



**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 Ingeniera en  
Electrónica e Instrumentación**

**CONTROL ÓPTIMO DE SEGUIMIENTO DE TRAYECTORIA PARA UN ROBOT  
MANIPULADOR AÉREO BASADO EN EL ERROR DINÁMICO DE CONTROL**

**Autor:**

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4 August 2023

## Meaningful Learning Processes of Service Robots for Tracking Trajectories through Virtual Environments.

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**Abstract.** This paper is devoted to the study and control of an aerial manipulator robot (AMR) to perform tracking tasks autonomously, in order to apply LQR linear system control algorithms and application methods in a 3D virtual environment. Prior to obtaining a linearized kinematic model of the robotic systems, which allows to perform missions that require both navigation and manipulation capabilities in partially structured areas or environments. Through the use of the advanced control algorithm, a virtualized environment was developed in a 3D simulator for educational processes as a form of testing, which allows to evaluate the movement and evolution of the control errors, both for verification and visualization of the RMA behavior. Finally, the stability and robustness of the proposed RMA control is tested and experimentally analyzed using the DJI Matrice 600 Pro UAV tethered to an anthropomorphic 3DOF robotic arm. Therefore, these results are exposed and discussed to validate the proposed controller and ensure its correct operation.

**Keywords:** Control, linearization, stability and robustness.

### 1 Introduction

In recent years, robotics research has fostered the development of multiple applications focused on improving and assisting humans. Its development has expanded in several areas, in order to generate sustainable solutions in the fields of industry, education, medicine, training, military fields, among others [1, 2]. Therefore, robotics is considered as a support and service tool outside of industry, giving rise to service robotics. Service robots are related to the interaction and collaborative work between robots and humans, in partially structured environments [2]. In this context, service robotics is intended to provide support for activities that may be considered risky for humans. Preventing users from being affected by activities in hostile environments, unfamiliar environments and/or repetitive activities that may affect the user [3]. The International Federation of Robotics (IFR) defines a service robot as a robot that performs useful tasks for humans or equipment to recognize and manipulate objects in different locations and from different heights, have locomotion on different types of surfaces, interact with a human, distinguish different people, among others [4, 5]. Since there are several areas of work, they have had to adapt to these new changes, the educational sector is one of the most influential factors in the process of teaching and researching these service robots. [6, 7].



Lecture Notes in Networks and Systems

Q4

Computer Networks and Communications  
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Acceptance Letter - Future of Information and Communication Conference (FICC) 2024

Dear Jhonatan Wladimir Tercero Gualpa Jessica S. Ortiz,

Congratulations! Your paper "Meaningful Learning Processes of Service Robots for Tracking Trajectories through Virtual Environments" has been accepted for oral presentation in the Future of Information and Communication Conference (FICC) 2024 to be held from 4-5 April 2024, Berlin, Germany.

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

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 of Information and Communication 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 of Information and Communication Conference (FICC) 2024.

Online Registration: <http://saiconference.com/FICC>

Regards,  
Supriya Kapoor  
Conference Manager  
Future of Information and Communication Conference (FICC) 2024  
<http://saiconference.com/FICC>

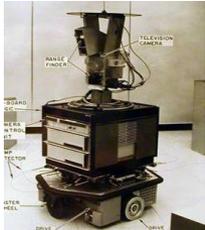
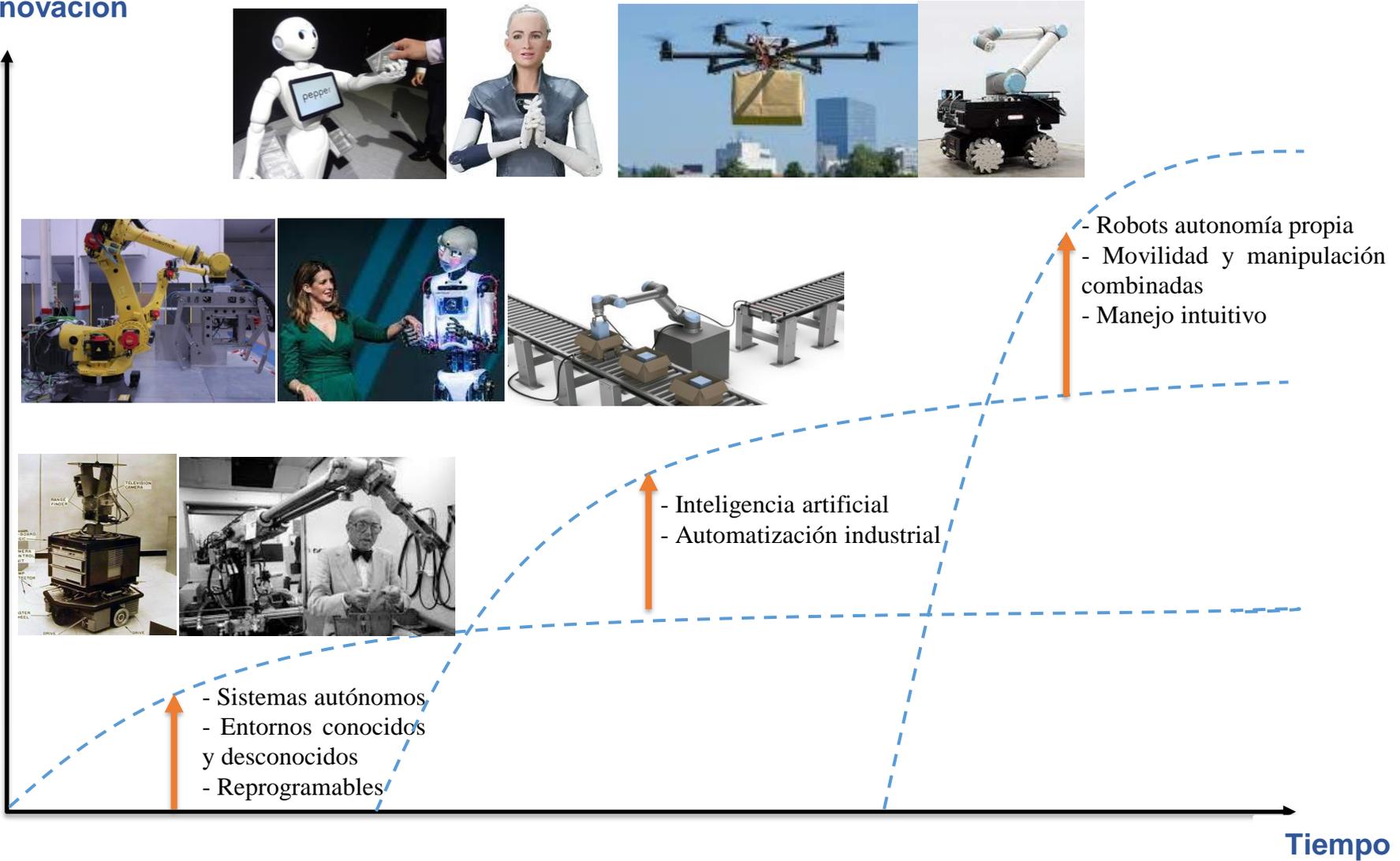




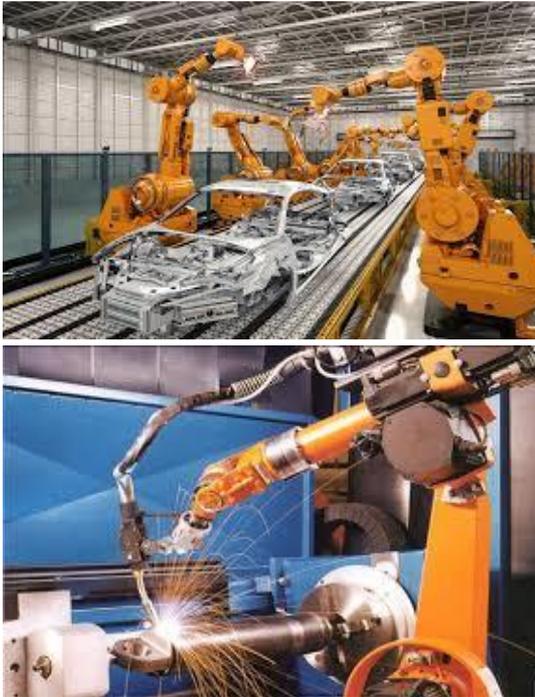


# Evolución de la Robótica

## Innovación



Industriales

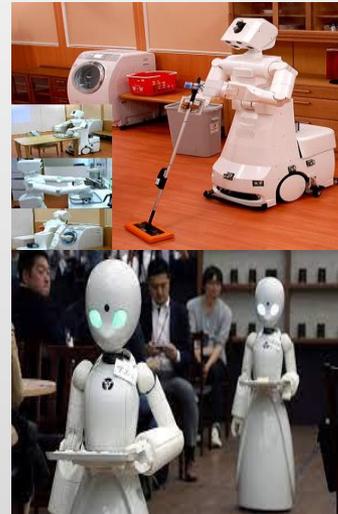


De servicio



PERSONALES

PROFESIONALES



# Aplicaciones de los UAV



**MATRICE  
600PRO**

Campo  
Militar



Campo  
Comercial



Campo  
Industrial



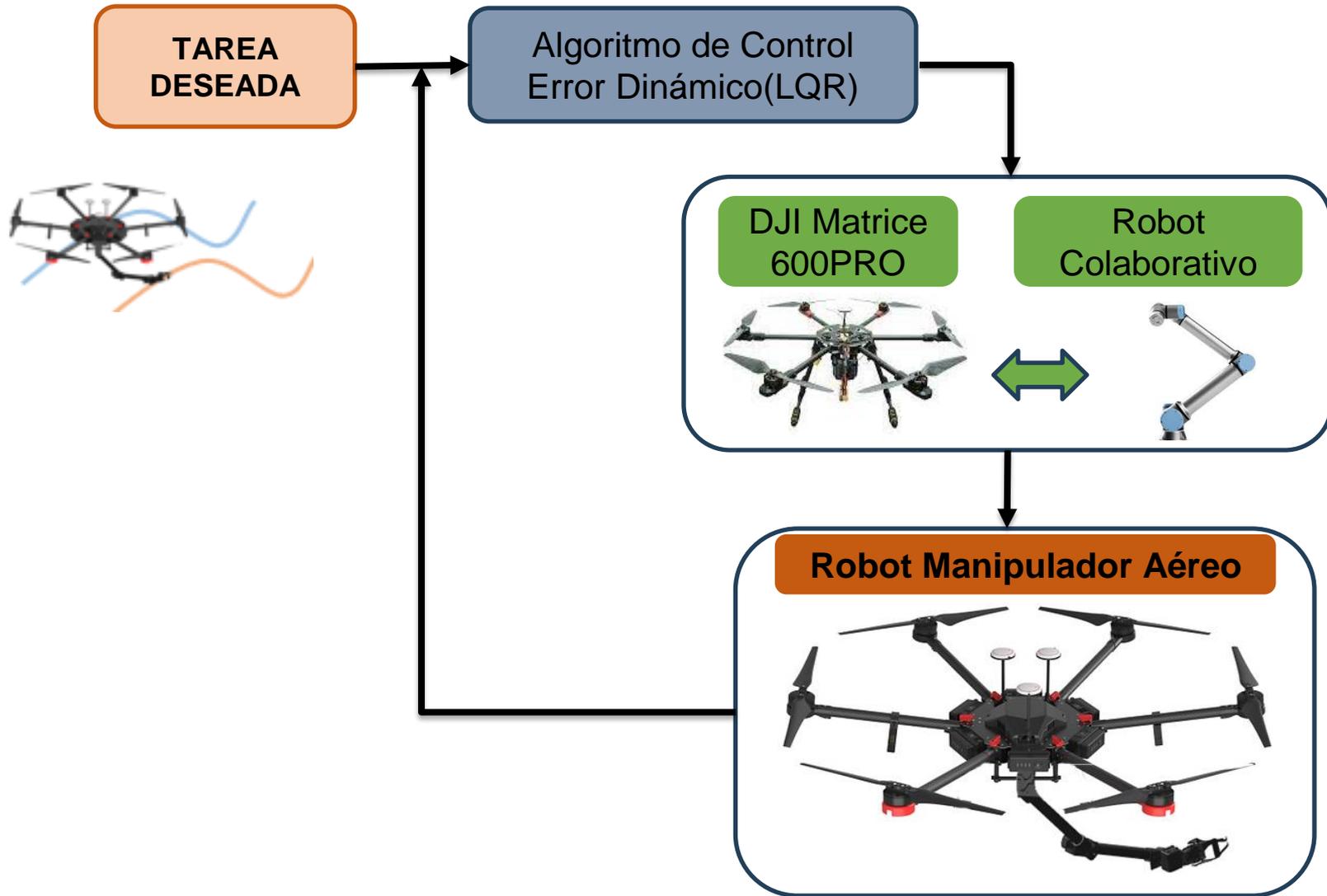
## ROBOTS MANIPULADORES

Robots  
industriales



Robots  
colaboradores



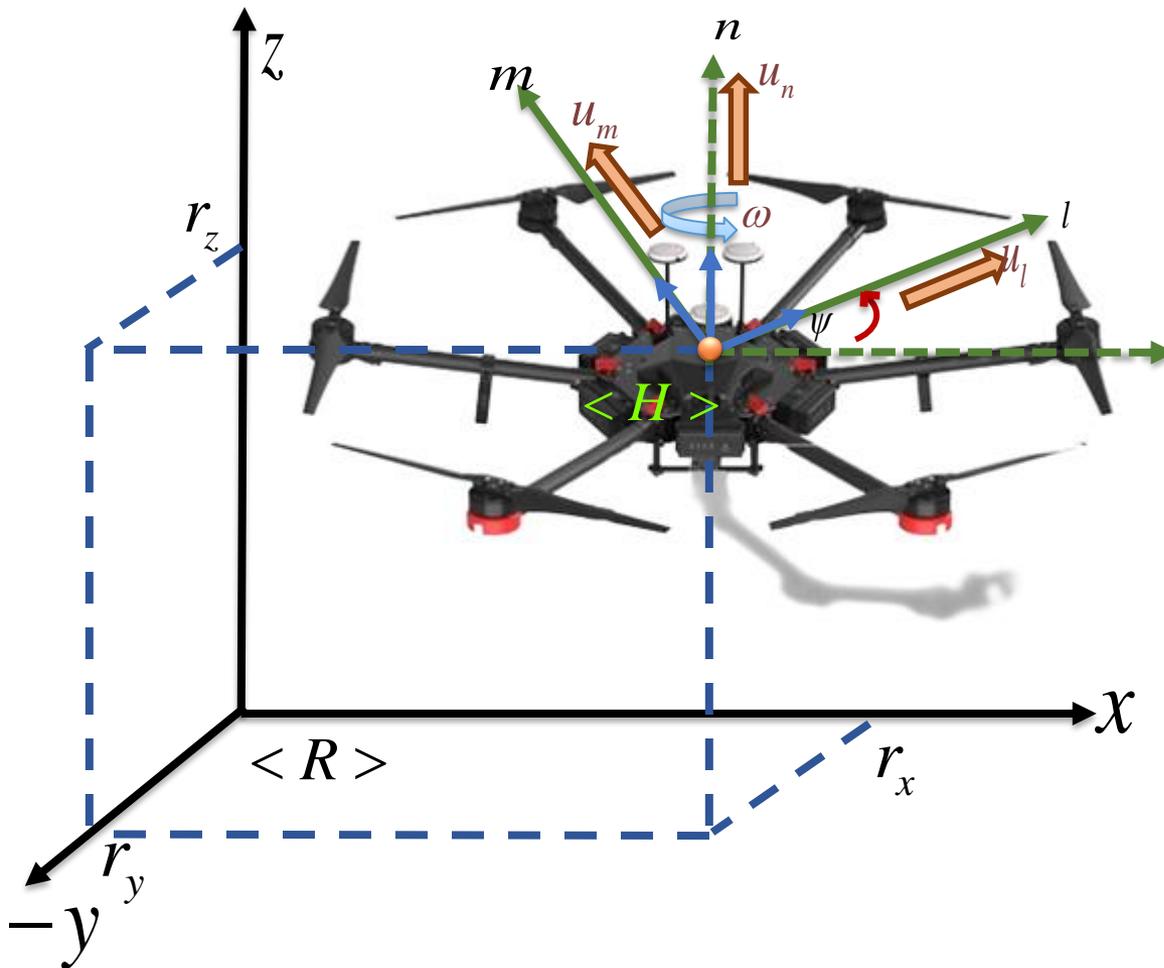


Implementar un **esquema de control avanzado** para ejecutar tareas de seguimiento de trayectorias óptimas a través de un robot manipulador aéreo, conformado por un brazo robótico tipo antropomórfico y un vehículo aéreo no tripulado de seis hélices rotativas.

- Investigar en las diversas **bases de datos científicas acerca de la modelación, y técnicas de control** para la ejecución de tareas de seguimiento de trayectoria de un robot manipulador aéreo.
- Determinar las **características y restricción de movimiento de un robot manipulador aéreo**, conformado por un brazo robótico tipo antropomórfico sobre un vehículo aéreo no tripulado de seis hélices.
- **Proponer un algoritmo de control** para tareas de seguimiento de trayectoria óptima de un robot manipulador aéreo considerando el error dinámico de control.

- **Analizar matemáticamente la estabilidad del algoritmo de control propuesto**, a fin de evaluar la evolución de los errores de control.
- **Simular y ajustar los parámetros del algoritmo de control propuesto** con el objetivo de analizar el desempeño del robot al ejecutar tareas de seguimiento de trayectoria.
- **Desarrollar pruebas experimentales sobre un robot manipulador aéreo**, conformado por un brazo robótico y un vehículo aéreo no tripulado de seis hélices, con el propósito de evaluar el algoritmo de control propuesto.





Velocidades en  $\langle H \rangle$

$m, n, l, \psi$

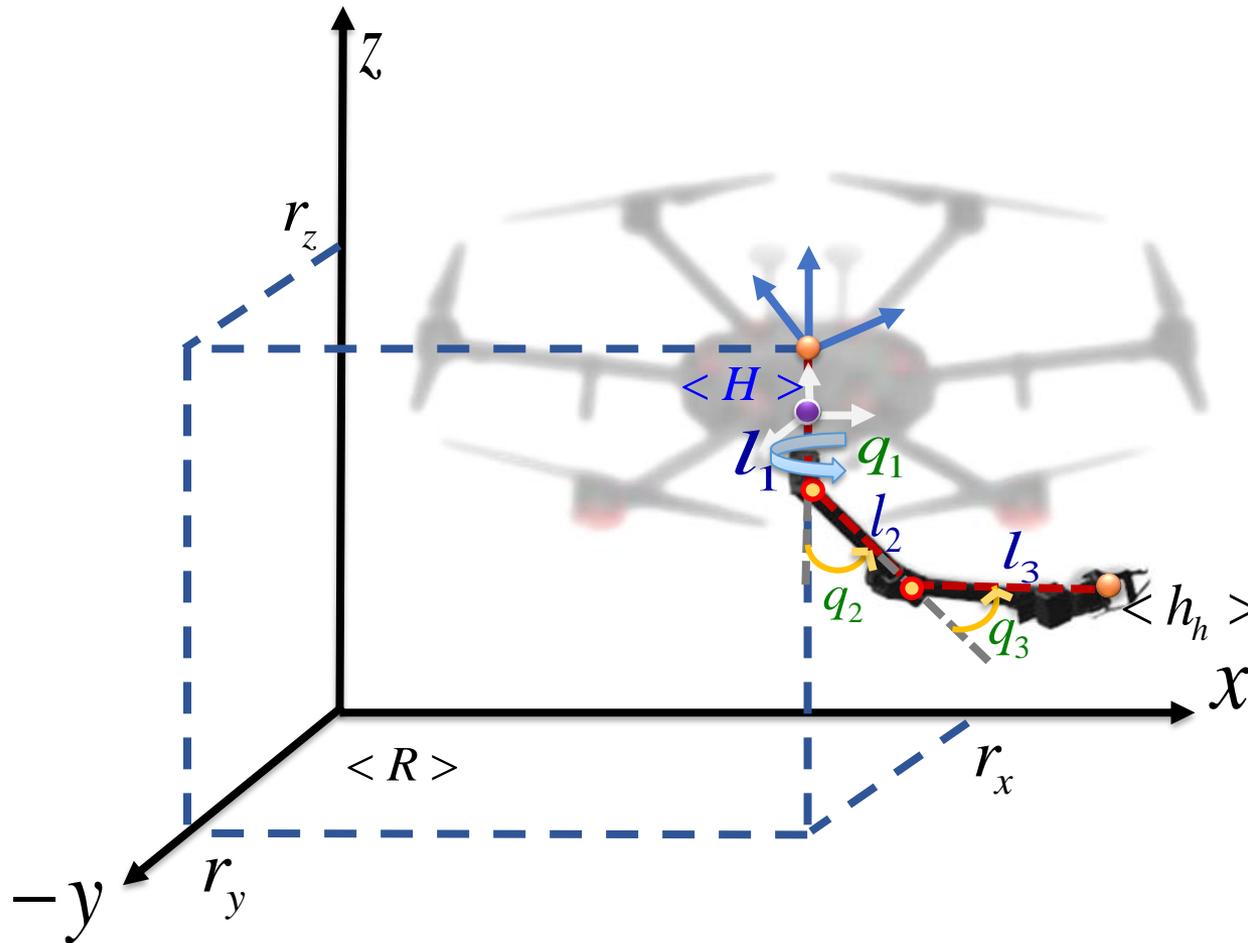
Velocidades de maniobrabilidad

$u_m, u_n, u_l, \omega$

Modelo Cinemático

$$\begin{bmatrix} \dot{r}_x \\ \dot{r}_y \\ \dot{r}_z \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 & 0 \\ \sin(\psi) & \cos(\psi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_l \\ u_m \\ u_n \\ \omega \end{bmatrix}$$

$$\dot{\mathbf{r}}(t) = \mathbf{\Gamma}(\psi) \mathbf{u}(t) \quad (1)$$



Eslabones

$$l_1, l_2, l_3$$

Articulaciones

$$q_1, q_2, q_3$$

Cinemática  
Directa

$$h_h = f(\mathbf{q})$$

## Cinemática Directa $h_h = f(\mathbf{q})$

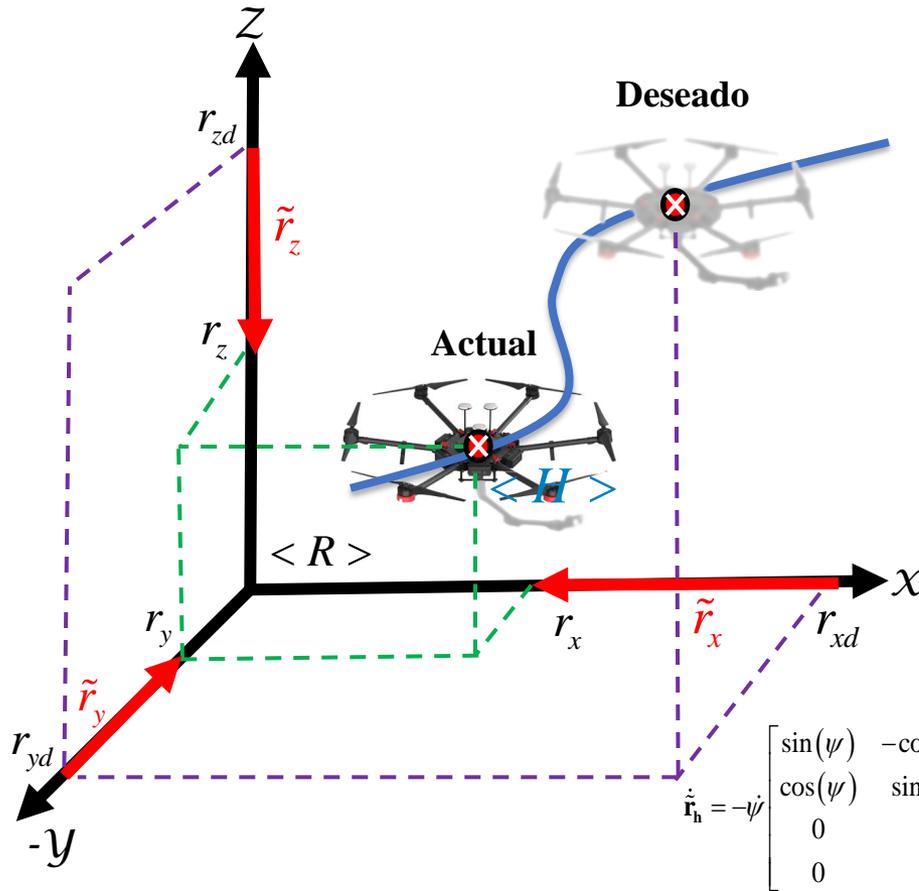
$$\begin{cases} h_l = l_2 \cos(q_2) \cos(q_1) + l_3 \cos(q_2 + q_3) \cos(q_1) \\ h_m = l_2 \cos(q_2) \sin(q_1) + l_3 \cos(q_2 + q_3) \sin(q_1) \\ h_n = l_1 + l_2 \sin(q_2) + l_3 \sin(q_2 + q_3) \end{cases}$$

## Modelo Cinemático $\frac{d}{dt} h_h = \frac{d}{dt} f(\mathbf{q})$

$$\begin{bmatrix} \dot{h}_l \\ \dot{h}_m \\ \dot{h}_n \end{bmatrix} = \begin{bmatrix} -S_1(l_2 S_2 + l_3 S_{23}) & C_1(l_2 C_2 + l_3 C_{23}) & C_1(l_3 C_{23}) \\ C_1((l_2 S_2) + l_3 S_{23}) & S_1(l_2 C_2 + l_3 C_{23}) & S_1(l_3 C_{23}) \\ 0 & l_2 S_2 + l_3 S_{23} & l_3 S_{23} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix}$$

$$\boxed{\dot{\mathbf{h}}_h(t) = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}(t)} \quad (2)$$





Actual

Deseado

$$\dot{\mathbf{r}}(t) = \mathbf{\Gamma}(\psi) \mathbf{u}(t) \quad \dot{\mathbf{r}}_d(t) = \mathbf{\Gamma}_d(\psi_d) \mathbf{u}_d(t)$$

Error de posición

$$\tilde{\mathbf{r}} = \mathbf{r}_d(t) - \mathbf{r}(t)$$

$$\tilde{\mathbf{r}} = \begin{bmatrix} r_{xd} - r_x & r_{yd} - r_y & r_{zd} - r_z & \psi_d - \psi \end{bmatrix}^T$$

$$\tilde{\mathbf{r}} = \begin{bmatrix} \tilde{r}_x & \tilde{r}_y & \tilde{r}_z & \tilde{\psi} \end{bmatrix}^T$$

Dinámica del Error

$$\tilde{\mathbf{r}}_h = \mathbf{\Gamma}^{-1}(\psi) \tilde{\mathbf{r}}$$

Derivar: 
$$\dot{\tilde{\mathbf{r}}}_h = \dot{\mathbf{\Gamma}}^{-1} \tilde{\mathbf{r}} + \mathbf{\Gamma}^{-1} \dot{\tilde{\mathbf{r}}}$$

Sustituir: 
$$\dot{\tilde{\mathbf{r}}}_h = \dot{\mathbf{\Gamma}}^{-1} \mathbf{\Gamma} \tilde{\mathbf{r}}_h + \mathbf{\Gamma}^{-1} \mathbf{\Gamma}_d \mathbf{u}_d - \mathbf{u}$$

Reemplazar:

$$\begin{bmatrix} \sin(\psi) & -\cos(\psi) & 0 & 0 \\ \cos(\psi) & \sin(\psi) & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 & 0 \\ \sin(\psi) & \cos(\psi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \tilde{r}_l \\ \tilde{r}_m \\ \tilde{r}_n \\ \tilde{\psi} \end{bmatrix} + \begin{bmatrix} \cos(\tilde{\psi}) & \sin(\tilde{\psi}) & 0 & 0 \\ -\sin(\tilde{\psi}) & \cos(\tilde{\psi}) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_{ld} \\ u_{md} \\ u_{nd} \\ \omega_d \end{bmatrix} - \begin{bmatrix} u_l \\ u_m \\ u_n \\ \omega \end{bmatrix}$$

Linealiza la Dinámica del Error:

$$\dot{\tilde{\mathbf{r}}}_h = -\tilde{\psi} \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{r}_l \\ \tilde{r}_m \\ \tilde{r}_n \\ \tilde{\psi} \end{bmatrix} + \begin{bmatrix} 1 & \tilde{\psi} & 0 & 0 \\ -\tilde{\psi} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_{ld} \\ u_{md} \\ u_{nd} \\ \omega_d \end{bmatrix} - \begin{bmatrix} u_l \\ u_m \\ u_n \\ \omega \end{bmatrix}$$

Simplificando:

$$\dot{\tilde{\mathbf{r}}}_h = \begin{bmatrix} \omega \tilde{r}_m + u_{ld} - u_{md} \tilde{\psi} - u_l \\ -\omega \tilde{r}_l + u_{ld} \tilde{\psi} + u_{md} - u_m \\ u_{nd} - u_n \\ \omega_d - \omega \end{bmatrix}$$

Modelo linealizado:

$$\begin{bmatrix} \dot{\tilde{r}}_l \\ \dot{\tilde{r}}_m \\ \dot{\tilde{r}}_n \\ \dot{\tilde{\psi}} \end{bmatrix} = \begin{bmatrix} 0 & \omega & 0 & -u_{md} \\ -\omega & 0 & 0 & u_{ld} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{r}_l \\ \tilde{r}_m \\ \tilde{r}_n \\ \tilde{\psi} \end{bmatrix} + \mathbf{I} \begin{bmatrix} \Delta u_l \\ \Delta u_m \\ \Delta u_n \\ \Delta \omega \end{bmatrix}$$

Sistema Linealizado:

$$\dot{\tilde{\mathbf{r}}}_h = \mathbf{A}\tilde{\mathbf{r}} + \mathbf{B}\Delta\mathbf{u}$$

(3)



Derivamos el error del extremo operativo:

$$\dot{\tilde{\mathbf{h}}}_h = \dot{\mathbf{R}}^{-1}\tilde{\mathbf{h}}_R + \mathbf{R}^{-1}\dot{\tilde{\mathbf{h}}}_R$$

Sustituyendo:

$$\dot{\tilde{\mathbf{h}}}_h = \dot{\mathbf{R}}^{-1}\mathbf{R}\tilde{\mathbf{h}}_h + \mathbf{R}^{-1}(\dot{\mathbf{h}}_{Rd} - \dot{\mathbf{h}}_h)$$

$$\dot{\tilde{\mathbf{h}}}_h = \dot{\mathbf{R}}^{-1}\mathbf{R}\tilde{\mathbf{h}}_h + \mathbf{R}^{-1}\mathbf{R}_d\dot{\mathbf{h}}_{hd} - \mathbf{R}^{-1}\mathbf{R}\dot{\mathbf{h}}_h$$

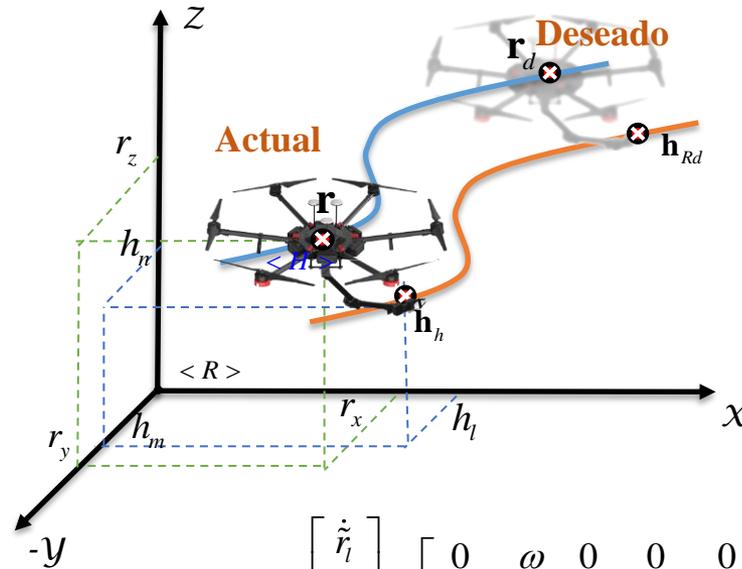
Modelo linealizado:

$$\dot{\tilde{\mathbf{h}}}_h = \begin{bmatrix} \omega\tilde{h}_m - \dot{h}_l + \dot{h}_{ld} - \dot{h}_{md} \\ -\omega\tilde{h}_l - \dot{h}_m + \dot{h}_{ld} - \dot{h}_{md} \\ \dot{h}_{nd} - \dot{h}_n \end{bmatrix}$$

Sistema Linealizado:

$$\dot{\tilde{\mathbf{h}}}_h = \mathbf{A}\tilde{\mathbf{h}} + \mathbf{B}\Delta\dot{\mathbf{h}}$$

(4)



Dos Sistemas Linealizados  
Unificados:

$$\dot{\tilde{\mathbf{e}}} = \begin{bmatrix} \dot{\tilde{r}}_l \\ \dot{\tilde{r}}_m \\ \dot{\tilde{r}}_n \\ \dot{\tilde{h}}_l \\ \dot{\tilde{h}}_m \\ \dot{\tilde{h}}_n \\ \dot{\tilde{r}}_\psi \end{bmatrix} = \begin{bmatrix} 0 & \omega & 0 & 0 & 0 & 0 & -u_{md} \\ -\omega & 0 & 0 & 0 & 0 & 0 & u_{ld} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \omega & 0 & \dot{h}_{ld} \\ 0 & 0 & 0 & -\omega & 0 & 0 & \dot{h}_{md} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{r}_l \\ \tilde{r}_m \\ \tilde{r}_n \\ \tilde{h}_l \\ \tilde{h}_m \\ \tilde{h}_n \\ \tilde{r}_\psi \end{bmatrix} + \mathbf{I} \begin{bmatrix} \Delta u_l \\ \Delta u_m \\ \Delta u_n \\ \Delta \dot{h}_l \\ \Delta \dot{h}_m \\ \Delta \dot{h}_n \\ \Delta \omega \end{bmatrix}$$

Sistema lineal de los errores  
de control:

$$\dot{\tilde{\mathbf{e}}} = \Lambda \tilde{\mathbf{e}} + \beta \Delta \mathbf{u} \quad (5)$$

Función de coste

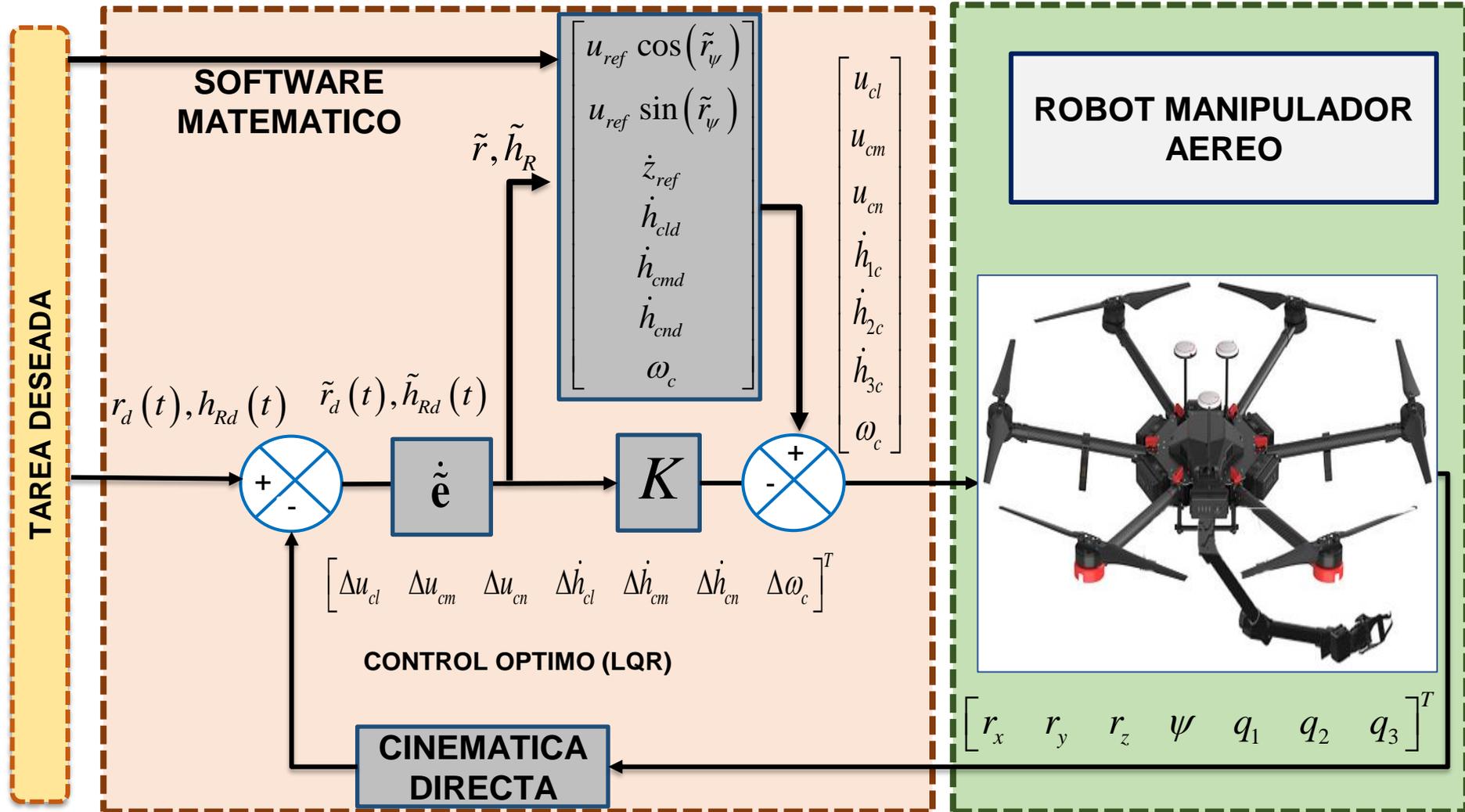
$$\mathbf{J}_F = \frac{1}{2} \int_0^{\infty} \left( \tilde{\mathbf{e}}_{(t)}^T \mathbf{Q} \tilde{\mathbf{e}}_{(t)} + \Delta \mathbf{v}_{(t)}^T \mathbf{R} \Delta \mathbf{v}_{(t)} \right) dt$$

Ley de control

$$\mathbf{u}_c = \mathbf{K} \mathbf{r} + \mathbf{u}_{ref}$$

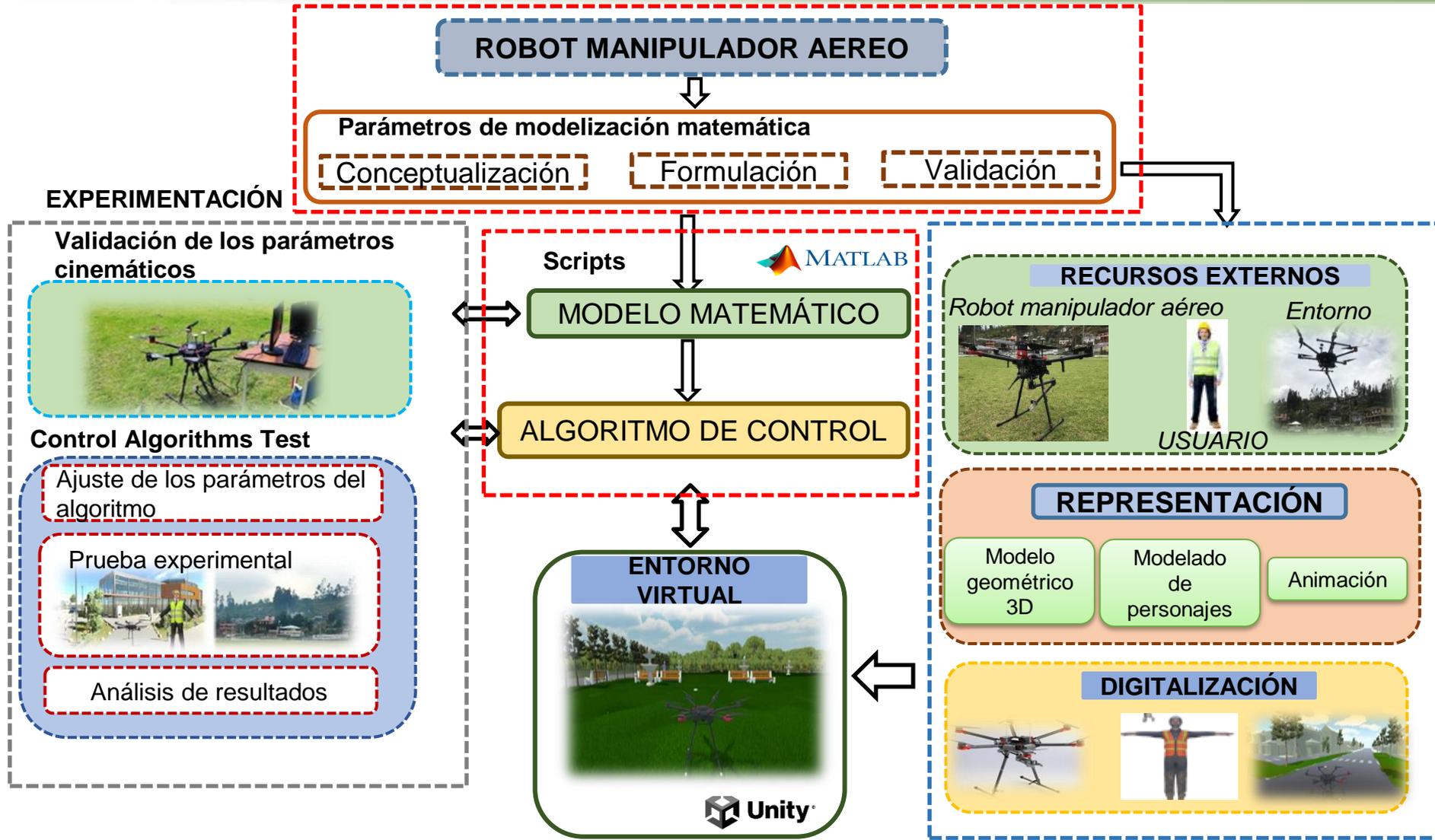
Realimentación del bucle

$$\begin{bmatrix} u_{cl} \\ u_{cm} \\ u_{cn} \\ \dot{h}_{cl} \\ \dot{h}_{cm} \\ \dot{h}_{cn} \\ \omega_c \end{bmatrix} = \begin{bmatrix} \Delta u_{cl} \\ \Delta u_{cm} \\ \Delta u_{cn} \\ \Delta \dot{h}_{cl} \\ \Delta \dot{h}_{cm} \\ \Delta \dot{h}_{cn} \\ \Delta \omega_c \end{bmatrix} + \begin{bmatrix} u_{ref} \cos(\tilde{\psi}) \\ u_{ref} \sin(\tilde{\psi}) \\ \dot{z}_{ref} \\ \dot{h}_{cld} \\ \dot{h}_{cmd} \\ \dot{h}_{cnd} \\ \omega_c \end{bmatrix}$$





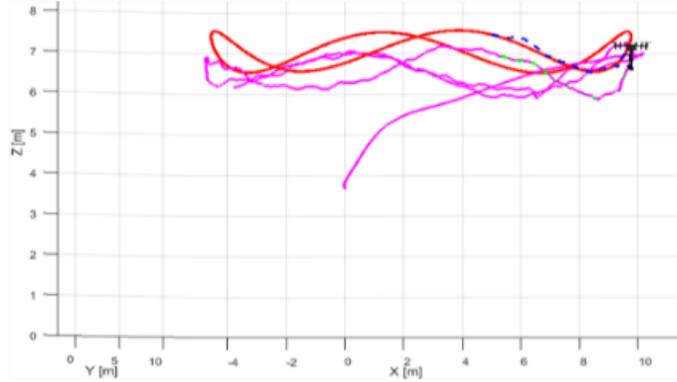
# Resultados Obtenidos



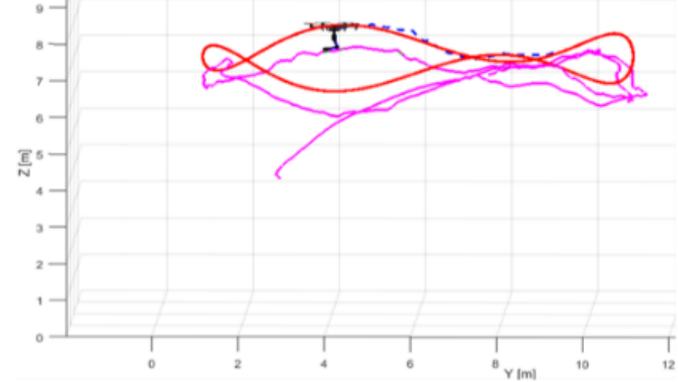
Video



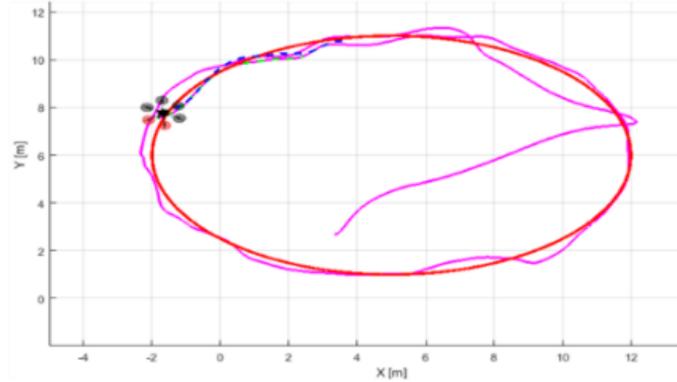
View [Z, X]



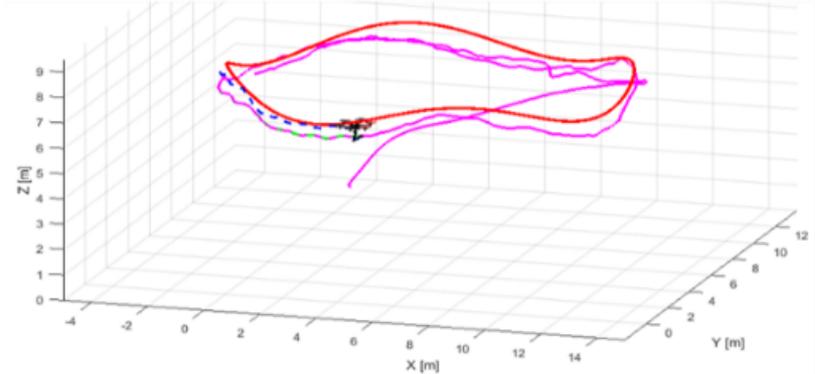
View [Z, Y]



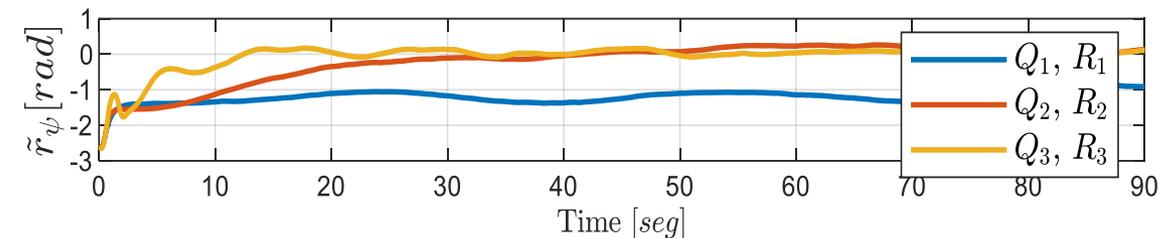
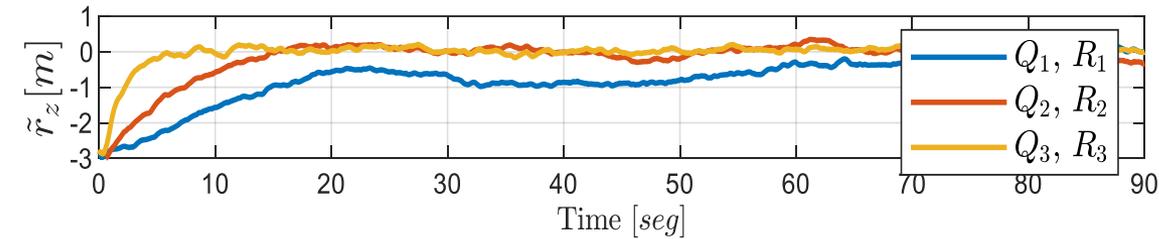
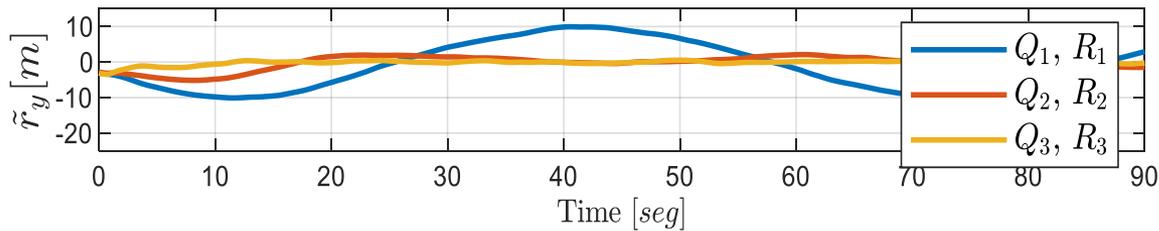
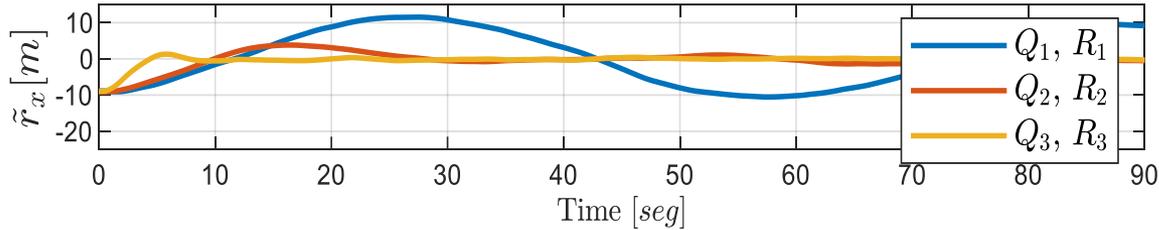
View [Y, X]



View [X, Y, Z]



# Errores de control del UAV

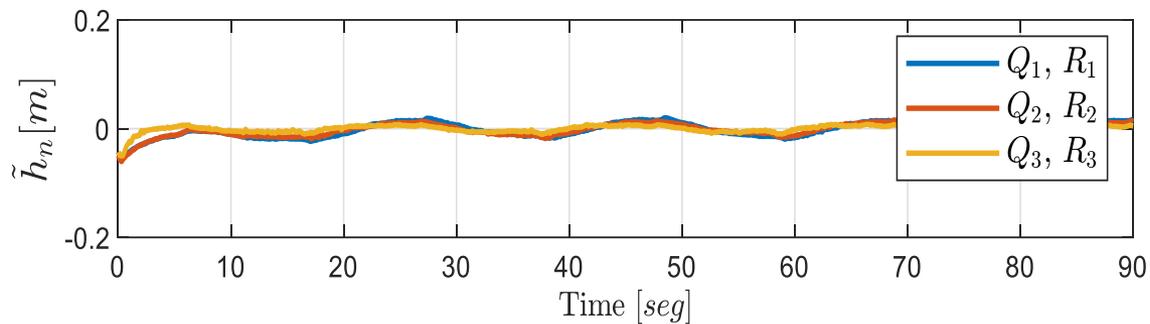
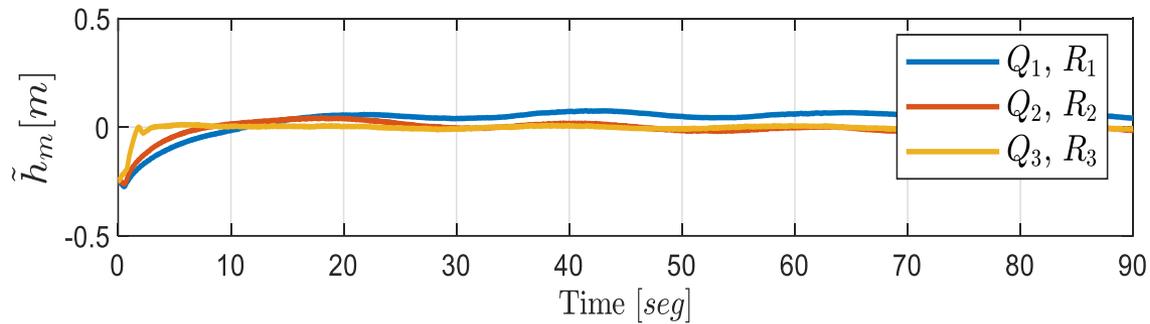
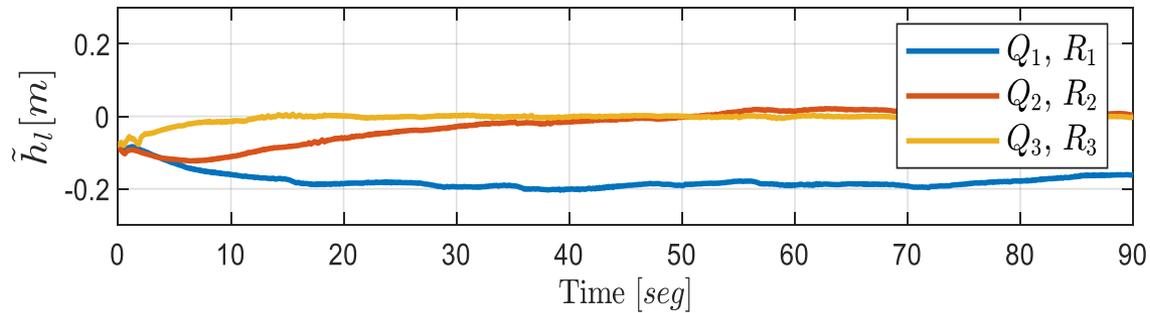


$Q_{123}$  Es una matriz cuadrática semidefinida que lleva los estados del sistema

$R_{123}$  Es una matriz cuadrada que contiene las acciones de corrección de errores

$$\tilde{r}_x, \tilde{r}_y, \tilde{r}_z, \tilde{r}_\psi$$

Es un vector de errores en el <R>



$Q_{123}$  Es una matriz cuadrática semidefinida que lleva los estados del sistema

$R_{123}$  Es una matriz cuadrada que contiene las acciones de corrección de errores

$$\tilde{h}_l, \tilde{h}_m, \tilde{h}_n$$

Es un vector de errores del extremo operativo



- Se obtuvo el modelo cinemático del manipulador aéreo, para esto se considera al robot aéreo como **dos sistemas independientes, robot aéreo y el brazo robótico**. Mediante estos modelos se realiza la obtención del **modelo del error de seguimiento de trayectoria**.
- Para el desarrollo del controlador se realizó la linealización del modelo cinemático del error, obteniendo un sistema de ecuaciones que representa el comportamiento del error de forma lineal. Con el modelo lineal se ha empleado la **técnica de control LQR para obtener una ganancia óptima para el controlador**.
- Con el uso del simulador del **robot aéreo DJI se realizó el ajuste de las ganancias**, una vez ajustadas estas ganancias por medio de simulación se procede a realizar pruebas experimentales con el robot físico, **evitando así ocasionar daños al robot durante el ajuste de las ganancias**.
- Los valores del funcional de coste se ajustan de acuerdo a los requerimientos del controlador, es decir, **mediante las ganancias Q y R se puede asignar peso a las acciones de control o a la compensación del error de seguimiento de trayectoria**. Como se puede ver en los tres experimentos realizados, el comportamiento del robot cambia de acuerdo a estas ganancias.



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