



UNIVERSIDAD DE LAS FUERZAS ARMADAS ESPE

DEPARTAMENTO DE ELÉCTRICA Y ELECTRÓNICA

CARRERA DE INGENIERÍA EN ELECTRÓNICA E INSTRUMENTACIÓN

**Artículo Académico Previo a la Obtención del Título de Ingeniera en Electrónica E
Instrumentación**

**“SISTEMAS DE ENTRENAMIENTO PARA EL CONTROL DE ROBOTS
MANIPULADORES MÓVILES EN REALIDAD AUMENTADA.”**

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Publisher: IEEE

Cite This



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Published in: 2020 15th Iberian Conference on Information Systems and Technologies (CISTI)

Date of Conference: 24-27 June 2020

INSPEC Accession Number: 19772764

Date Added to IEEE Xplore: 15 July 2020

DOI: 10.23919/CISTI49556.2020.9141012

► ISBN Information:

Publisher: IEEE

Print on Demand(PoD) ISSN: 2166-0727

Conference Location: Sevilla, Spain, Spain

Training Systems for Control of Mobile Manipulator Robots in Augmented Reality

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Abstract — In this article, an augmented reality application interface was developed, using a technological tool oriented towards teaching-learning that allows a mobile manipulator robot training system to be created. Focusing on the simulation of autonomous control algorithms and the implementation of animations made in the Unity 3D software, which will allow the user to interact with the real world through a mobile device where the rear camera will be used to capture the image and the touch screen for visualization. It is verified that the application is intuitive and understandable for the user to operate, in order to provide the necessary knowledge of the operation and structure of the robot.

Keywords - Augmented reality; control algorithms; Unity 3D; animations.

I. INTRODUCTION

Immersive technology gives way to new, more useful and reasonable communication channels [1]. Through the creation of simulated artificial realities (VR), the reproduction of reality itself with visual elements (AR), and mixed reality (MR) will be the union of the two, where it is possible to conform tools that serve to design, educate, manipulate, inform, etc. [2]. The (VR) and (AR) have benefits in several sectors because of their great potential of visualization that is able to provide an extra value to the contents and data [3].

The AR begins to appear in the computer and scientific world in the early 1990s, with faster and more efficient technologies, real-time graphic representation techniques, combining the physical world with digital objects [4], it offers high levels of natural interaction as the computer vision techniques it uses allow it to detect user interactions [5]. The term refers to a set of methods that allow virtual content such as images, 3D models superimposed in real time, where the main idea is to create an environment in which information and virtual objects are merged with the real ones [6]. The technological advances allow AR experiences are no longer only possible on portable computers, but also tend to use smart phones [7], which require features specific for processing of information and the develop the application interface [8]. As it is a mobile device-based implementation, it has the advantage of being able to transport the interface to the place of operation [9].

The applications that are made in the AR, in the field of the industrial engineering is based on the design of the specific characteristics of an industrial environment and of several processes, which allows the user to accede to all the information in detail and to avoid damages to the plants or shutdowns of

production [10]. In the field of health, it allows a more general diagnosis by having graphic interfaces of the human body; in marketing and tourism, AR begins to appear as an alternative technology because it allows the subject to interact with the real world [11], addition to developing advertising and generating profits for companies. The AR presented in education as a trend that is imposed by the development of new teaching-learning methods, which allow students to interact with new environments and promote their interest in discovering things [12][13].

Within the area of robotics there is a field known as service robotics that introduces autonomous robots specifically designed to assist humans, offering different services based on its mechanical design, in which there are some types of robots such as air, land, water. For mobility use wheels, legs, propellers, each of them can be used depending on the application and the environment to develop [14]. In the creation of the application interface, three-dimensional CAD geometry and assembly information is used [15], where the programmer can generate several AR scenes in 2D or 3D, which allows the human being to interact with the real world through a device. Addition to assisting users during the execution of their tasks in an efficient and fast manner, saving time, money, labor and material expenses.

Another application of the AR is based on mobile robotics, for development complex simulation models, expensive hardware and a highly controlled environment are needed, therefore there is a need for robot developers to have a more flexible option to perform experiments [16].

This article focuses on the application of augmented reality technology as a tool for the simulation of a system oriented to the teaching-learning of mobile manipulator robots with the aim of providing greater knowledge in the movement of the robot. In addition, autonomous control algorithms will be proposed and evaluated to perform locomotion and manipulation tasks. To this end, a mobile device will be used where the rear camera allows the capture of the image and the touch screen for the visualization of the graphic interface application, in order to perform functional tests.

II. FORMULATION OF THE PROBLEM

In the educational field, the incorporation of technologies is more and more frequent since they bring an enrichment to the teaching-learning process, creating a unique experience at the moment of interacting in the digital environment in an individual way inciting self-discovery and acquiring skills that in the future

2020 15th Iberian Conference on Information Systems and Technologies (CISTI)
24 - 27 June 2020, Sevilla, Spain
ISBN: 978-989-54659-0-3

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ENGINEERING CARRER IN ELECTRONICS AND INSTRUMENTATION

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(b) Virtual Robot



Franklin Silva

Zoom Meeting

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II. SYSTEM STRUCTURE



The diagram illustrates the system structure across three layers:

- LAYER 1:**
 - 3D model placement.
 - Kinematic control of the mobile manipulator.
 - Application interface.
- LAYER 2:**
 - 3D MARKERS
 - 3D MARKERS
- LAYER 3:**
 - Virtual Object Scanner
 - Object Scan
 - Tool

Additional components and processes include:

- Script Manager - Library manager
- Add database
- Upload object data file
- Download the database to Unity Editor.
- Control algorithm of the mobile manipulator



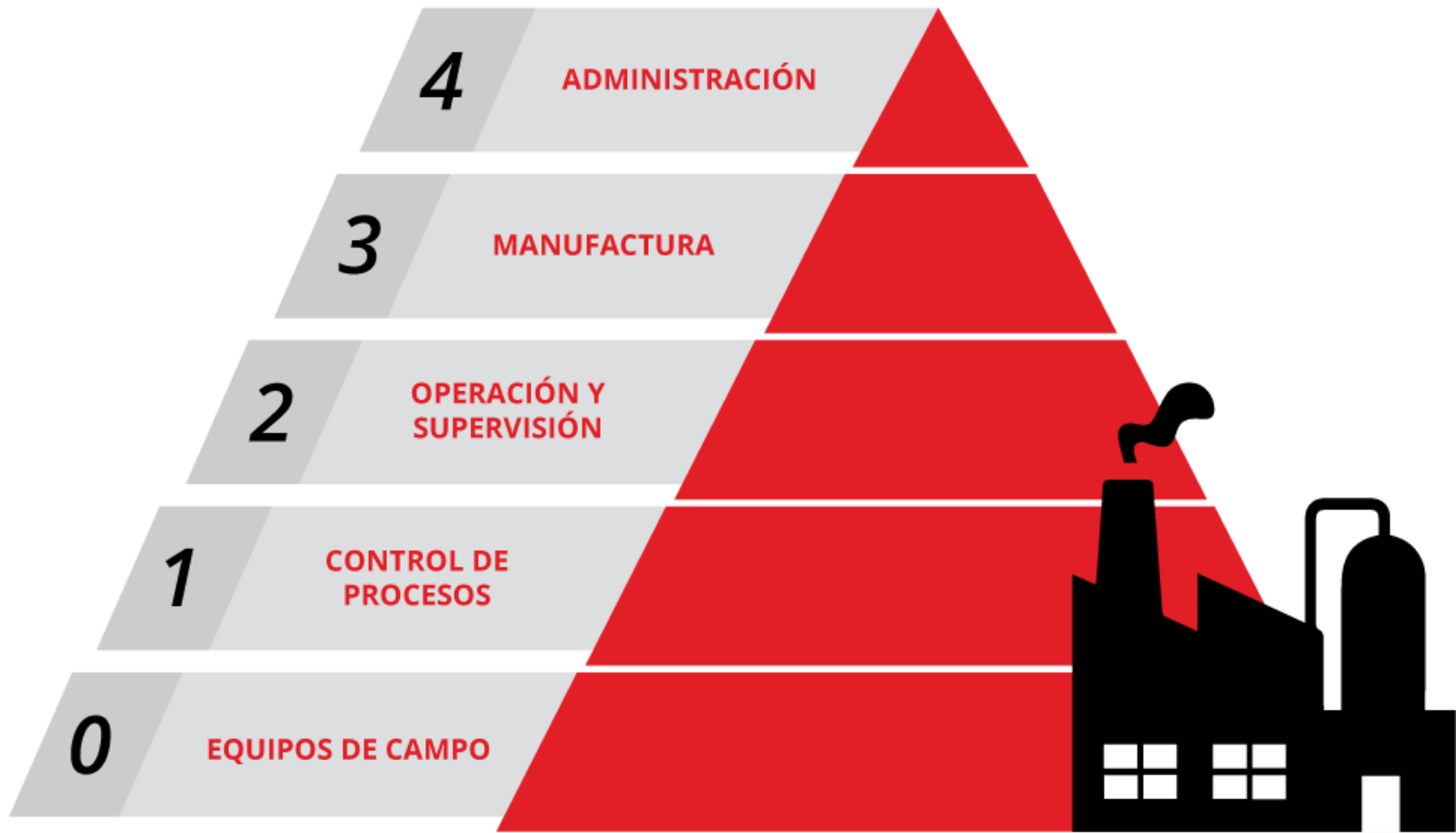
Franklin Silva

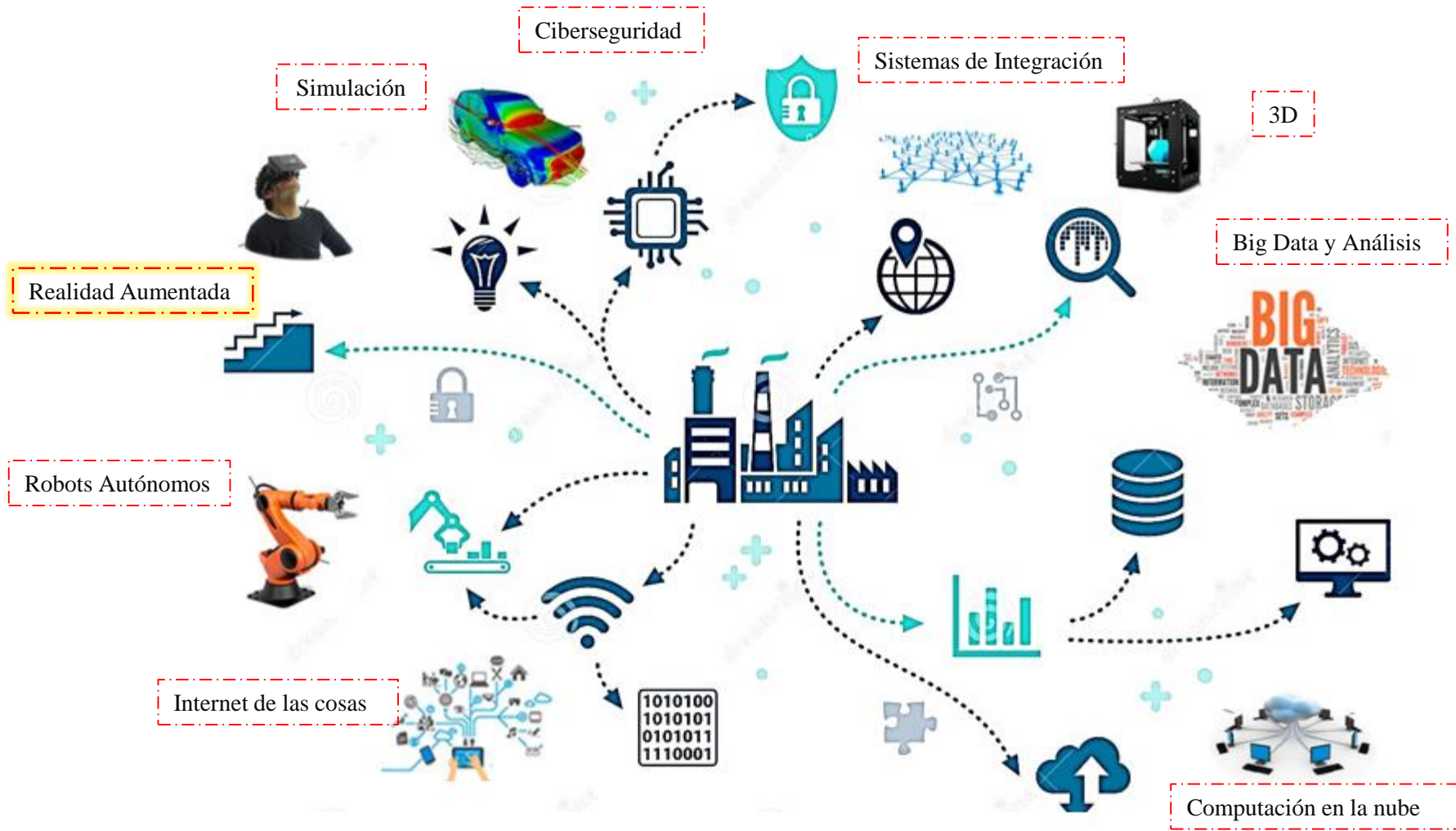
Zoom Meeting

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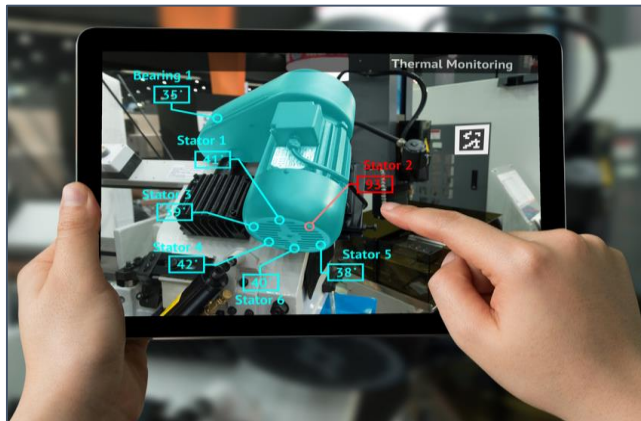




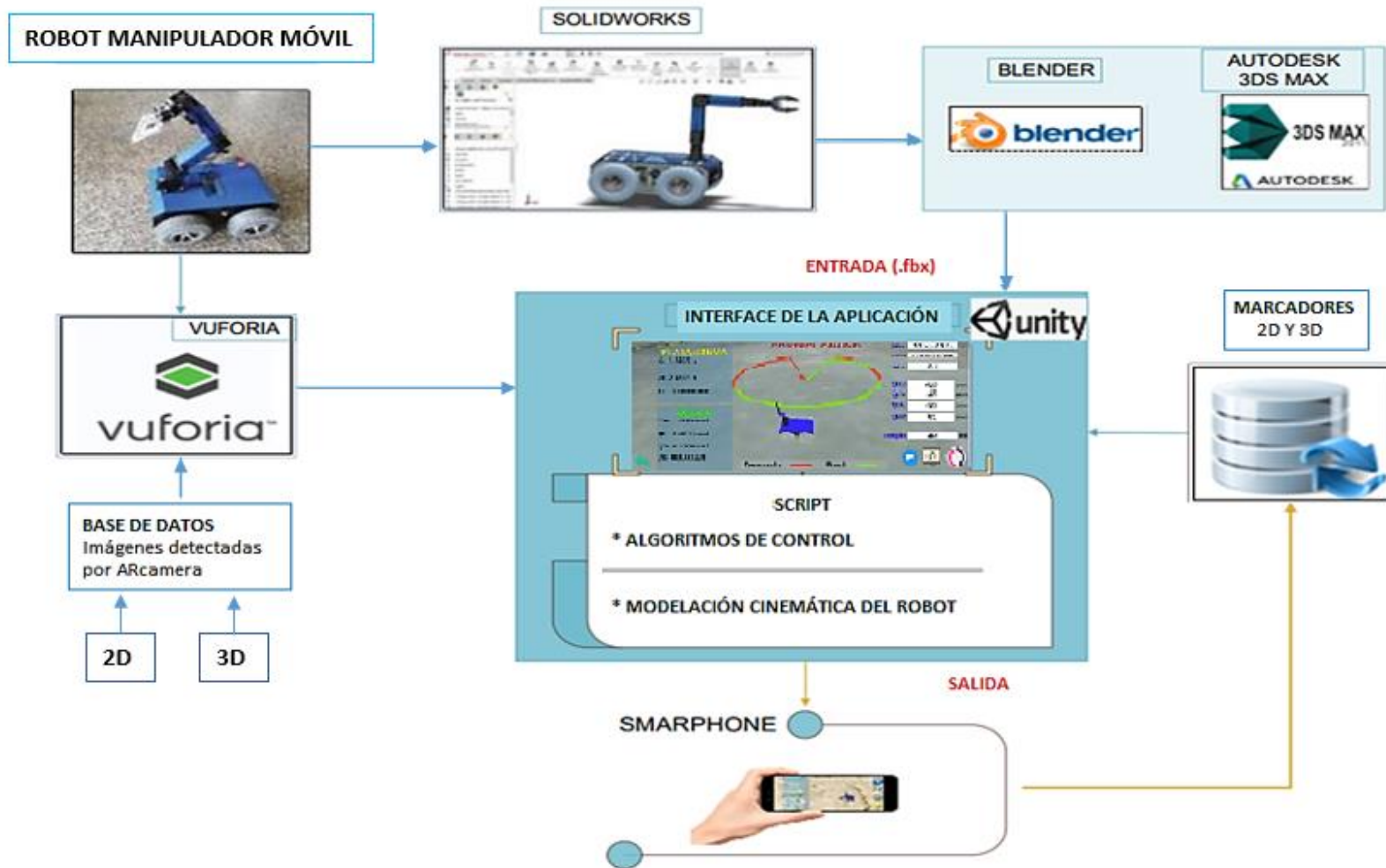
Realidad Virtual



Realidad Aumentada



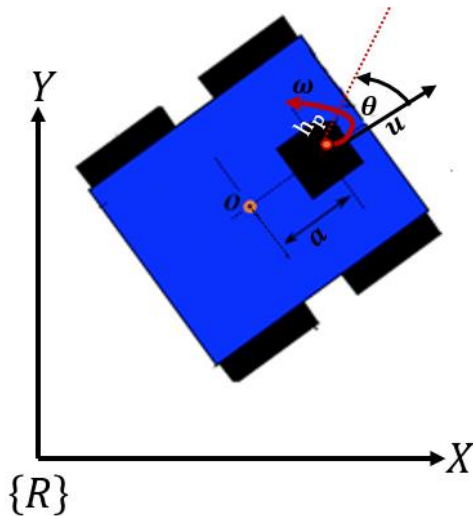
PLANTEAMIENTO DEL PROBLEMA



Implementar un **sistema de entrenamiento en realidad aumentada** que permita simular algoritmos de control en lazos cerrados para la ejecución de tareas de locomoción y manipulación de objetos a través de robots manipuladores móviles.

- ✓ **Realizar una investigación bibliográfica** sobre el control de movimiento de robots manipuladores móviles, con el propósito de proponer un algoritmo de control en lazo cerrado.
- ✓ Determinar el **modelo cinemático de forma matricial y sus restricciones de movimiento** de un robot manipulador móvil conformado por un brazo robótico de 3GDL sobre una plataforma tipo unicycle, a fin de implementar algoritmos de control en lazo cerrado.
- ✓ Proponer un **algoritmo de control autónomo** de un robot manipulador móvil basado en la cinemática del robot, a fin de realizar **tareas de locomoción y manipulación de objetos**.
- ✓ Determinar la **estabilidad del algoritmo** de control propuesto con el propósito que los errores de control converjan a cero, garantizando así, estabilidad asintótica.
- ✓ Desarrollar una **aplicación en realidad aumentada para el entrenamiento de robots autónomos** que considera marcadores 2D y 3D de los robots disponibles en el Laboratorio de Investigación en Automatización, Robótica y Sistemas Inteligentes.
- ✓ **Validar los resultados de los algoritmos de control propuestos** y de la aplicación de realidad aumentada a través de los robots disponibles en el Laboratorio de Investigación en Automatización, Robótica y Sistemas Inteligentes.





Donde:

a : distancia desde O al punto de control

h_p : punto de control

u : velocidad lineal

ω : velocidad angular

θ : orientación de la plataforma

Cinemática Directa

$$h_{px} = X_r + a \cos(\theta)$$

$$h_{py} = Y_r + a \sin(\theta)$$

$$h_{p\theta} = \theta$$

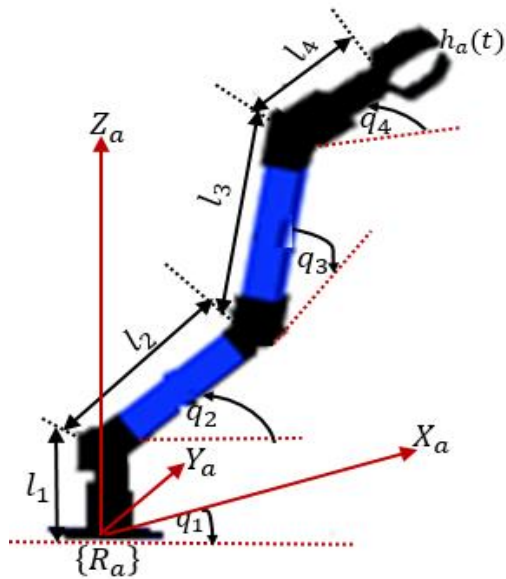


Modelo Cinemático

$$\begin{bmatrix} \dot{h}_{px} \\ \dot{h}_{py} \\ \dot{h}_{p\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -a \sin(\theta) \\ \sin(\theta) & a \cos(\theta) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ \omega \end{bmatrix}$$

Restricción de Movimiento

$$\dot{h}_{px} \sin(\theta) - \dot{h}_{py} \cos(\theta) + a\omega = 0$$



Donde:

l_1, l_2, l_3, l_4 : dimensiones del brazo robótico

q_1, q_2, q_3, q_4 : ángulos de giro para cada GDL

$h_a(t)$: posición del punto de interés

Cinemática Directa

$$h_{ax} = l_2 \cos(q_2) \cos(q_1) + l_3 \cos(q_2 + q_3) \cos(q_1) + l_4 \cos(q_2 + q_3 + q_4) \cos(q_1)$$

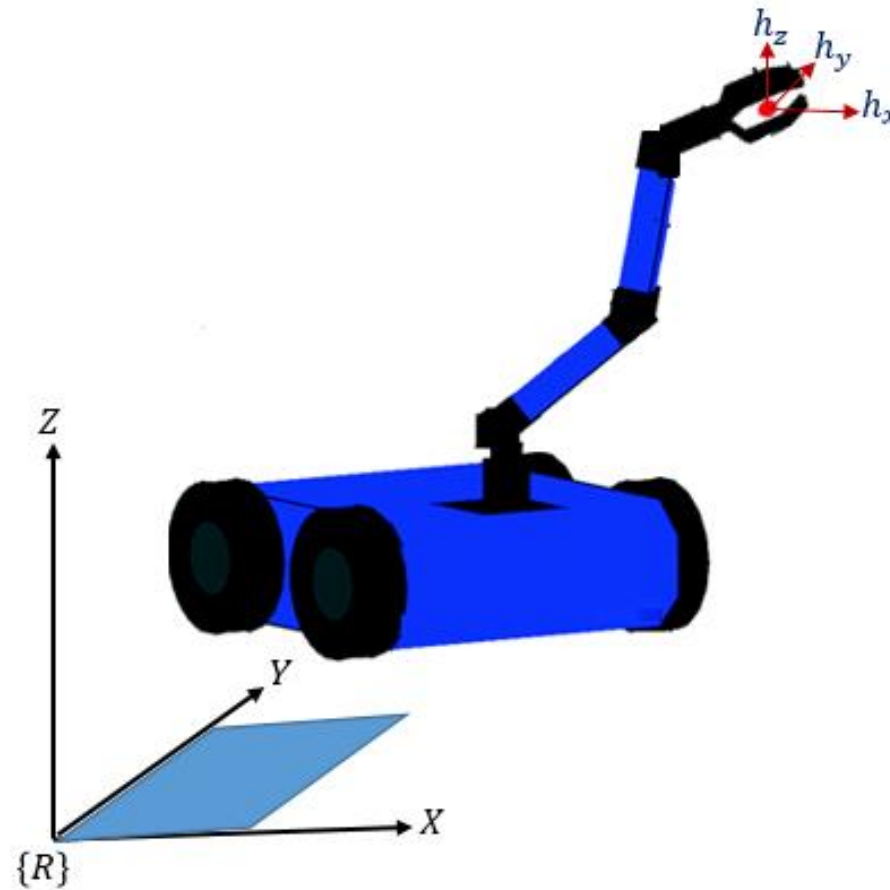
$$h_{ay} = l_2 \cos(q_2) \sin(q_1) + l_3 \cos(q_2 + q_3) \sin(q_1) + l_4 \cos(q_2 + q_3 + q_4) \sin(q_1)$$

$$h_{az} = l_1 + l_2 \sin(q_2) + l_3 \sin(q_2 + q_3) + l_4 \sin(q_2 + q_3 + q_4)$$

Modelo Cinemático

$$\begin{bmatrix} \dot{h}_{ax} \\ \dot{h}_{ay} \\ \dot{h}_{az} \end{bmatrix} = \begin{bmatrix} (-l_2 C_2 - l_3 C_{23} - l_4 C_{234}) S_1 & (-l_2 S_2 - l_3 S_{23} - l_4 S_{234}) C_1 & (-l_3 S_{23} - l_4 S_{234}) C_1 & (-l_4 S_{234}) C_1 \\ (l_2 C_2 - l_3 C_{23} - l_4 C_{234}) C_1 & (-l_2 S_2 - l_3 S_{23} - l_4 S_{234}) S_1 & (-l_3 S_{23} - l_4 S_{234}) S_1 & (-l_4 S_{234}) S_1 \\ 0 & l_2 C_2 + l_3 C_{23} + l_4 C_{234} & l_3 C_{23} + l_4 C_{234} & l_4 C_{234} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix}$$

El modelo cinemático de un robot manipulador móvil representa la velocidad del efector final.



Cinemática Directa

$$h_x = X_r + a \cos(\theta) + l_2 \cos(q_2) \cos(q_1 + \theta) + l_3 \cos(q_2 + q_3) \cos(q_1 + \theta) + l_4 \cos(q_2 + q_3 + q_4) \cos(q_1 + \theta)$$

$$h_y = Y_r + a \sin(\theta) + l_2 \cos(q_2) \sin(q_1 + \theta) + l_3 \cos(q_2 + q_3) \sin(q_1 + \theta) + l_4 \cos(q_2 + q_3 + q_4) \sin(q_1 + \theta)$$

$$h_z = l_1 + l_2 \sin(q_2) + l_3 \sin(q_2 + q_3) + l_4 \sin(q_2 + q_3 + q_4)$$

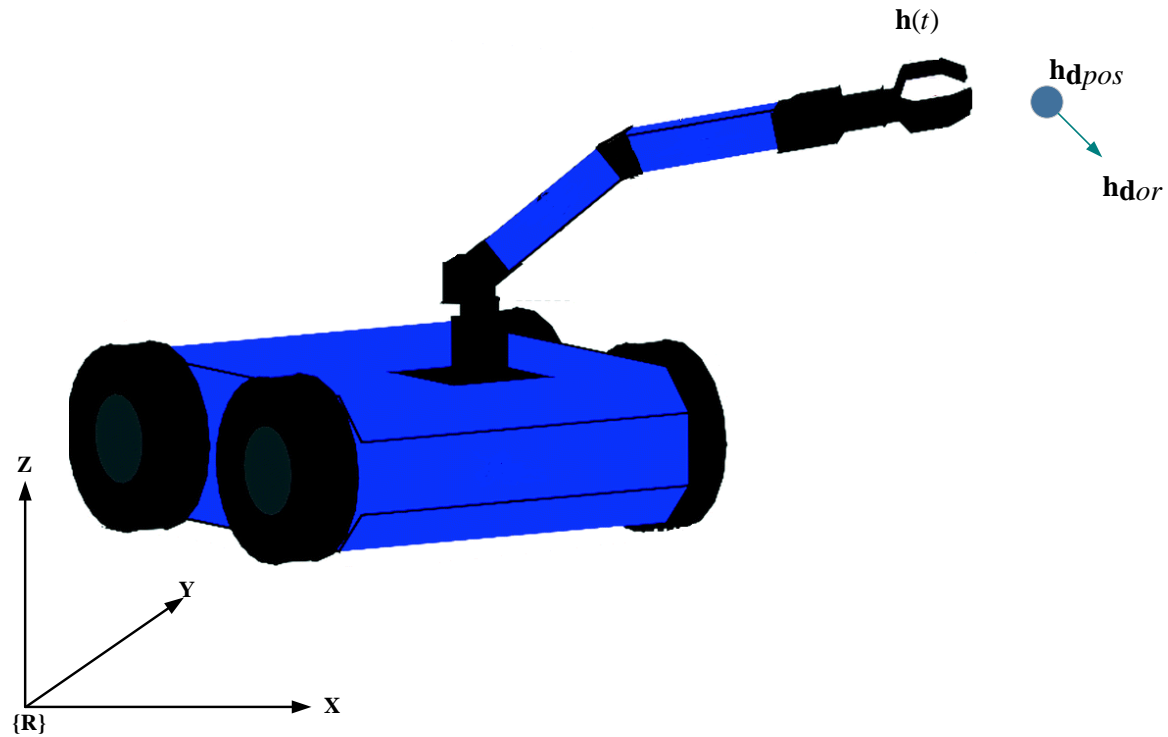
Modelo Cinemático

$$\begin{bmatrix} \dot{h}_x \\ \dot{h}_y \\ \dot{h}_z \end{bmatrix} = \begin{bmatrix} C_\theta & -aS_\theta - (l_2C_2 + l_3C_{23} + l_4C_{234})S_{1\theta} & (-l_2C_2 - l_3C_{23} - l_4C_{234})S_{1\theta} & (-l_2S_2 - l_3S_{23} - l_4S_{234})C_{1\theta} & (-l_3S_{23} - l_4S_{234})C_{1\theta} & (-l_4S_{234})C_{1\theta} \\ S_\theta & aC_\theta + (l_2C_2 + l_3C_{23} + l_4C_{234})C_{1\theta} & (l_2C_2 + l_3C_{23} + l_4C_{234})C_{1\theta} & (-l_2S_2 - l_3S_{23} - l_4S_{234})S_{1\theta} & (-l_3S_{23} - l_4S_{234})S_{1\theta} & (-l_4S_{234})S_{1\theta} \\ 0 & 0 & 0 & l_2C_2 + l_3C_{23} + l_4C_{234} & l_3C_{23} + l_4C_{234} & l_4C_{234} \end{bmatrix} \begin{bmatrix} u \\ \omega \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix}$$



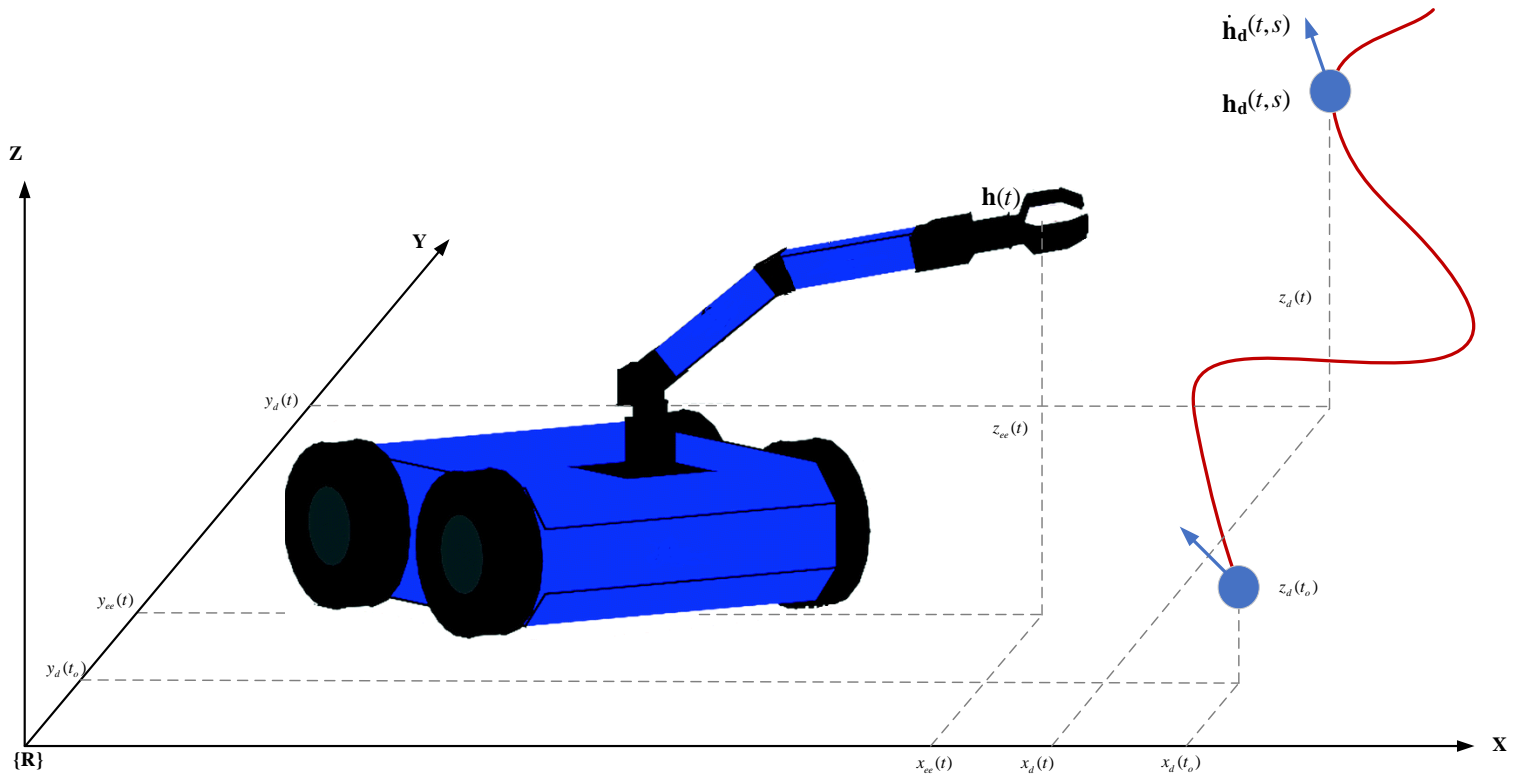
$$\dot{\mathbf{h}}(t) = \mathbf{J}(\mathbf{q}) \mathbf{v}(t)$$





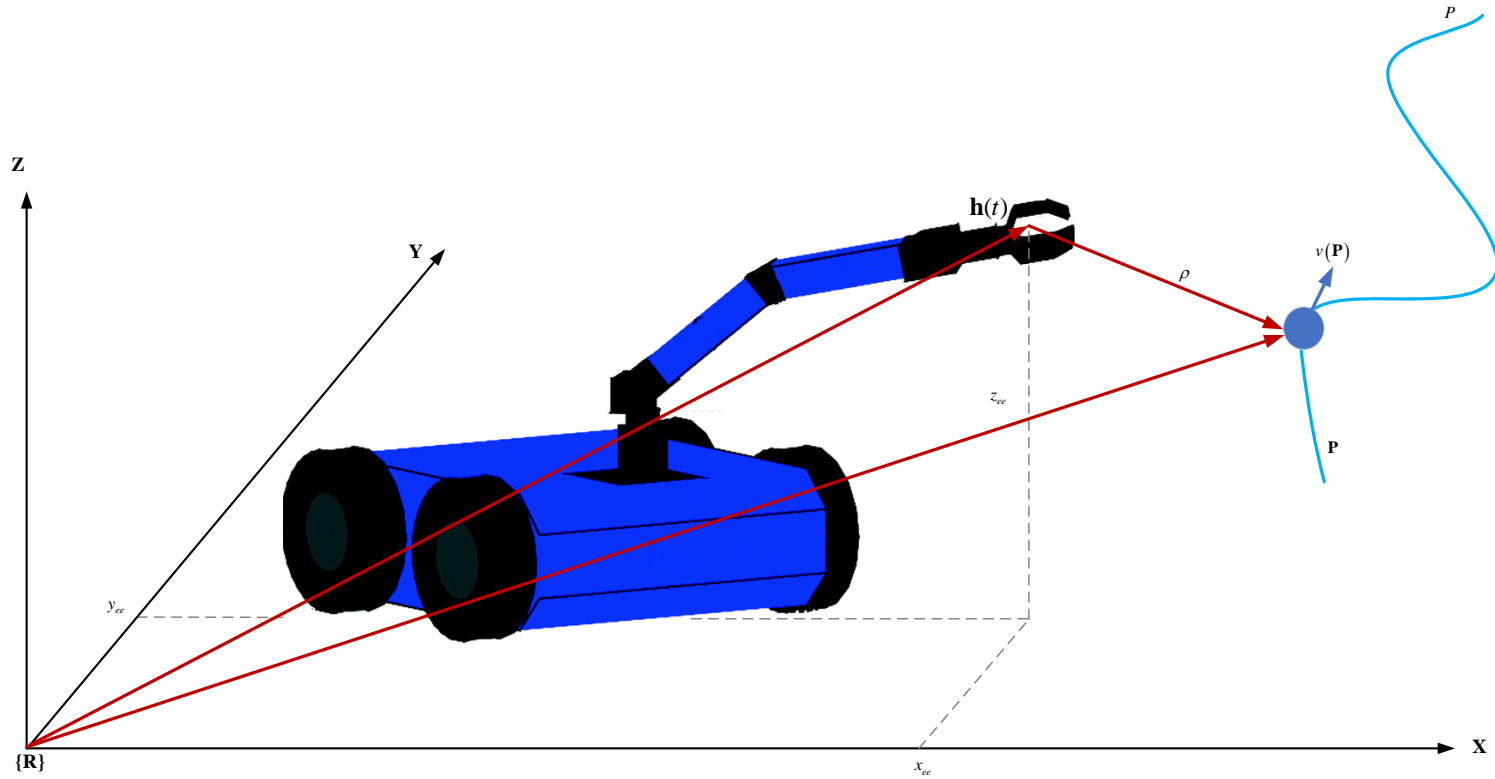
$$\mathbf{h}_d(t, s, \mathbf{h}) = \mathbf{h}_d \quad (\text{Constant})$$

$$\mathbf{v}_{hd}(t, s, \mathbf{h}) = \dot{\mathbf{h}}_d \equiv \mathbf{0}$$



$$\mathbf{h}_d(t, s, \mathbf{h}) = \mathbf{h}_d(t, s)$$

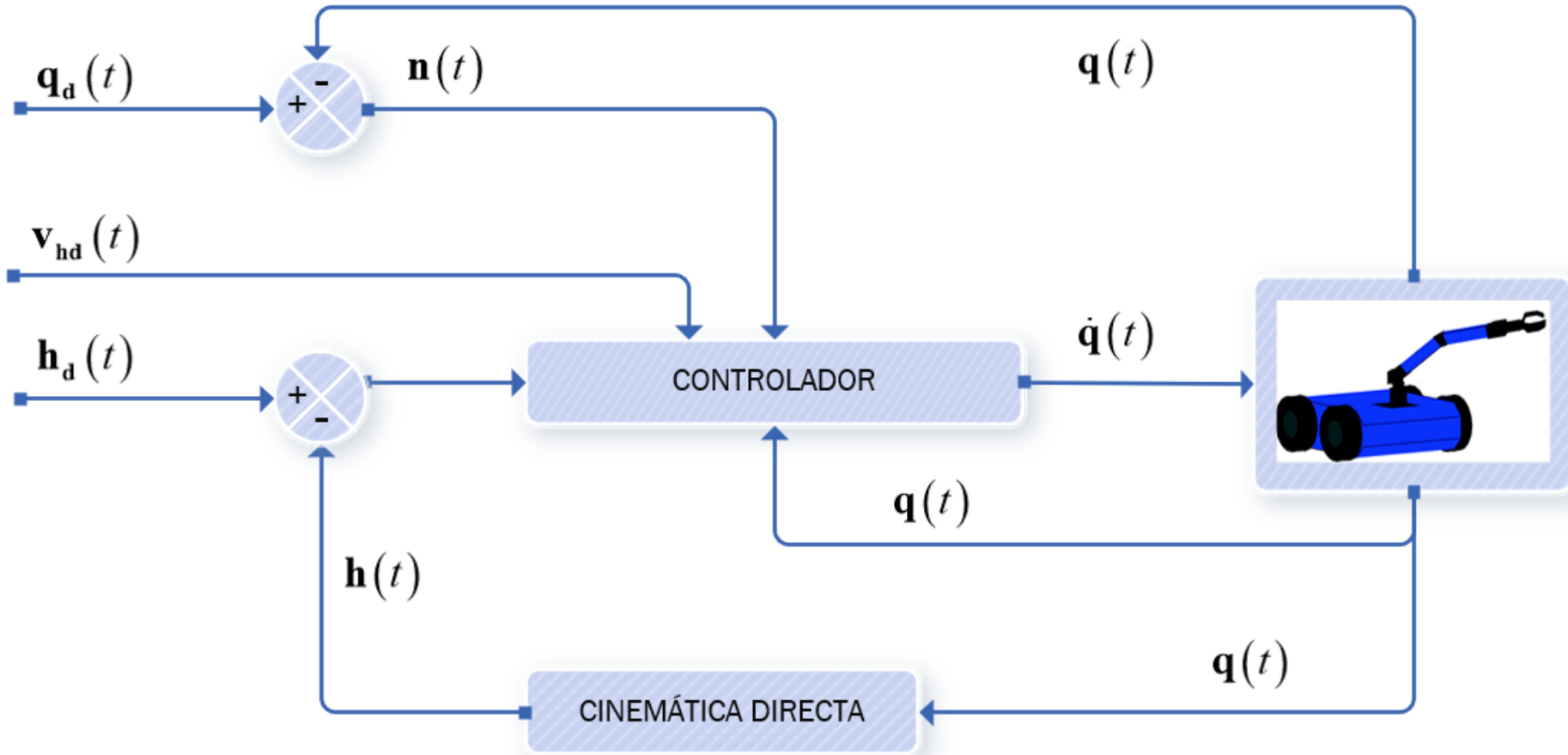
$$\mathbf{v}_{hd}(t, s, \mathbf{h}) = \dot{\mathbf{h}}_d(t, s)$$



$$\mathbf{h}_d(t, s, \mathbf{h}) = \mathbf{P}(s, \mathbf{h})$$

$$\mathbf{v}_{hd}(t, s, \mathbf{h}) = \mathbf{v}_p(s, \mathbf{h})$$

ESQUEMA DE CONTROL UNIFICADO



$$\mathbf{V}_c = \underbrace{\mathbf{J}^\# \left(\mathbf{v}_{hd} + \mathbf{L}_K \tanh \left(\mathbf{L}_K^{-1} \mathbf{K} \tilde{\mathbf{h}} \right) \right)}_{\mathbf{T}_1} + \underbrace{\left(\mathbf{I} - \mathbf{J}^\# \mathbf{J} \right) \mathbf{L}_D \tanh \left(\mathbf{L}_D^{-1} \mathbf{D} \boldsymbol{\eta} \right)}_{\mathbf{T}_2}$$

Objetivo Primario



Controlador

Objetivo Secundario



Sistema Redundante

Considerando la hipótesis de un seguimiento perfecto de la velocidad es decir:

$$\mathbf{V} \equiv \mathbf{V}_c \quad \text{entonces: } \tilde{\mathbf{h}}(t) \rightarrow \mathbf{0} \text{ y } t \rightarrow \infty$$

Ecuación en bucle cerrado:

$$\left(\mathbf{v}_{hd} - \dot{\mathbf{h}} \right) + \mathbf{L}_K \tanh\left(\mathbf{L}_K^{-1} \mathbf{K} \tilde{\mathbf{h}} \right) = \mathbf{0}$$

Considerando $\Upsilon = \dot{\mathbf{h}}_d - \mathbf{v}_{hd}$ y que $\dot{\tilde{\mathbf{h}}} = \dot{\mathbf{h}}_d - \dot{\mathbf{h}}$ tenemos:

$$\dot{\tilde{\mathbf{h}}} + \mathbf{L}_K \tanh\left(\mathbf{L}_K^{-1} \mathbf{K} \tilde{\mathbf{h}} \right) = \Upsilon$$

Para la estabilidad se considera la siguiente función candidata de Lyapunov:

$$\mathbf{V}(\tilde{\mathbf{h}}) = \frac{1}{2} \tilde{\mathbf{h}}^T \tilde{\mathbf{h}}$$

La derivada temporal en las trayectorias del sistema es:

$$\dot{\mathbf{V}}(\tilde{\mathbf{h}}) = \tilde{\mathbf{h}}^T \Upsilon - \tilde{\mathbf{h}}^T \mathbf{L}_K \tanh\left(\mathbf{L}_K^{-1} \mathbf{K} \tilde{\mathbf{h}} \right)$$

Condición para que $\dot{\mathbf{V}}(\tilde{\mathbf{h}})$ sea definida negativa:

$$\left| \tilde{\mathbf{h}}^T \mathbf{L}_K \tanh(\mathbf{L}_K^{-1} \mathbf{K} \tilde{\mathbf{h}}) \right| > \left| \tilde{\mathbf{h}}^T \Upsilon \right|$$

Para valores grandes $\tilde{\mathbf{h}}$ y para que $\dot{\mathbf{V}}$ sea definido negativo:

$$\|\mathbf{L}_K\| > \frac{\|\Upsilon\|}{\tanh(k_{\text{aux}})}$$

Para valores pequeños $\tilde{\mathbf{h}}$ y para que $\dot{\mathbf{V}}$ sea definido negativo es:

$$\|\tilde{\mathbf{h}}\| > k_{\text{aux}} \frac{\|\Upsilon\|}{\lambda_{\min}(\mathbf{K}) \tanh(k_{\text{aux}})}$$

Por lo tanto $\tilde{\mathbf{h}}$ esta limitado por:

$$\|\tilde{\mathbf{h}}\| \leq \frac{k_{\text{aux}} \|\Upsilon\|}{\zeta \lambda_{\min}(\mathbf{K}) \tanh(k_{\text{aux}})} \quad \text{con } 0 < \zeta < 1$$

Control de posición: la velocidad deseada es $\mathbf{v}_{hd} = \dot{\mathbf{h}}_d \equiv \mathbf{0}$ entonces $\Upsilon \equiv \mathbf{0}$

Control trayectoria: la velocidad deseada es $\mathbf{v}_{hd} \equiv \dot{\mathbf{h}}_d$ entonces $\Upsilon \equiv \mathbf{0}$

Control de camino: la velocidad deseada es $\mathbf{v}_{hd} = \dot{\mathbf{h}}_d - \Upsilon$

Considerando la ecuación de lazo cerrado tenemos:

$$\dot{\tilde{\mathbf{h}}} + \mathbf{K}\tilde{\mathbf{h}} = \Upsilon$$

Aplicando la transformada de Laplace tenemos:

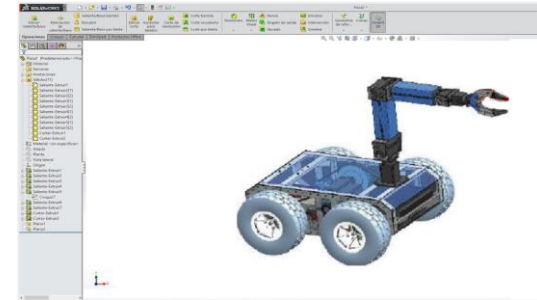
$$\tilde{\mathbf{h}}(s) = (s\mathbf{I} + \mathbf{K})^{-1} \Upsilon(s)$$

Por lo tanto el error de localización del efector final verifica que $\tilde{\mathbf{h}}(t) \rightarrow \mathbf{0}$ es asintóticamente.



CAD

Capa 1



Robot Real Akasha

CARACTERISTICAS

Capa 2

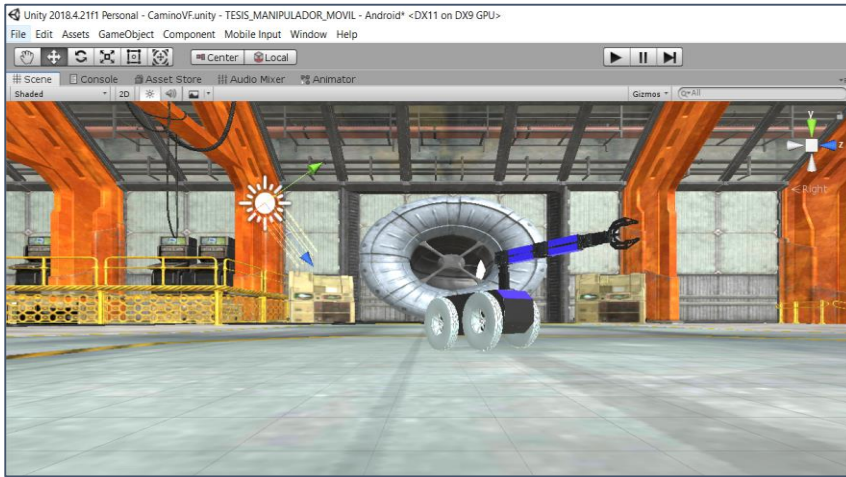


UNITY

Capa 3



Capa 3.1



CONTROL CAMINO

PLATAFORMA
X= 2,1569 m
Y= -1,7415 m
phi= -8,4814 rad

BRAZO
Q1= -1,0658 rad
Q2= -0,1942 rad
Q3= -0,1906 rad
Q4= 0,8036 rad

Hxd: $2,2 \cdot \sin(0,3 \cdot t)$ m
Hyd: $2,2 \cdot \cos(0,3 \cdot t)$ m
Hzd: 0,3 m

Q1d: -60 grados
Q2d: -45 grados
Q3d: -30 grados
Q4d: 45 grados

Tiempo: 40 seg

Deseado: — Real: —



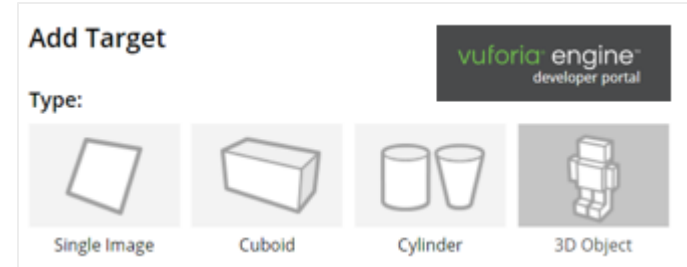
Capa 3.2

Add Target

vuforia engine™
developer portal

Type:

Single Image Cuboid Cylinder 3D Object



IDENTIFICACIÓN 3D

Referencia Escaneo y obtención de puntos característicos Validación



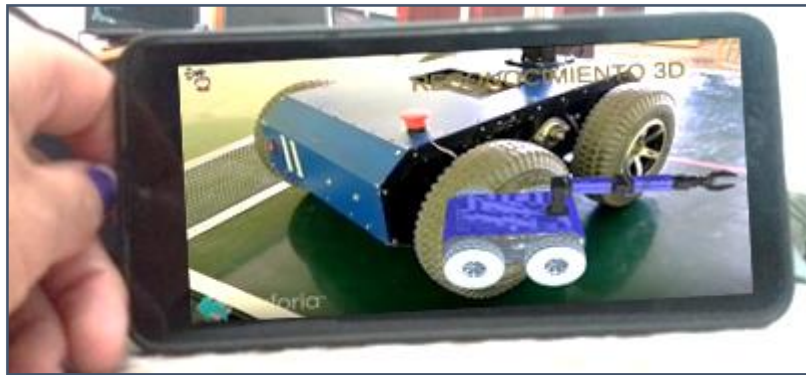
IDENTIFICACIÓN 2D



Capa 4



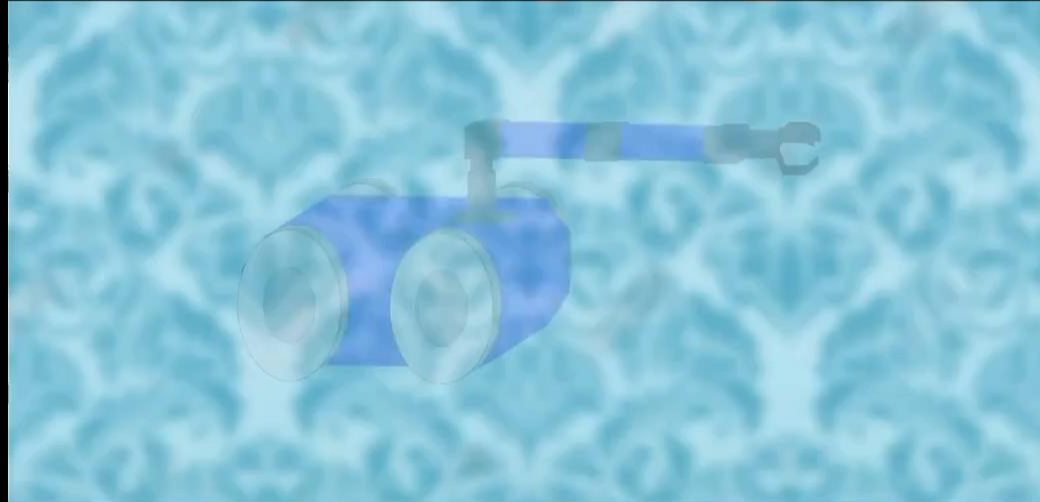
a. Reconocimiento del marcador 2D



b. Reconocimiento del marcador 3D







RESULTADOS OBTENIDOS

Preguntas	Puntuación					Operación
	0	1	2	3	4	
Le gustaría usar la aplicación con frecuencia.				5	10	3,67
Considera que la aplicación es compleja e innecesaria.	11	4				3,73
Usted cree que el uso de la aplicación en la realidad aumentada fue fácil de usar.				5	10	3,67
Necesitas un manual o ayuda para usar la aplicación.	15					4,00
Usted cree que las funciones de la aplicación están correctamente distribuidas e integradas.			3	1	11	3,53
Hay flexibilidad en el uso de la aplicación.			1	4	10	3,60
Cree que la gente aprendería al usar la aplicación.				1	14	3,93
Al usar la aplicación, me resulta muy difícil.	10	4	1			3,60
Considera que la interacción de la aplicación con el usuario fue intuitiva y amigable.				5	10	3,67
Creas que necesitas tener conocimientos previos para usar la aplicación	11	4				3,73
TOTAL						37,13

El resultados de la prueba del SUS es del 92,83%.



CONCLUSIONES

- ✓ La realidad aumentada es una herramienta tecnológica que contribuye a la enseñanza-aprendizaje, que permite, interactuar con todas las capacidades físicas del entorno dentro de todas las áreas de investigación.
- ✓ El modelo cinemático permite determinar las características de movimiento y las restricciones que puede tener el sistema robótico, para ser utilizado en los algoritmos de control, basándose en un controlador cinemático redundante.
- ✓ Fue posible implementar un esquema de control unificado que considera los tres problemas básicos de control, tal como, posición, trayectoria y seguimiento de camino, a través de una sola ley de control y mediante un switch se puede realizar cualquier tipo de tarea compleja o sencilla.
- ✓ Mediante la teoría de Lyapunov se realizó el análisis de estabilidad del sistema demostrando que los errores de control convergen a cero, siendo asintóticamente estable.
- ✓ La aplicación desarrollada es amigable para el usuario y permite interactuar con el robot virtualizado, a través de un smartphone.



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