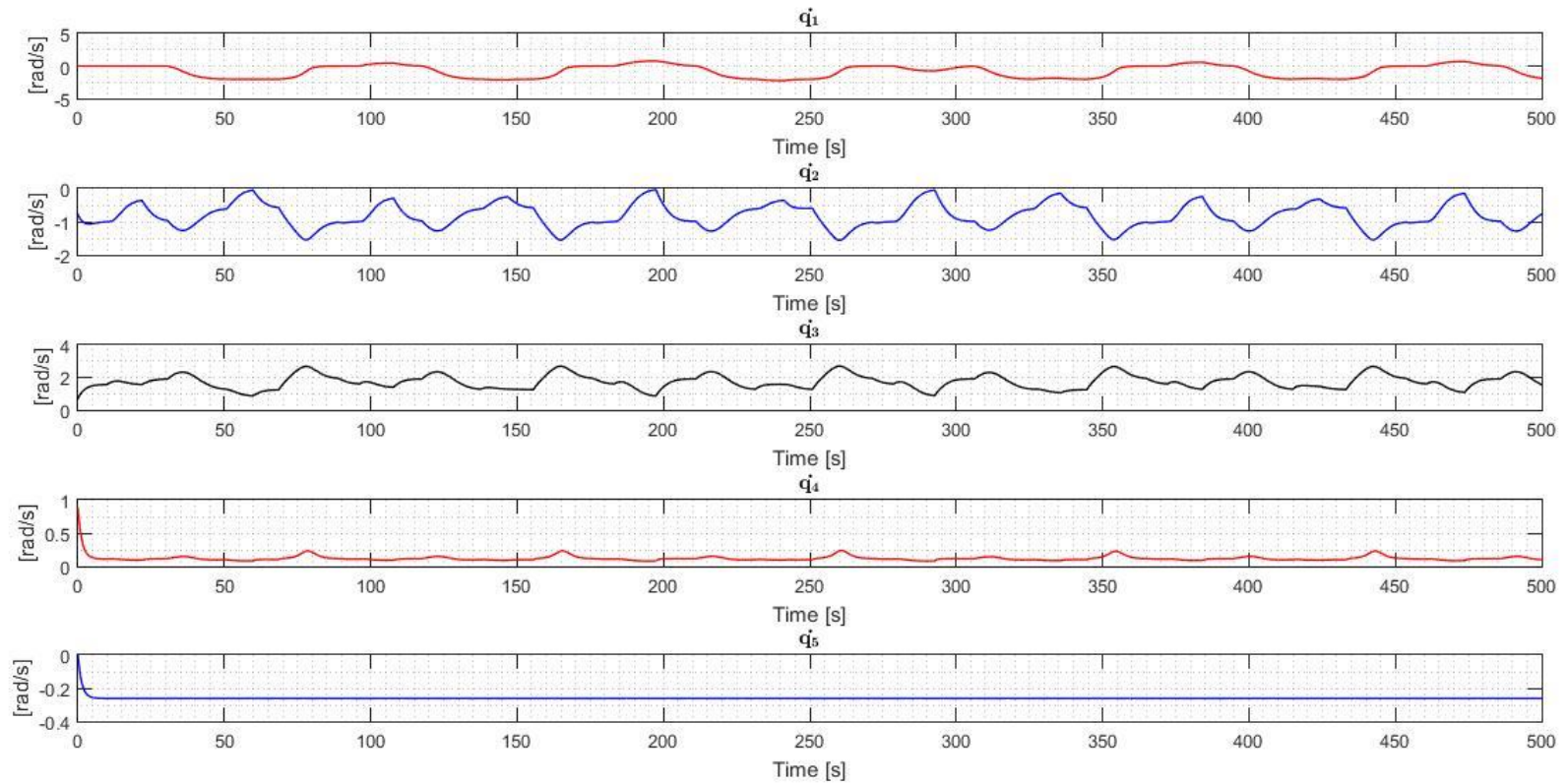


Vídeo

Errores de Control



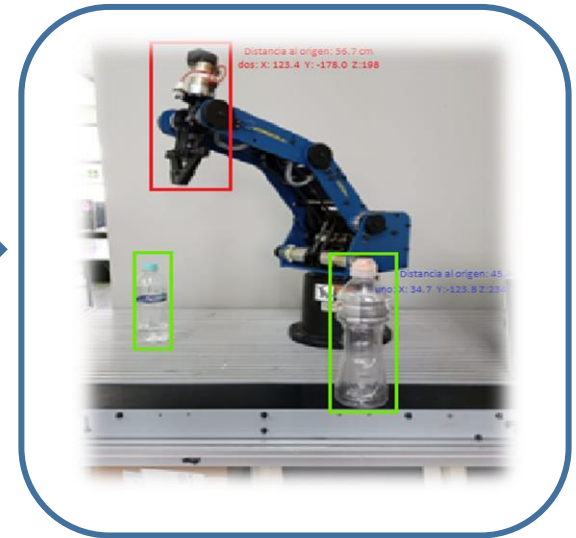
Acciones de Control



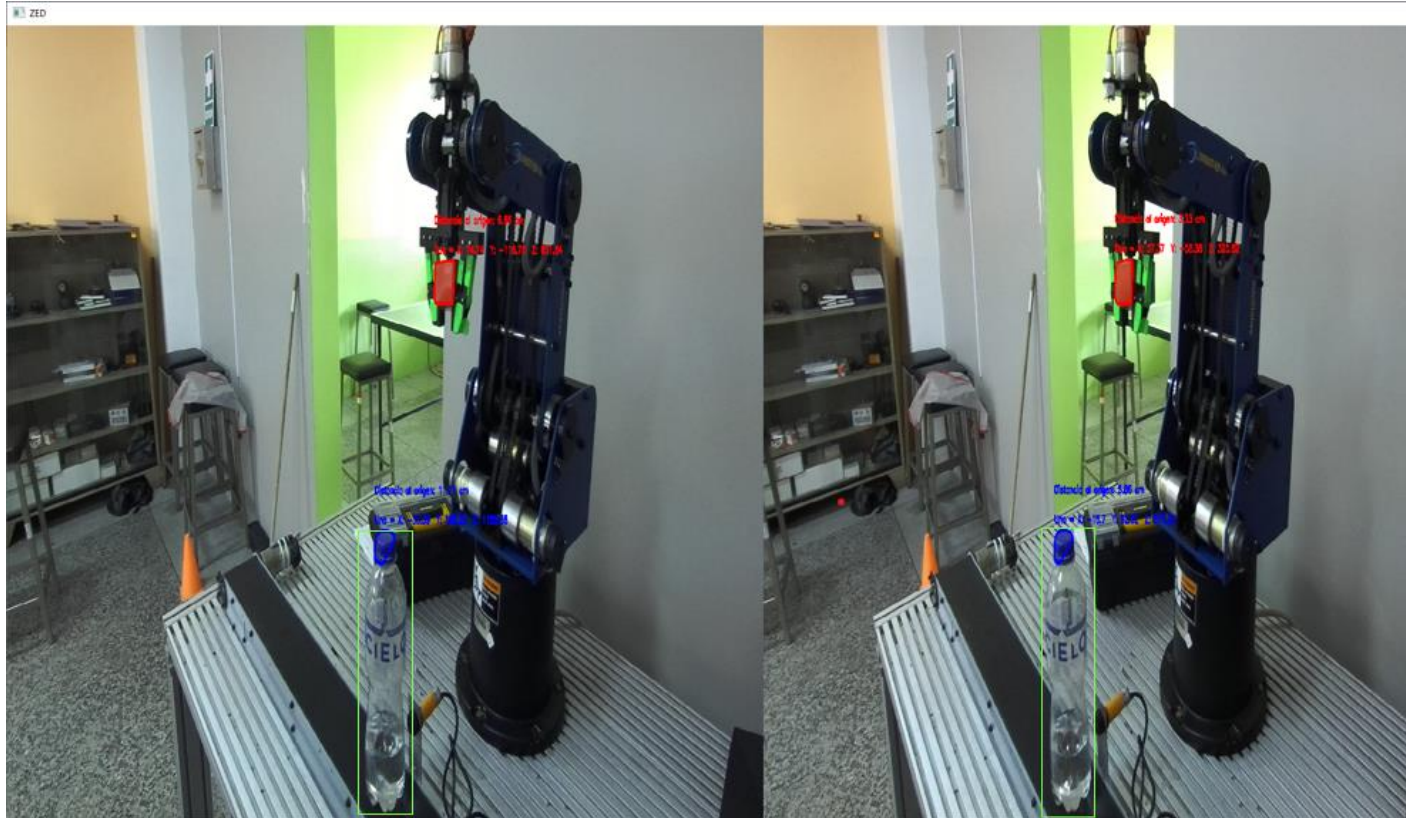


Adquisición de imágenes del espacio de trabajo

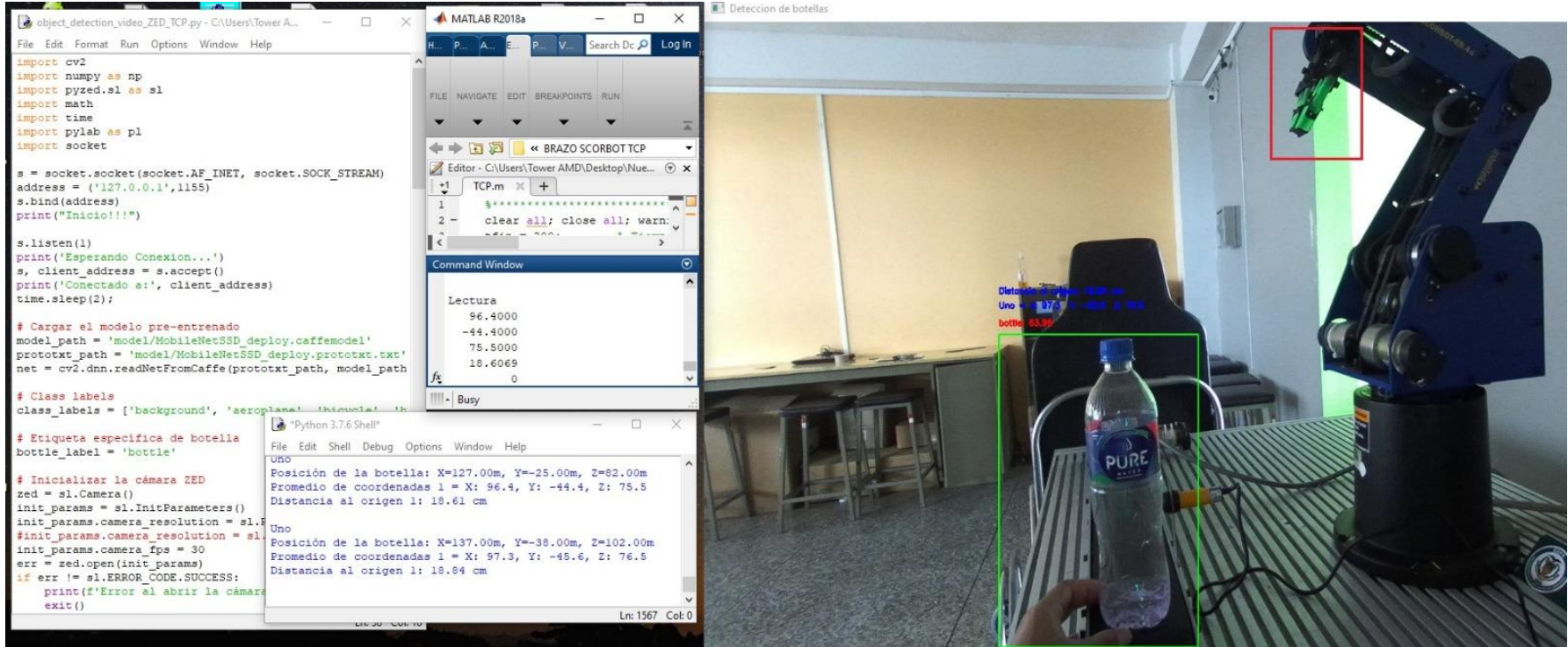
Cámara ZED



Detección de la botella y del extremo operativo



Posición de la botella y del extremo operativo
respecto a la cámara de visión

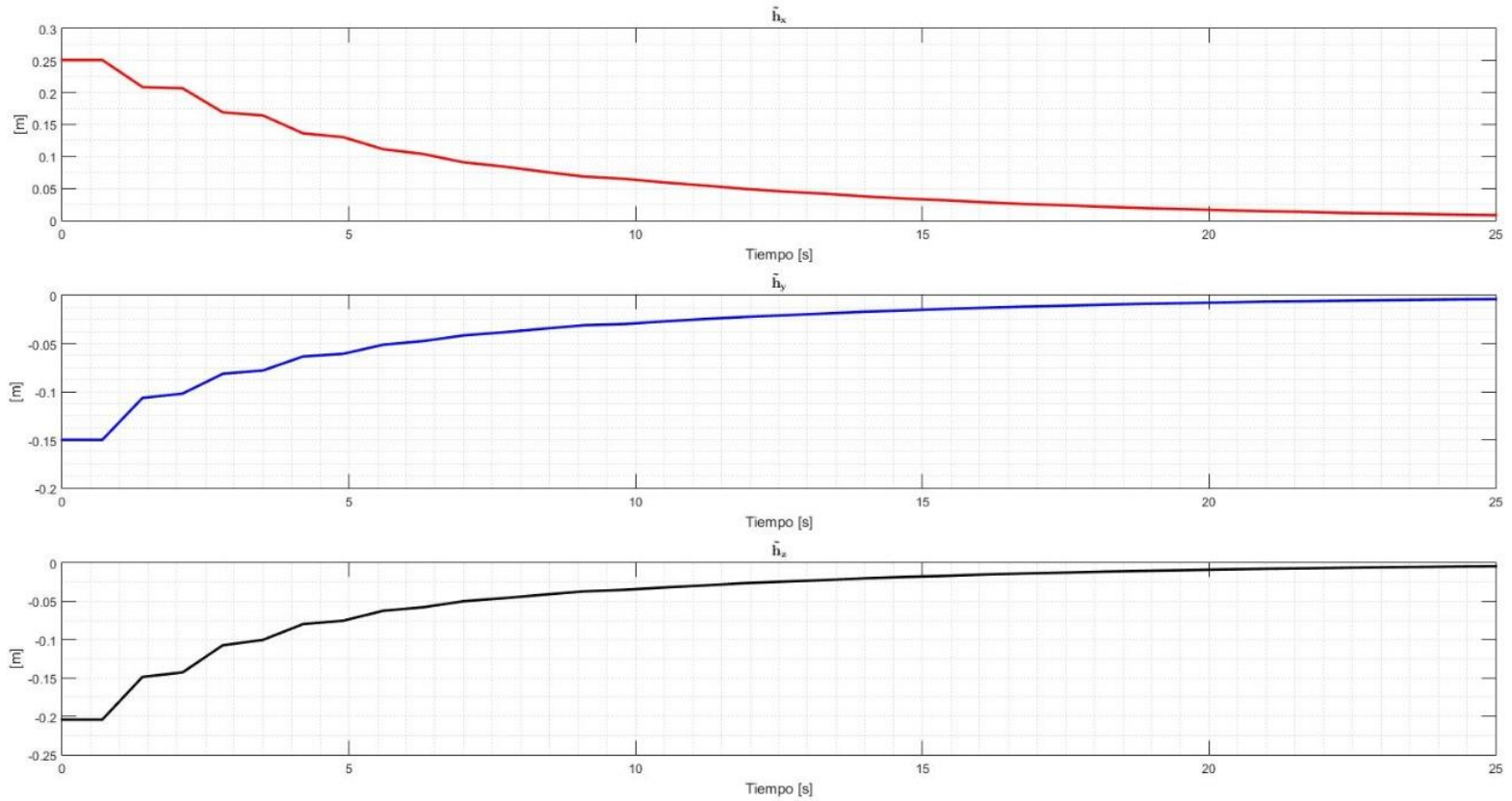


Vídeo

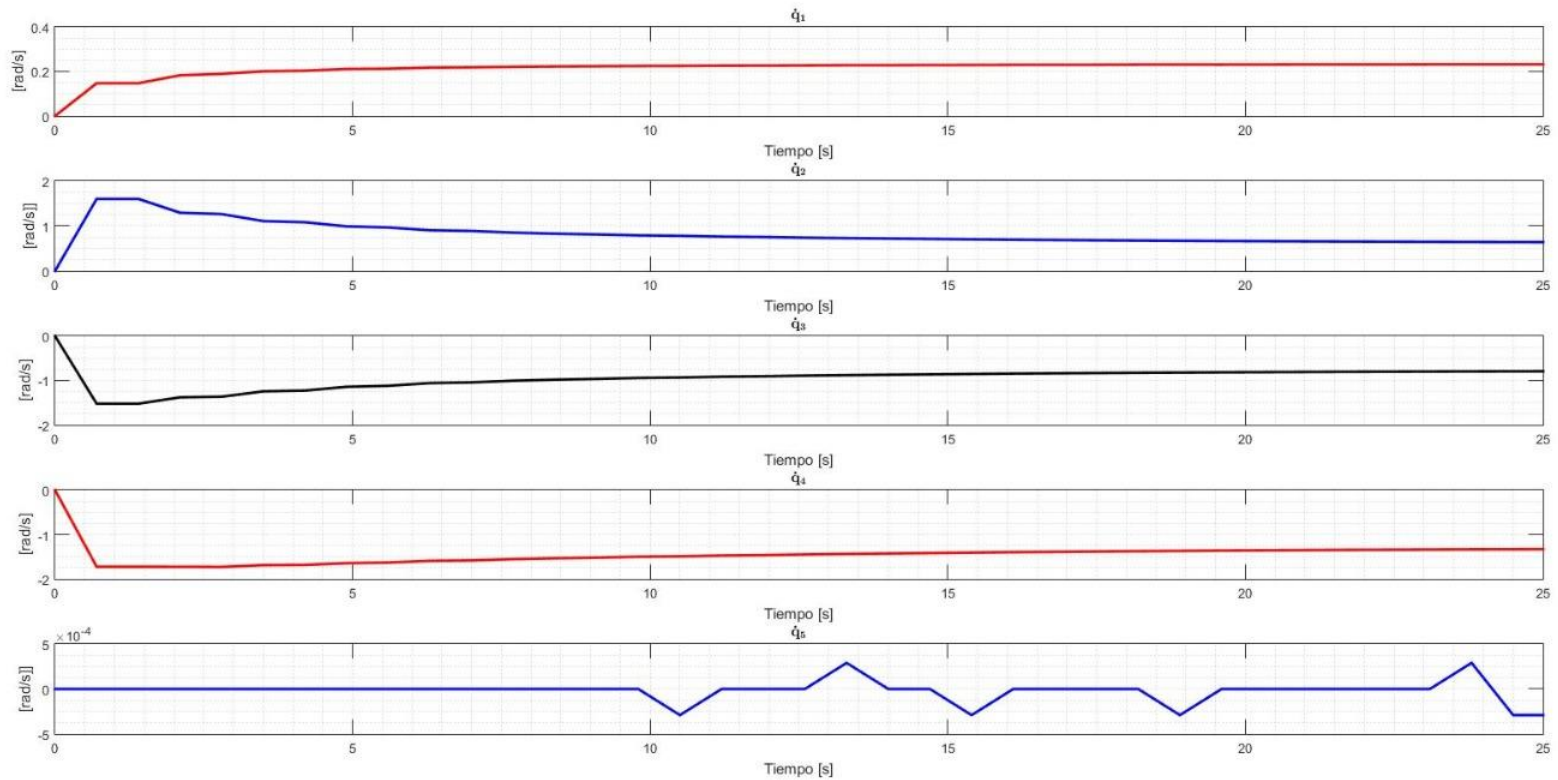


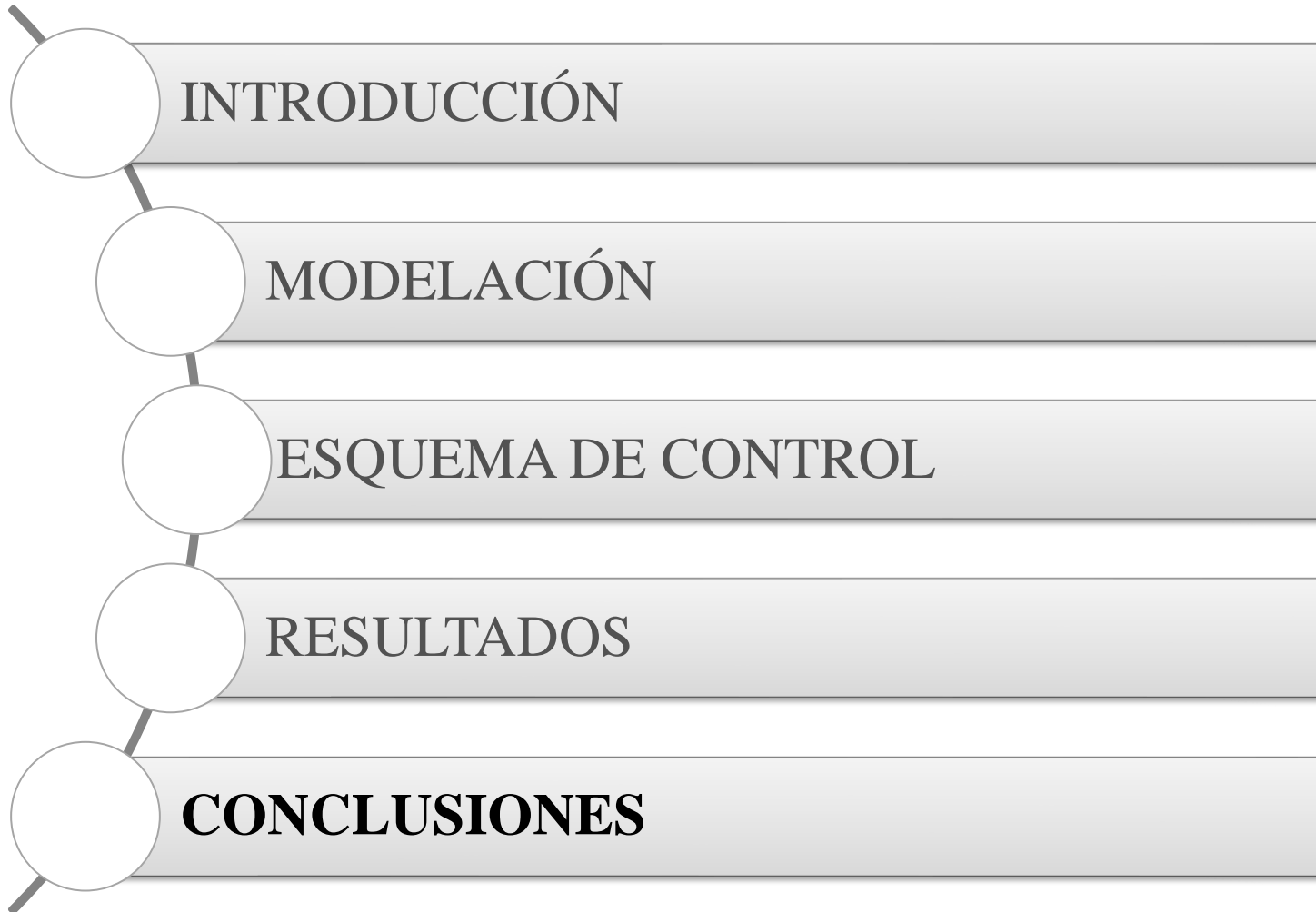
Vídeo

ERRORES DE CONTROL



ACCIONES DE CONTROL





- ✓ Se implementó un control servo visual **basado en la posición** para un proceso de **envasado de botellas** utilizando el robot manipulador Scorbot-ER-4U. **El esquema de control** propuesto considera la configuración **cámara para mano**, para determinar la **posición** del extremo **operativo del robot manipulador** y la **posición de la botella al manipular**.
- ✓ El esquema de control se evaluó mediante **simulación y experimentalmente**. Para las pruebas de simulación, se desarrolló **un entorno virtual** en el motor gráfico UNITY3D, y por otro lado se realizó pruebas experimentales de laboratorio con el **robot manipulador** Scorbot-ER-4U y la **cámara de visión estereoscópica ZED 2**
- ✓ A partir de las pruebas de simulación y experimentales, se comprobó que los errores de control **convergen a cero**, según el análisis de **estabilidad realizado con la teoría de Lyapunov**.



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