



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 Ingeniería en Electrónica E
Instrumentación**

**“CONTROL PREDICTIVO NO LINEAL PARA EL SEGUIMIENTO DE TRAYECTORIA DE VEHÍCULOS AÉREOS NO
TRIPULADOS”**

NONLINEAR PREDICTIVE CONTROL FOR THE TRACKING OF UNMANNED AERIAL VEHICLES

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Nonlinear Predictive Control for the Tracking of Unmanned Aerial Vehicles

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Abstract—In the following article a nonlinear predictive controller (MPC) is presented as a teaching and learning tool, to test the tracking of different flight paths in a safe way in unmanned aerial vehicles (UAV). This MPC is based on the kinematic model of the UAV and performs the function of minimizing control errors, restricting control actions, increasing system efficiency, maintaining stable flight operation and extending rotor life by restricting UAV input speeds. In addition, the comparison of the data obtained experimentally from Matlab with the data from the DJI Assistant is carried out by simulating the flight path within the virtual environment.

Keywords—virtual environment; nonlinear predictive control; kinematic model; tracking; unmanned aerial vehicles.

I. INTRODUCTION

Robotics is constantly evolving over time and with it comes improved performance in the field of science and technology, giving robots greater autonomy, intelligence and energy efficiency [1]. The services provided by robots allow to increase productivity, reduce flaws, failures and improve the quality of processes, these services are in great demand not only in the industrial sector, but also in the commercial, educational, medical and domestic sectors, among others [2]. The basic structure that makes up a robot is given by mechanical systems, actuators, sensors and control systems [3]. The types of robots that exist can be classified: (i) according to their function in motion control, autonomous and/or teleoperated; (ii) depending on the function in the environment in which the task is performed, aquatic, terrestrial and aerial [4]. Aerial robots are known as UAVs (unmanned aerial vehicles) [5]. The different applications that UAVs can perform are: (i) search and browse [6]; (ii) security and military applications [7]; (iii) forest fire prevention, mapping and aerial photography [8]; (iv) agriculture and geology [9], among other things. The trend in recent years is to accomplish the task in an efficient and safe way so advanced control algorithms are being developed. It is convenient to test these advanced algorithms in software that allows to safely emulate the operation of UAVs, for which virtual environments are being used [10].

Virtual environments are recreations of real environments and/or environments created on computers that help with the interaction and manipulation of objects. These environments can be oriented to the areas of: (i) teaching - learning; and (ii) training [11]. There are own virtual simulators, such as the DJI Assistant, which allows to calibrate, simulate and obtain the flight information of the UAV. In which you can implement

different advanced control algorithms to analyze the behavior of the system against a specific task.

Advanced control algorithms are automatic control strategies that analyze the behavior of MIMO systems (multiple input - multiple output), time invariant systems, among others [12]. This type of controllers are developed through computer platforms that are in charge of interpreting a mathematical model and evaluating the system's performance through simulations [13]. Among the best known advanced control strategies are: (i) expert control, that is the greatest exponent of this type of controller is fuzzy control, which consists of the use of fuzzy algebra in order to represent a resemblance to human thought; (ii) robust control, this type of controller defines the characteristics of the system regardless of the disturbances that occur; (iii) adaptive control, this type of controller is used in time invariant systems; (iv) neuronal control, this type of controller can be compared to the neural networks in the human brain, consisting of a learning stage and a recognition stage; (v) optimal control, this type of control is based on the implementation of a functional and an optimization criterion that allows the adjustment of the control objectives; and, (vi) model based predictive control, this type of control is based on the future predictions of a system through its past actions [14-15]. However, it should be noted that predictive controllers have been a relevant issue in the field of research and industry at present [16-18].

The idea of model based predictive control (MPC) is that in using an explicit mathematical model, minimizing a target and moving in a sliding horizon [19]. MPC control algorithms are computationally developed to provide a response to a control action [20]. The elements that make up the MPC are: (i) optimizer, finds the best result in the performance of a task, also optimizes future control actions; (ii) cost function, is a positive function related to an associated cost that varies over the path of the prediction horizon; (iii) constraints, are the limits within which the system evolves; and, (iv) process model, which describes the behavior of the system and can be linear or nonlinear [21-23]. Ultimately, the advances made in MPC control have positioned it as one of the best controllers when it comes to implementation in kinematic and/or dynamic systems with long sampling periods [24-28].

II. PROBLEM FORMULATION

The proposal of the article is to implement a model based predictive control algorithm (MPC) of an unmanned aerial vehicle (UAV) for autonomous trajectory tracking tasks. So it



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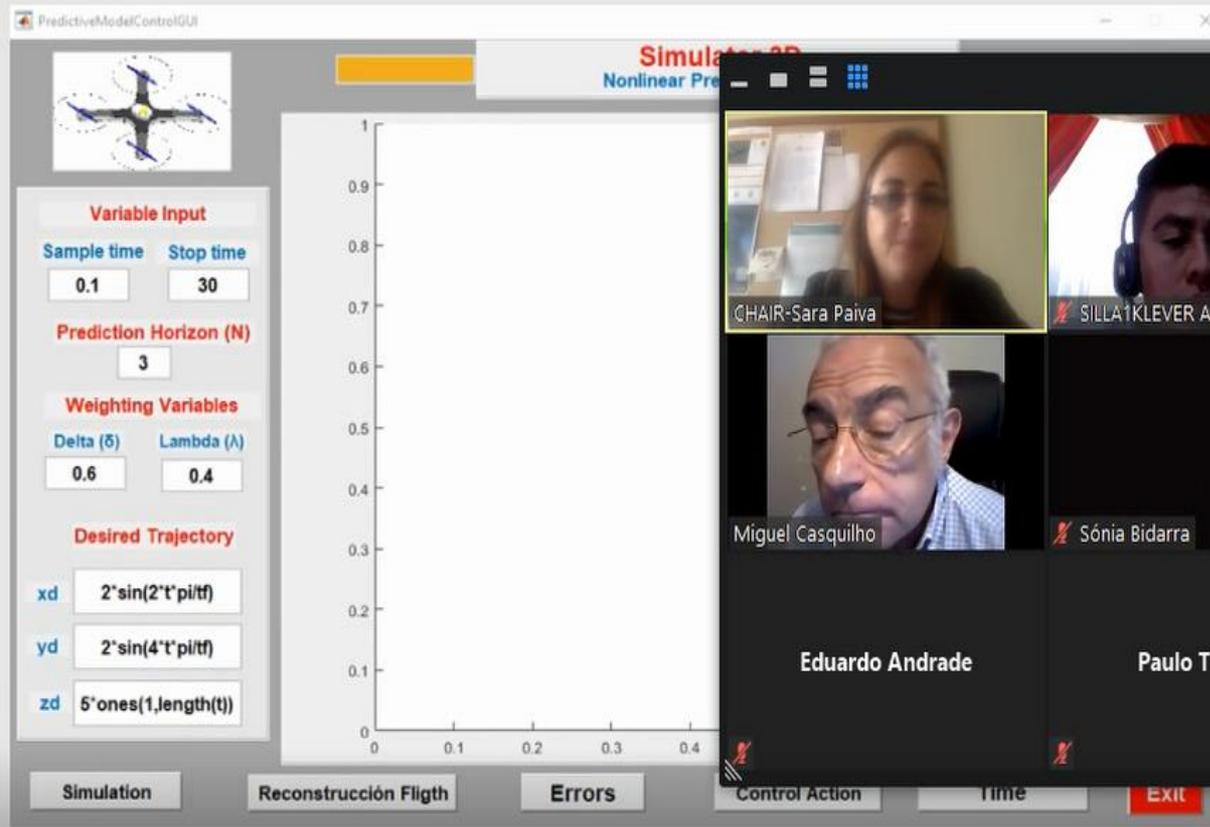
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PredictiveModelControlGUI



Variable Input

Sample time: 0.1 Stop time: 30

Prediction Horizon (N)

3

Weighting Variables

Delta (δ): 0.6 Lambda (λ): 0.4

Desired Trajectory

xd: $2 \cdot \sin(2 \cdot t \cdot \pi / t_f)$

yd: $2 \cdot \sin(4 \cdot t \cdot \pi / t_f)$

zd: $5 \cdot \text{ones}(1, \text{length}(t))$

Simulation Reconstrucción Flight Errors

Simulador 2D
Nonlinear Pre



CHAIR-Sara Paiva

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Miguel Casquilho

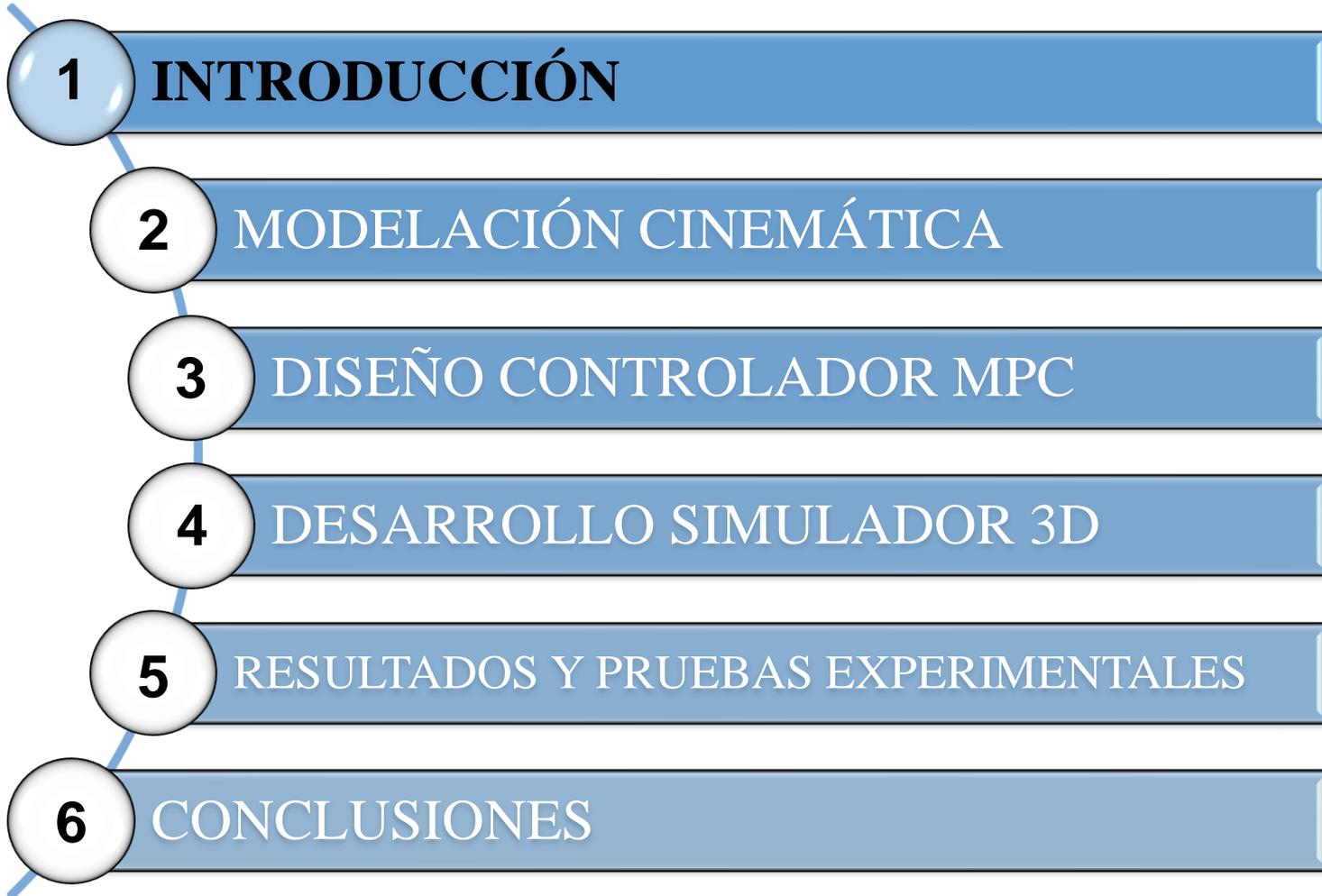
Sónia Bidarra

Eduardo Andrade

Paulo Teixeira

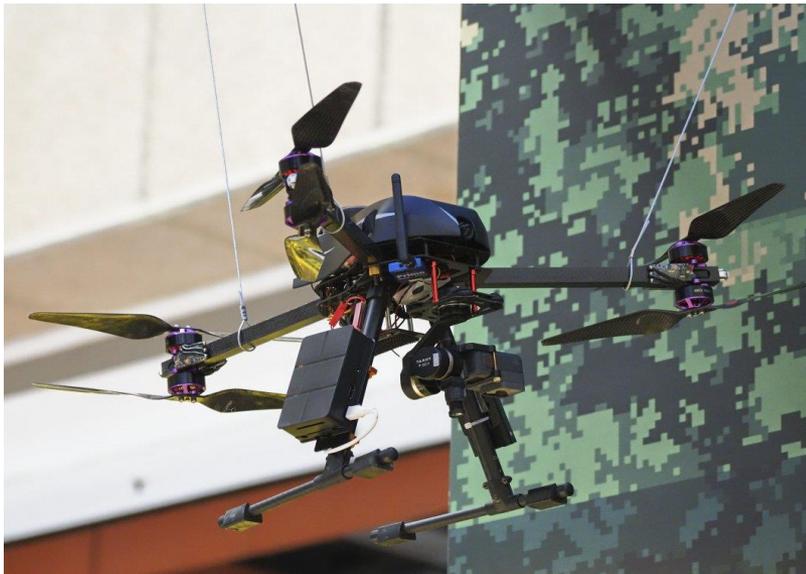
Control Action Time EXIT





1. INTRODUCCIÓN

1.1 ANTECEDENTES



1. INTRODUCCIÓN

1.2 PROBLEMÁTICA

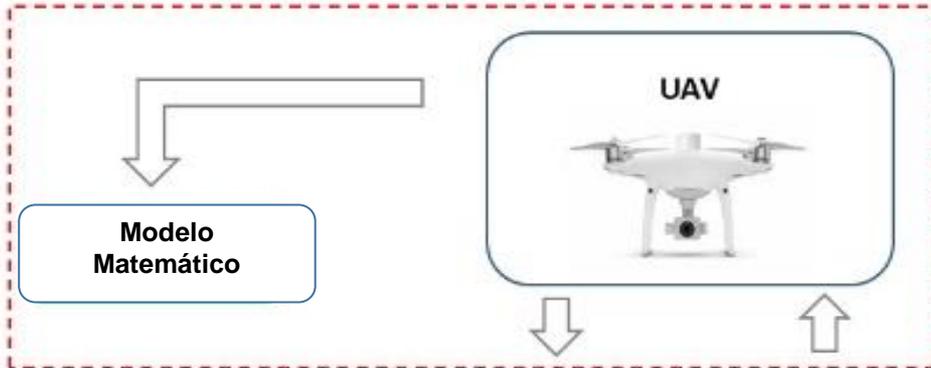


- Monitoreo en Tiempo Real.
- Búsqueda de objetivos en áreas hostiles.
- Tareas que exigen realizar trabajos de amplia cobertura.
- Proporcionar estabilidad frente a perturbaciones externas.

1. INTRODUCCIÓN

1.3 PLANTEAMIENTO DEL PROBLEMA

Fase 1



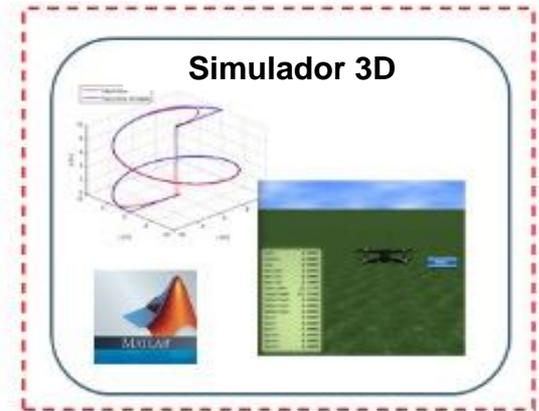
Fase 2



Fase 4



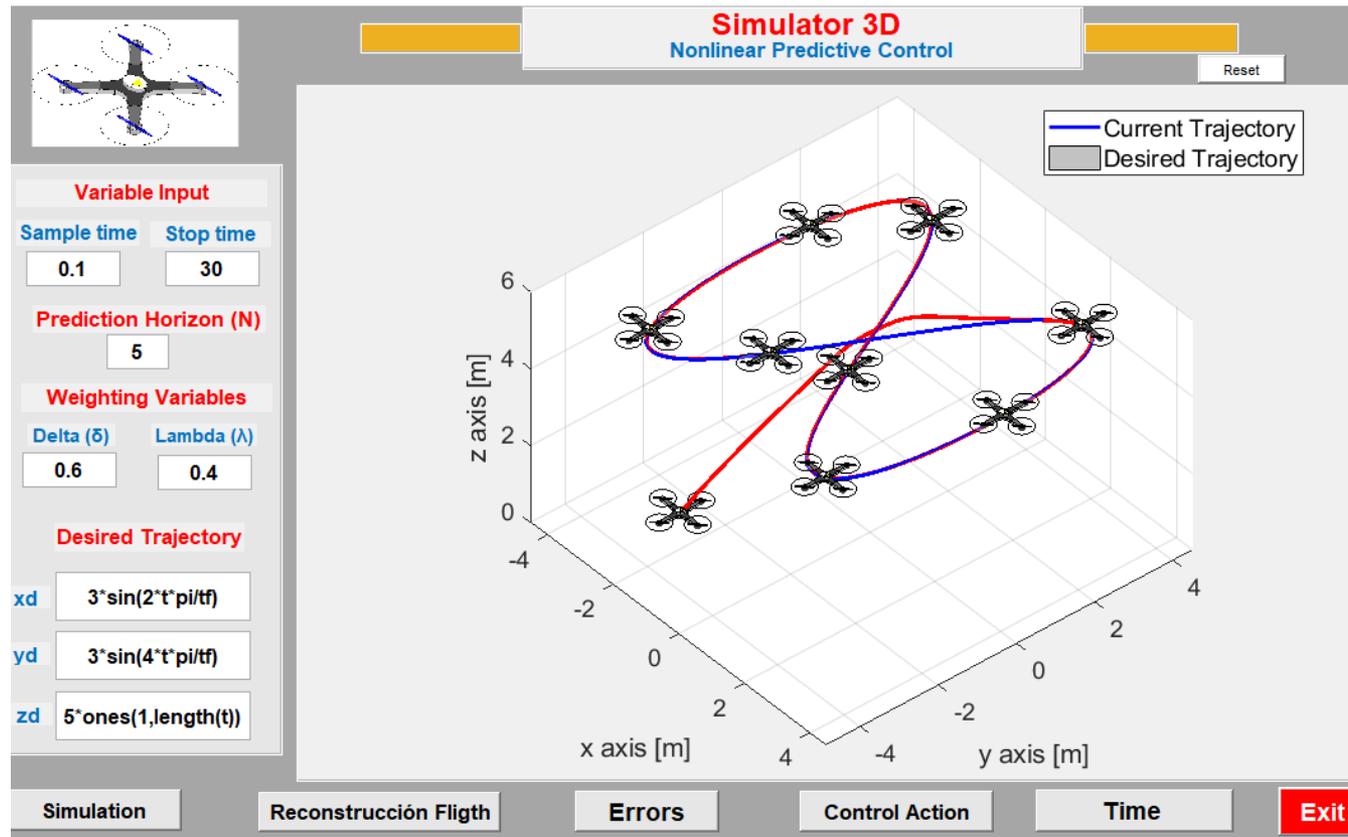
Fase 3



1. INTRODUCCIÓN

1.4 OBJETIVO GENERAL

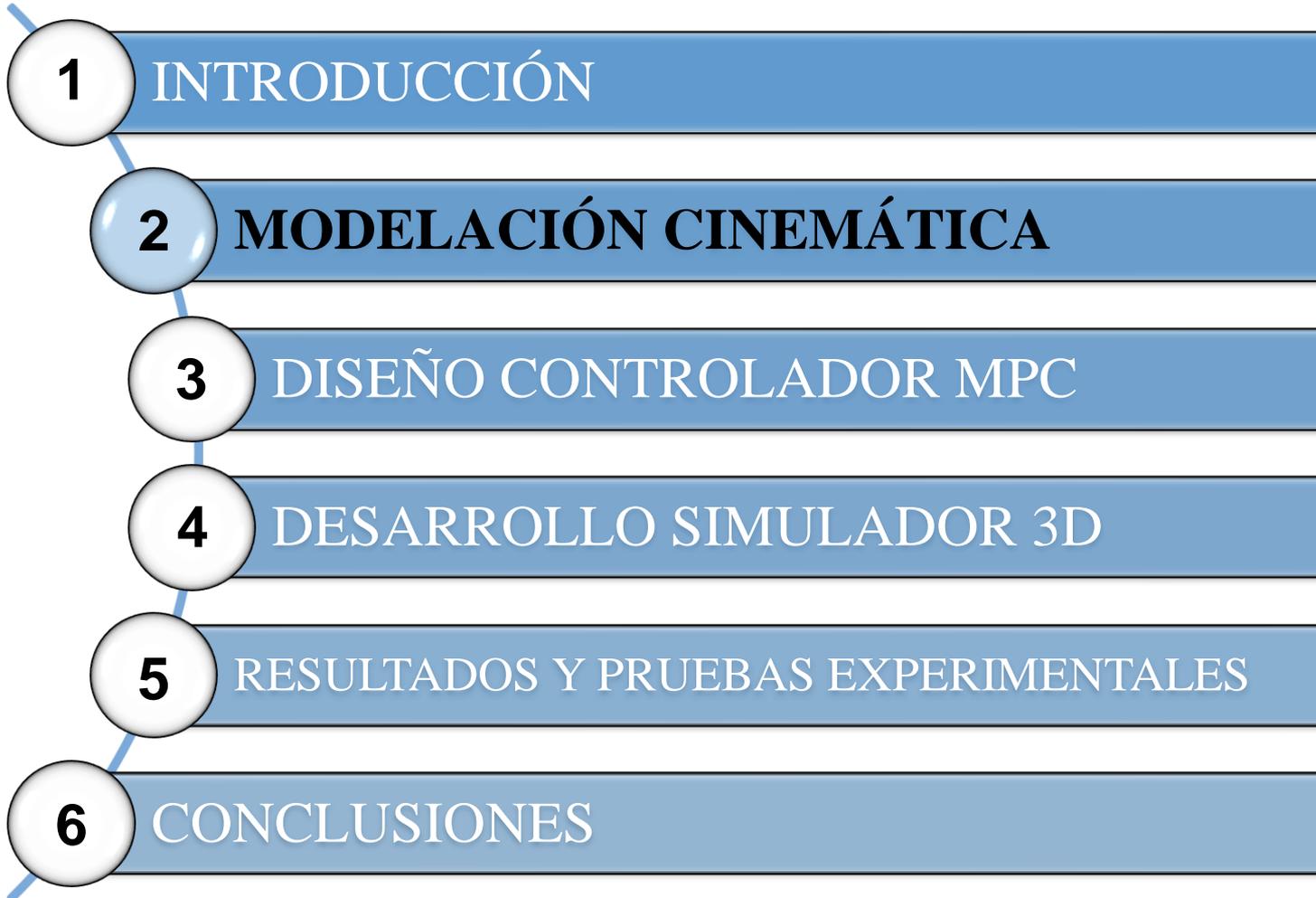
Proponer un **algoritmo de control predictivo basado en el modelo no lineal de un vehículo aéreo no tripulado**, para tareas de seguimiento de trayectoria de manera autónoma.



1. INTRODUCCIÓN

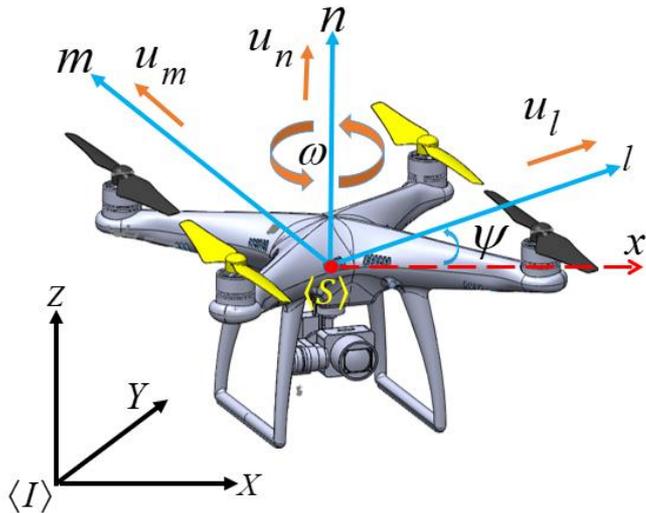
1.5 OBJETIVOS ESPECÍFICOS

- Investigar en bases de datos científicas las características de movimiento de los vehículos aéreos no tripulados, (UAV en sus siglas en inglés), con el propósito de proponer algoritmos de control avanzado para el control autónomo del mismo.
- Modelar las características de movimiento de un UAV a fin de definir las restricciones de control.
- Proponer un algoritmo de control predictivo basado en el modelo (MPC en sus siglas en inglés) de un UAV, a fin de realizar tareas de seguimiento de trayectoria de forma autónoma.
- Desarrollar un simulador 3D que permita implementar el algoritmo de control MPC, con el fin de analizar el comportamiento de navegación ante errores de modelaje y perturbaciones externas.
- Evaluar experimentalmente el algoritmo de control MPC propuesto, a fin de comprobar que los errores de control estén en las cercanías de cero cuando el tiempo tienda a infinito; es decir, que el algoritmo de control sea globalmente uniformemente estable.



2. MODELACIÓN CINEMÁTICA

2.1 MODELO CINEMÁTICO UAV



Donde:

$\langle I \rangle$: Sistema de Referencia Inercial.

$\langle S \rangle$: Sistema de Referencia Móvil.

u_l, u_m, u_n : Velocidades lineales de desplazamiento.

ω : Velocidad angular

Cinemática Directa

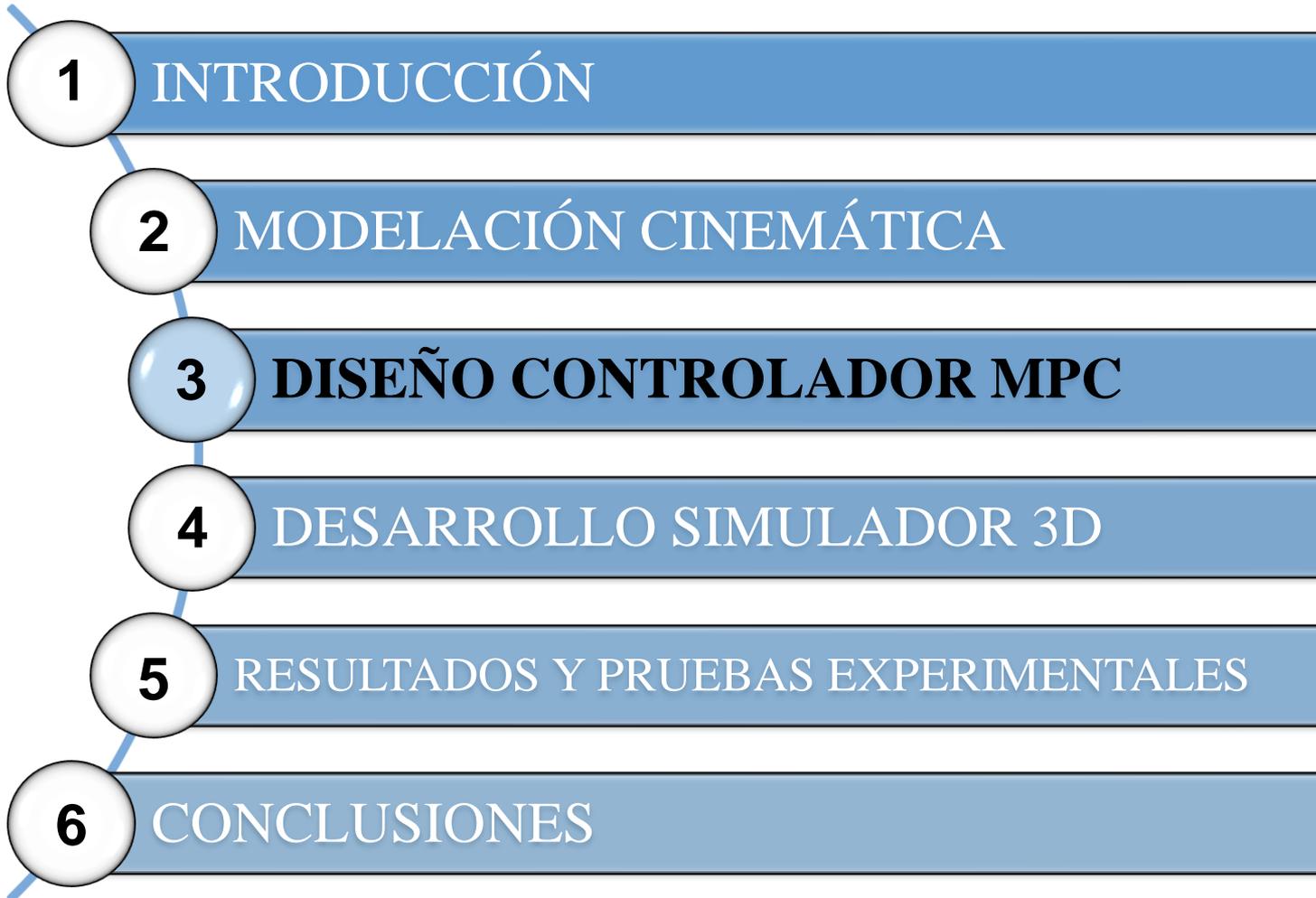
$$\begin{cases} \dot{x}_S = u_l \cos(\psi) - u_m \sin(\psi) \\ \dot{y}_S = u_l \sin(\psi) + u_m \cos(\psi) \\ \dot{z}_S = u_n \\ \dot{\psi}_S = \omega \end{cases}$$



Modelo Cinemático

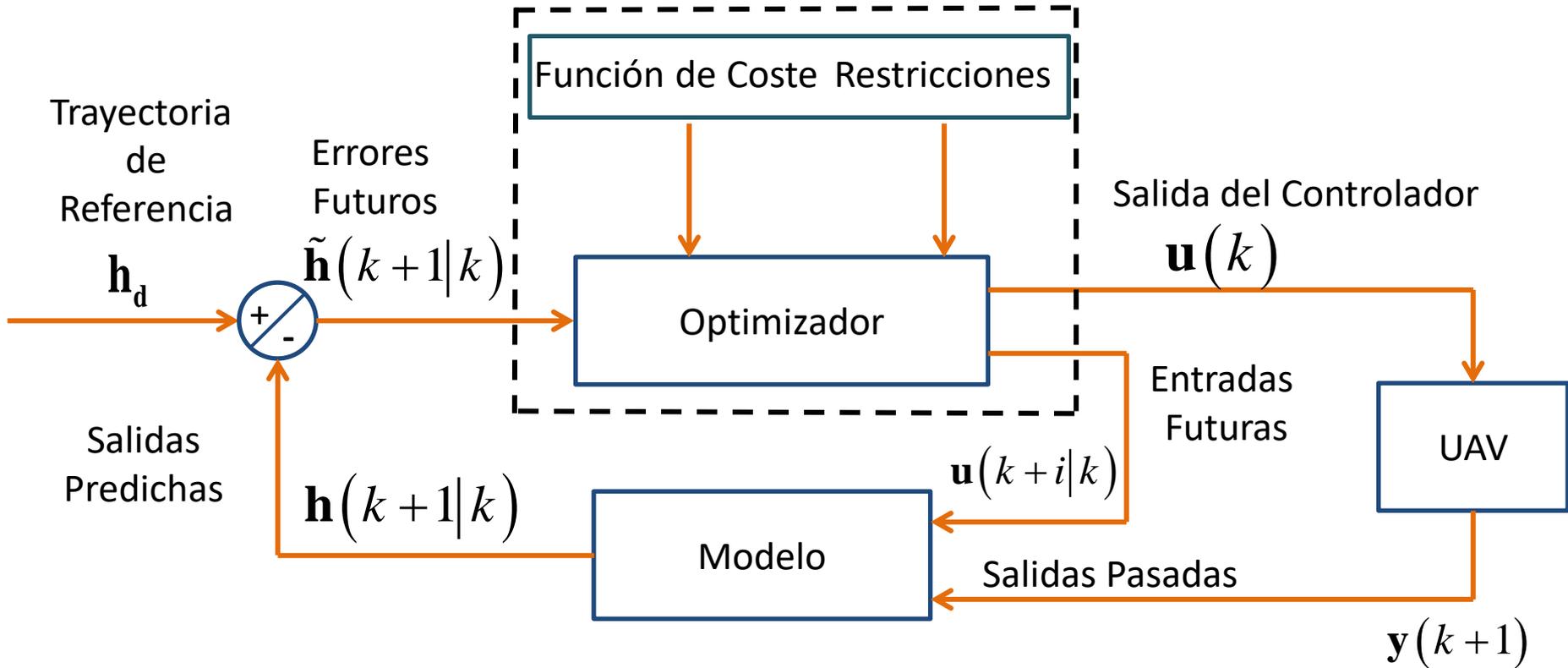
$$\begin{bmatrix} \dot{x}_S \\ \dot{y}_S \\ \dot{z}_S \\ \dot{\psi}_S \end{bmatrix} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 & 0 \\ \sin(\psi) & \cos(\psi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_l \\ u_m \\ u_n \\ \omega \end{bmatrix}$$

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



3. DISEÑO DEL CONTROLADOR

3.1 ESQUEMA DE CONTROL - MPC



3. DISEÑO DEL CONTROLADOR

3.2 ESTRUCTURA MPC EN ESPACIOS DE ESTADO

$$\begin{cases} \dot{\mathbf{h}} = f(\mathbf{h}, \mathbf{u}) \\ \mathbf{y} = g(\mathbf{h}) \end{cases} \quad \text{----->} \quad \text{Espacio de Estados}$$

$$\mathbf{h} = [x_s \quad y_s \quad z_s \quad \psi_s] \quad \text{----->} \quad \text{Vector de estados del sistema}$$

$$\mathbf{u} = [u_{l_s} \quad u_{m_s} \quad u_{n_s} \quad u_{\omega_s}] \quad \text{----->} \quad \text{Vector de las variables de control}$$

$$\begin{cases} \mathbf{h}(k+1) = (\mathbf{h}(k), \mathbf{u}(k)) \\ \mathbf{y}(k) = \mathbf{h}(k) \end{cases} \quad \text{----->} \quad \text{Modelo Discretizado}$$

$$\mathbf{y}(k) = [x_s(k) \quad y_s(k) \quad z_s(k) \quad \psi_s(k)]^T \quad \text{----->} \quad \text{Vector de salida del sistema discretizado.}$$

3. DISEÑO DEL CONTROLADOR

3.3 FUNCIONAL DE COSTE

$$F = \sum_{i=1}^N \delta_i \left\| \tilde{\mathbf{h}}(k+i|k) \right\|_Q^2 + \sum_{i=1}^N \lambda_i \left\| \Delta \mathbf{u}(k+i-1|k) \right\|_P^2$$

Donde:

k : período de muestreo.

N : horizonte de predicción.

i : predicción futura.

δ : pondera los esfuerzos de los errores de control.

λ : pondera los esfuerzos de las acciones de control.

Q : matriz definida positiva que pesa de los estados de control.

P : matriz definida positiva que pesa de las acciones de control.

$$Q > 0$$

$$P > 0$$

DEFINIDA
POSITIVA

$$\tilde{\mathbf{h}}(k+i|k) = \mathbf{h}(k+i|k) - \mathbf{h}_d(k+i)$$

ERROR FUTURO

$$\Delta \mathbf{u}(k+i|k) = \mathbf{u}(k+i|k) - \mathbf{u}(k+i-1|k)$$

VARIACIÓN DE
VELOCIDADES DE
MANIOBRABILIDAD

$$\mathbf{u}_{\min} \leq \mathbf{u}(k) \leq \mathbf{u}_{\max}$$

RESTRICCIONES

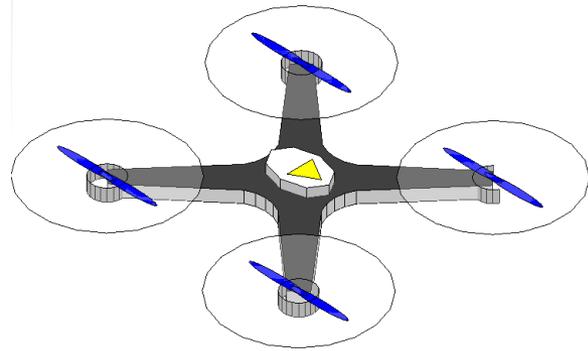


4. SIMULADOR 3D

4.1 DESARROLLO SOFTWARE

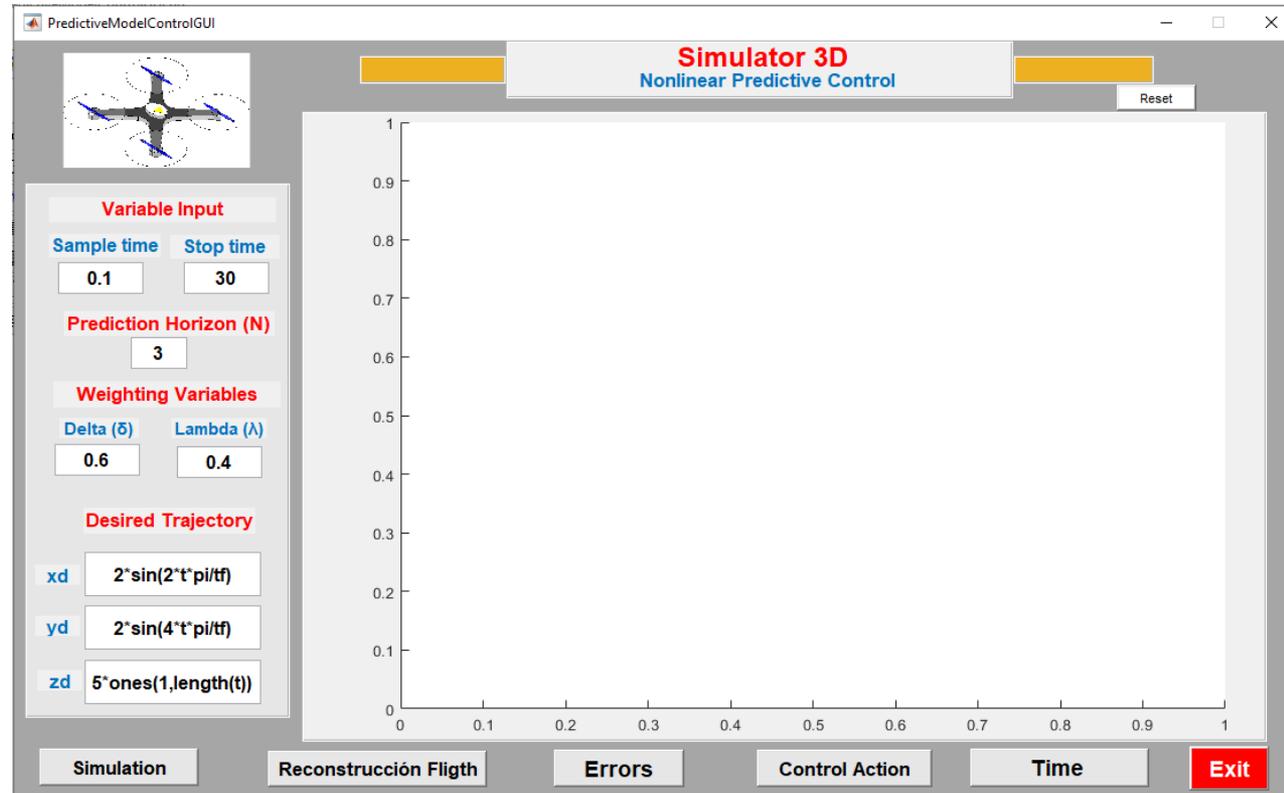
ETAPA 1

CAD



ETAPA 2

MATLAB



Simulator 3D
Nonlinear Predictive Control

Reset

Variable Input

Sample time: 0.1 Stop time: 30

Prediction Horizon (N): 3

Weighting Variables

Delta (δ): 0.6 Lambda (λ): 0.4

Desired Trajectory

xd: $2 \cdot \sin(2 \cdot t \cdot \pi / t_f)$

yd: $2 \cdot \sin(4 \cdot t \cdot \pi / t_f)$

zd: $5 \cdot \text{ones}(1, \text{length}(t))$

Simulation Reconstrucción Flight Errors Control Action Time Exit

4. SIMULADOR 3D

4.2 OPCIONES DEL SIMULADOR

PredictiveModelControlGUI

Simulator 3D
Nonlinear Predictive Control

Reset

— Current Trajectory
— Desired Trajectory

Variable Input

Sample time: 0.1 Stop time: 30

Prediction Horizon (N): 3

Weighting Variables

Delta (δ): 0.6 Lambda (λ): 0.4

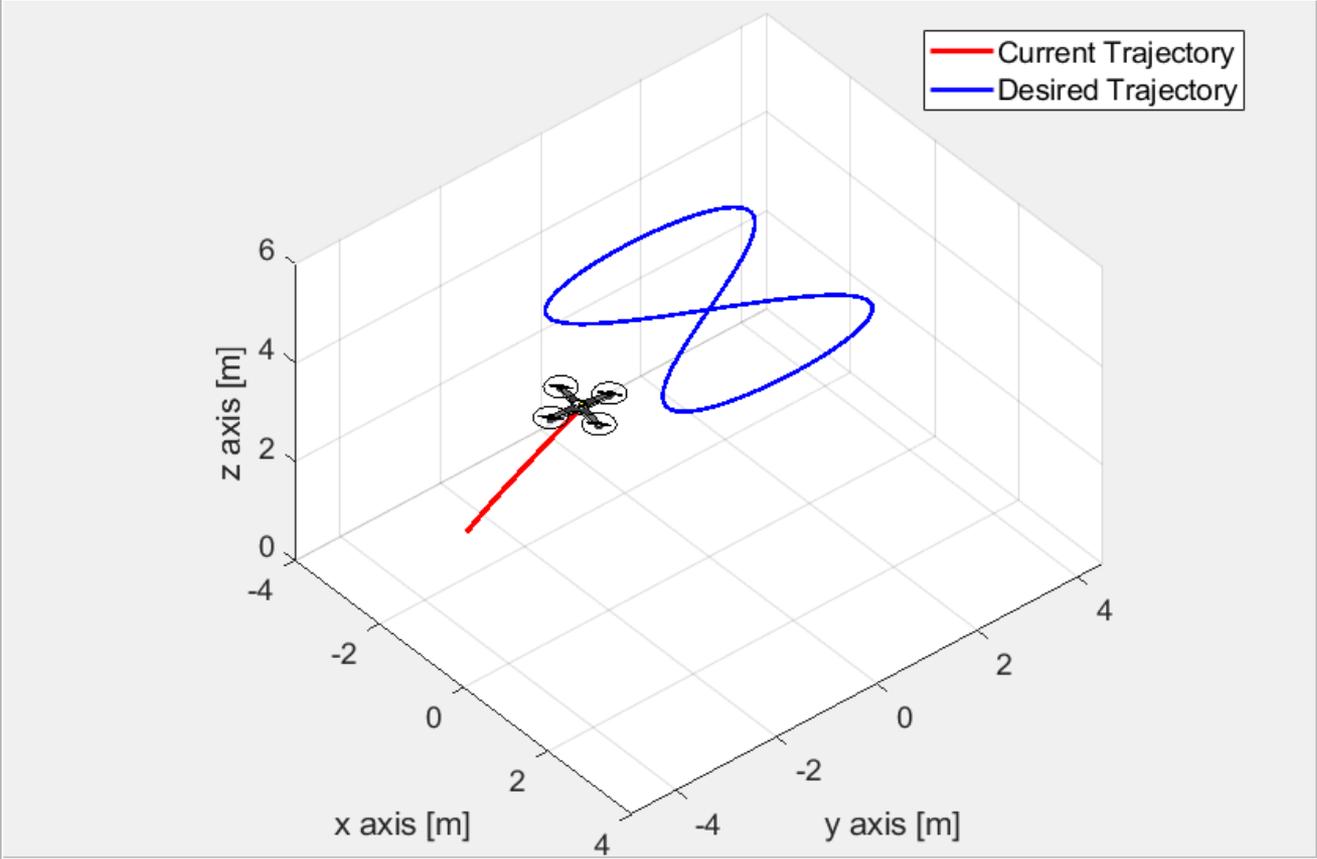
Desired Trajectory

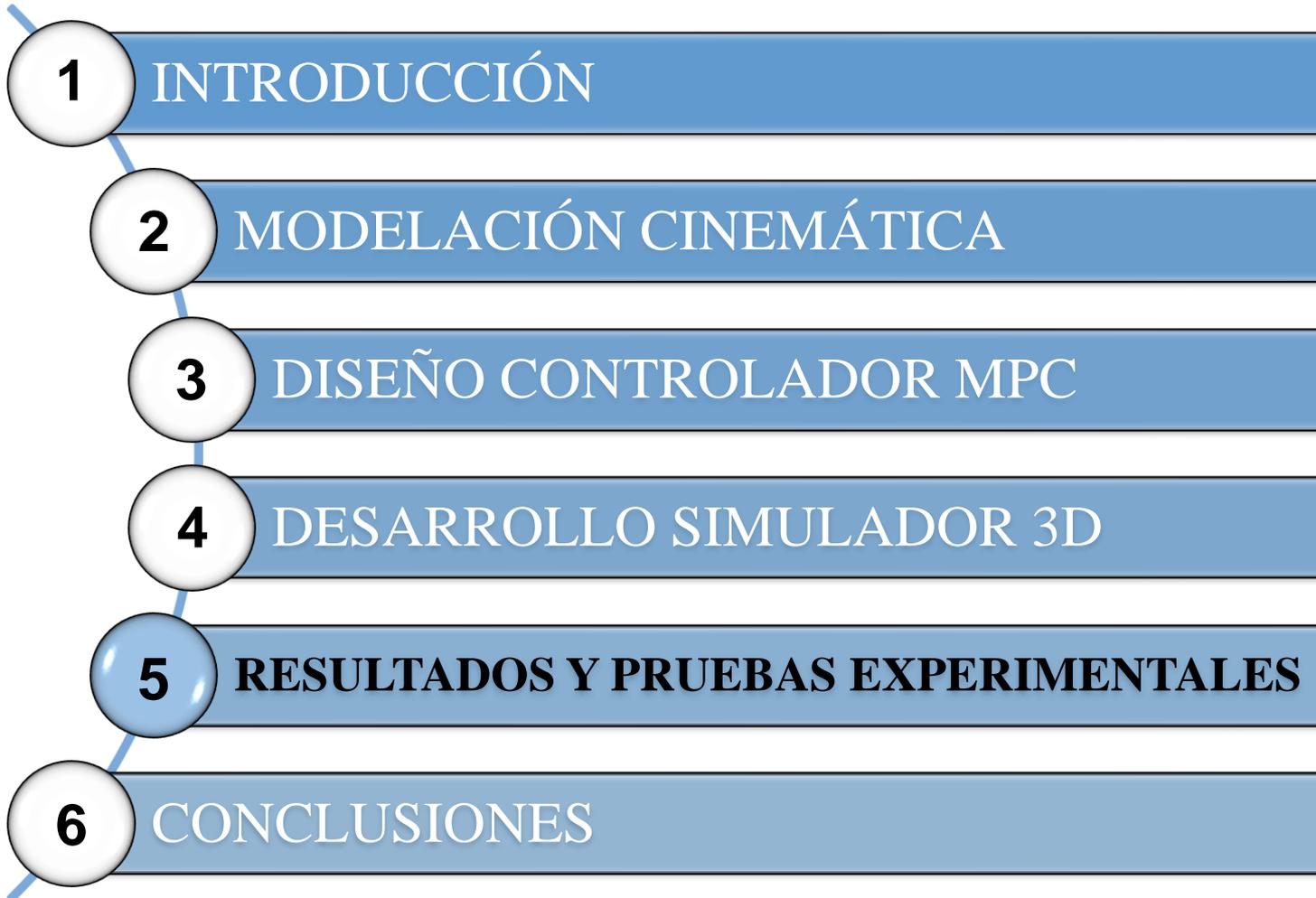
xd: $2 \cdot \sin(2 \cdot t \cdot \pi / t_f)$

yd: $2 \cdot \sin(4 \cdot t \cdot \pi / t_f)$

zd: $5 \cdot \text{ones}(1, \text{length}(t))$

Simulation Reconstrucción Flight Errors Control Action Time Exit

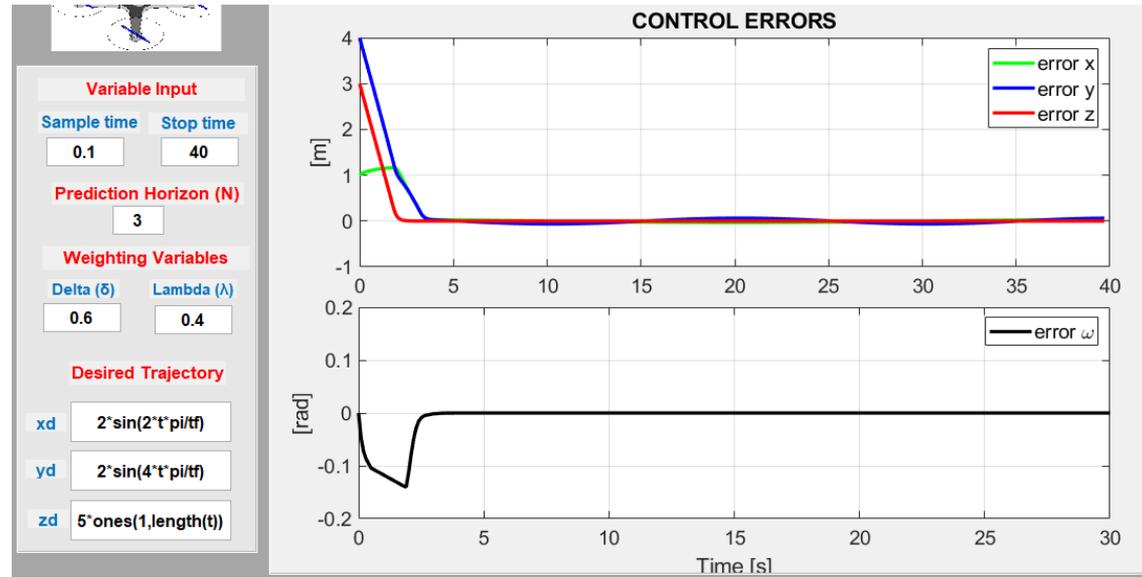
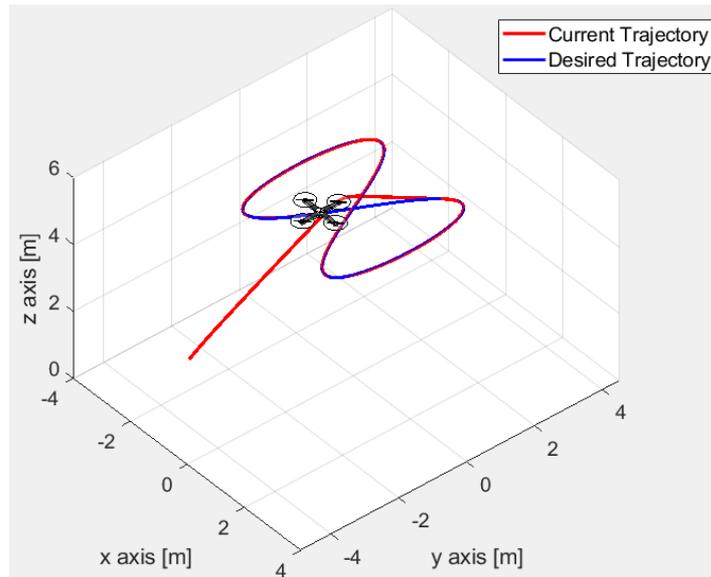




5. RESULTADOS

5.1 ERRORES DE CONTROL

Para $N=3$, $\delta = 0.6$ $\lambda = 0.4$



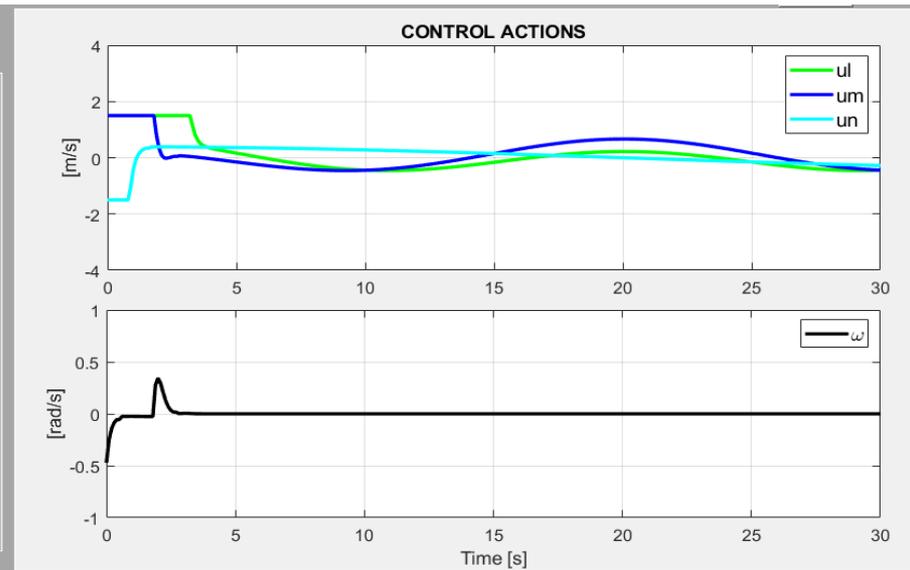
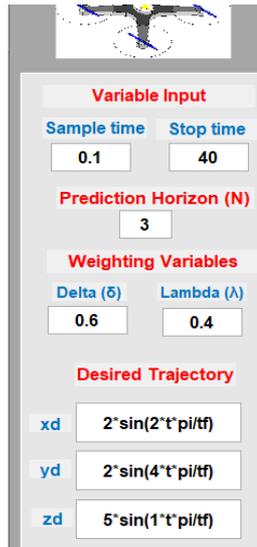
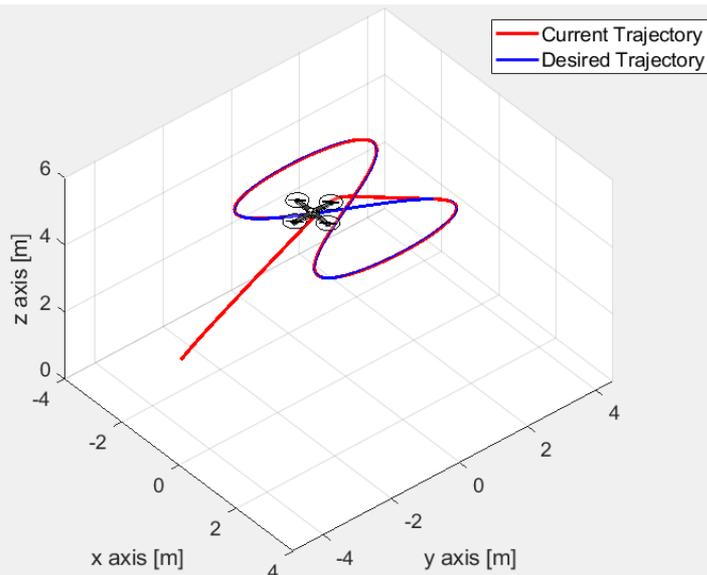
Se puede observar la trayectoria Deseada vs la Obtenida.

Los errores de control tienden a cero demostrando así la estabilidad del controlador.

5. RESULTADOS

5.2 ACCIONES DE CONTROL

Para $N=3$, $\delta = 0.6$ $\lambda = 0.4$

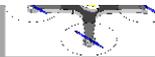
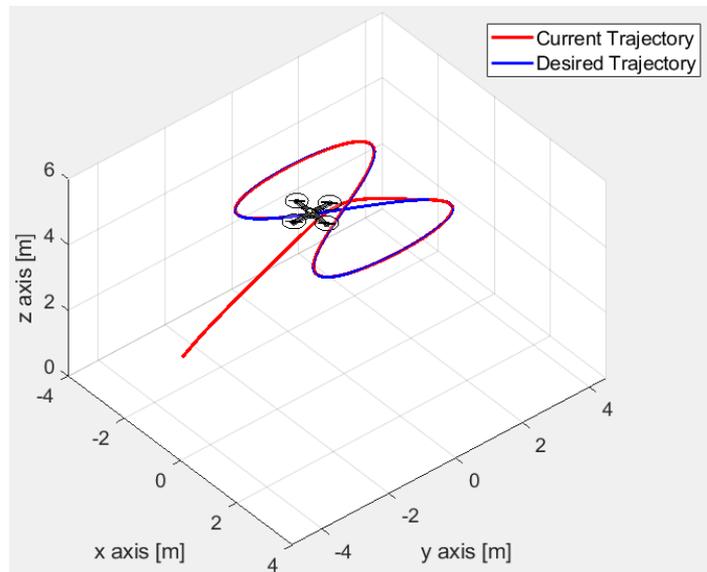


Las acciones de control tienden a oscilar entre valores cercanos a cero, y también se puede observar que respeta el rango de restricciones de las velocidades de maniobrabilidad.

5. RESULTADOS

5.3 ERRORES DE CONTROL

Para $N=5$, $\delta = 0.6$ $\lambda = 0.4$



Variable Input

Sample time: 0.1 Stop time: 40

Prediction Horizon (N): 5

Weighting Variables

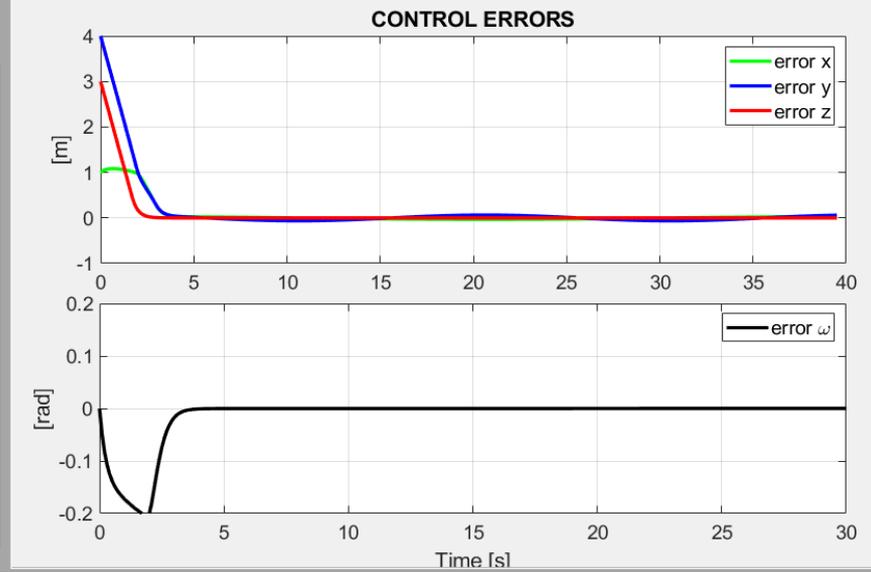
Delta (δ): 0.6 Lambda (λ): 0.4

Desired Trajectory

x_d : $2 \cdot \sin(2 \cdot t \cdot \pi / t_f)$

y_d : $2 \cdot \sin(4 \cdot t \cdot \pi / t_f)$

z_d : $5 \cdot \text{ones}(1, \text{length}(t))$

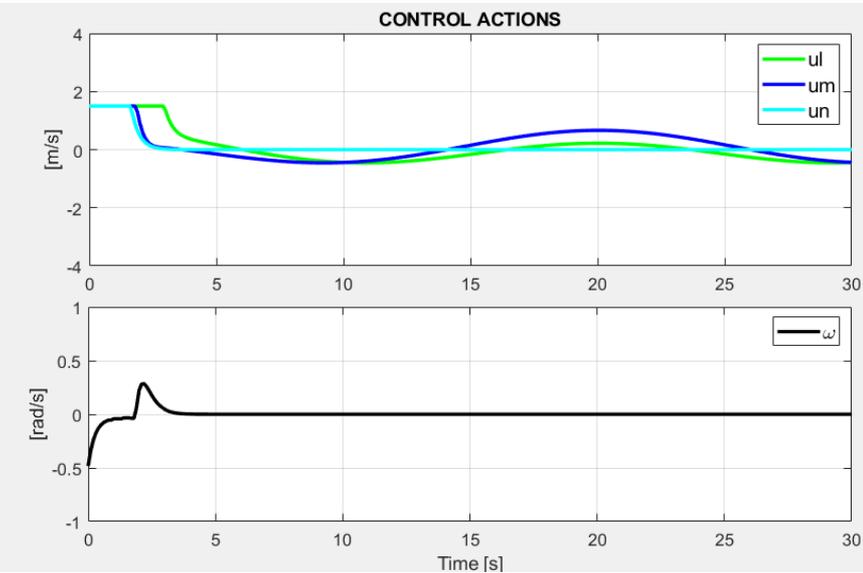
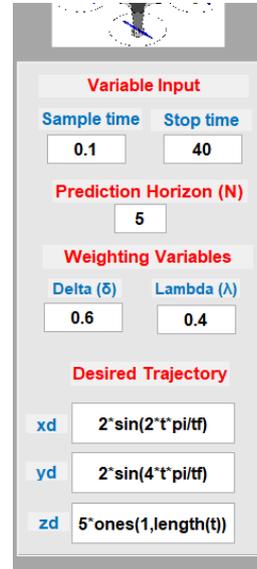
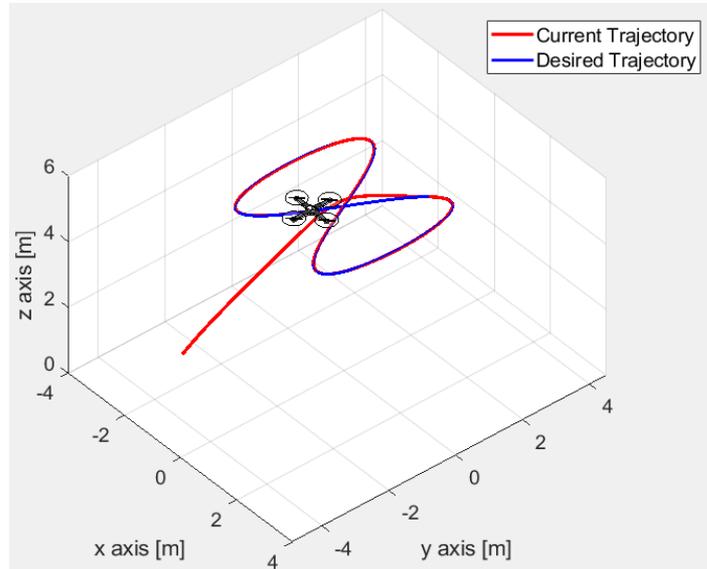


Para un horizonte de predicción $N=5$, se observa que el arranque del UAV para alcanzar la trayectoria deseada es mucho más suave, teniendo como resultado que los errores de control tiendan más rápido a cero debido al numero de iteraciones.

5. RESULTADOS

5.4 ACCIONES DE CONTROL

Para $N=5$, $\delta = 0.6$ $\lambda = 0.4$

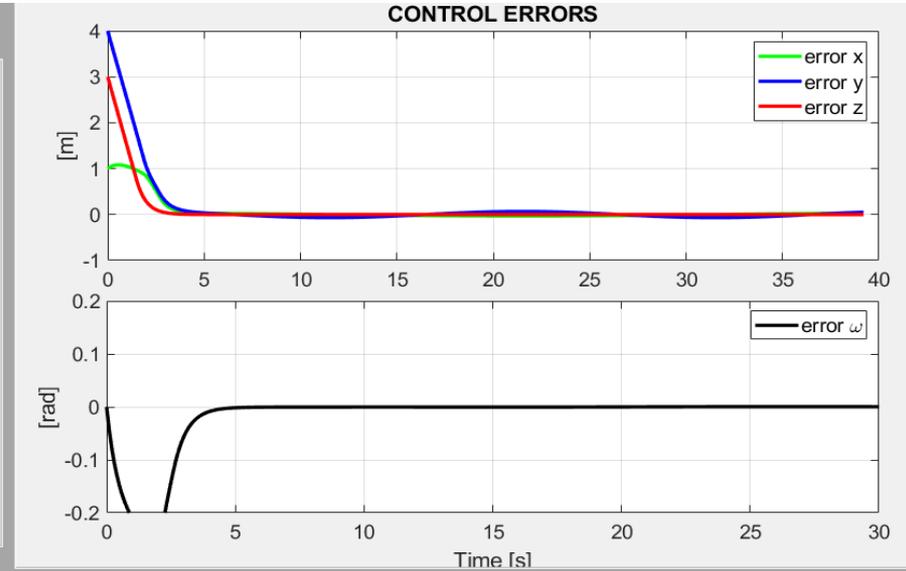
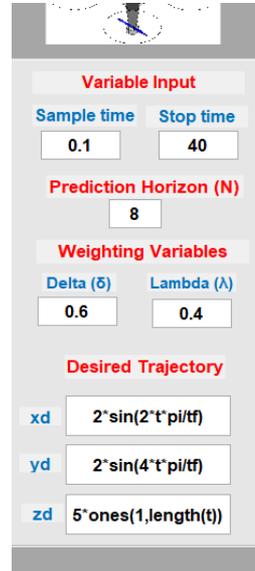
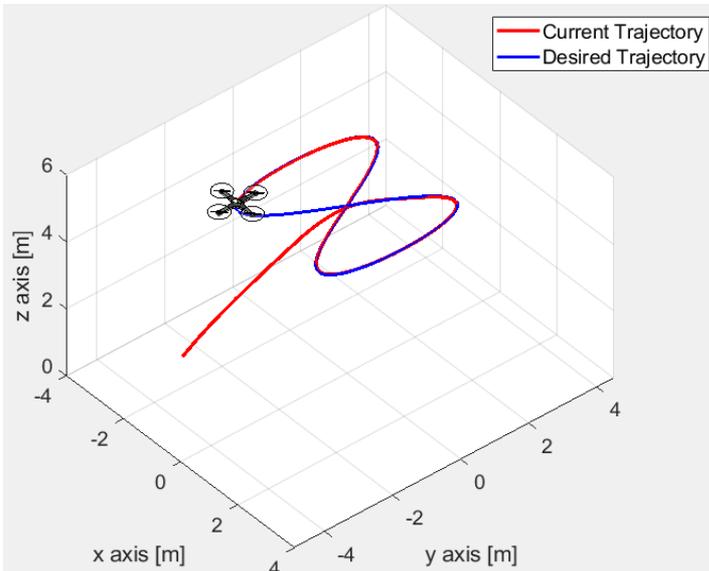


Las acciones de control tienden a cero más rápido que con un horizonte de predicción mayor.

5. RESULTADOS

5.5 ERRORES DE CONTROL

Para $N=8$, $\delta = 0.6$ $\lambda = 0.4$

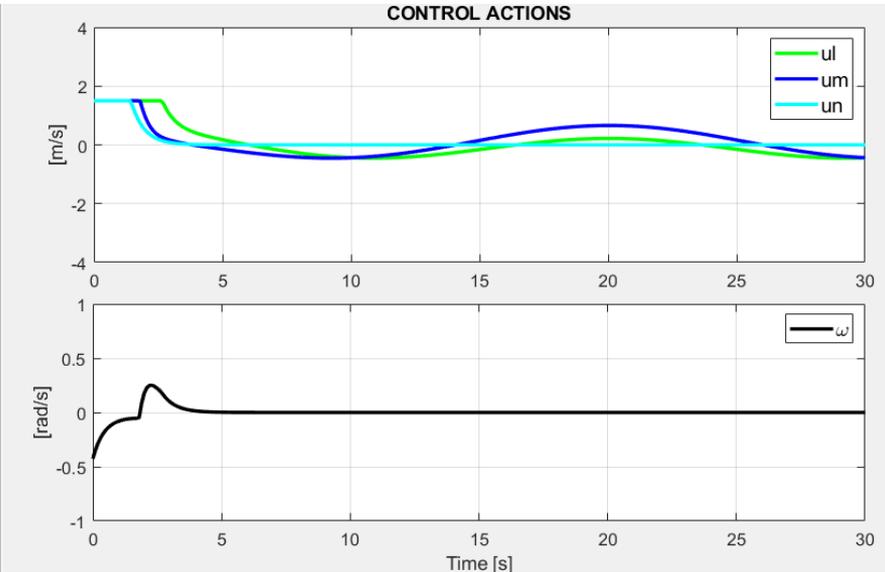
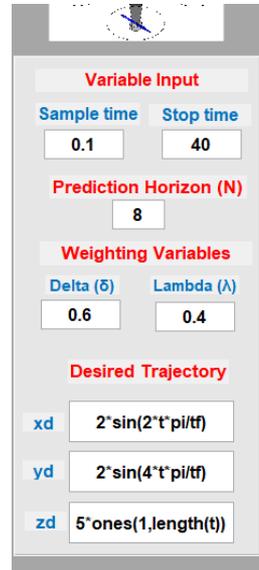
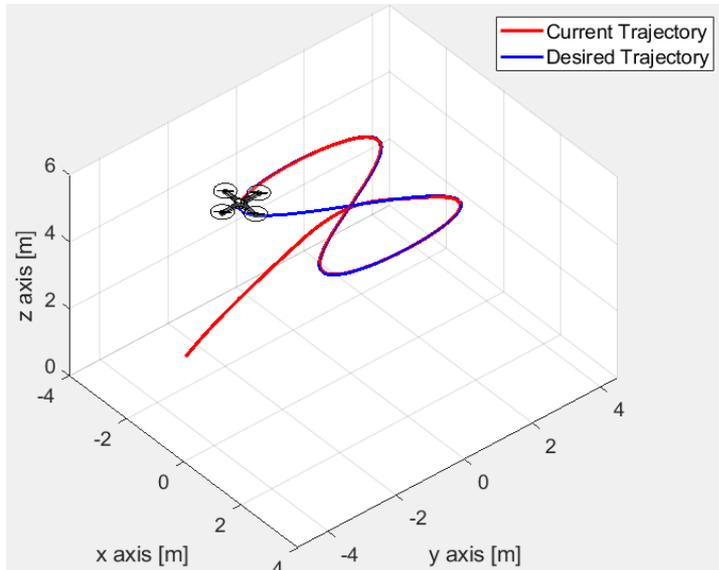


Con un Horizonte de predicción $N=8$, el performance del controlador predictivo mejora notoriamente, haciendo que los errores de control tiendan a cero con más rapidez.

5. RESULTADOS

5.6 ACCIONES DE CONTROL

Para $N=8$, $\delta = 0.6$ $\lambda = 0.4$

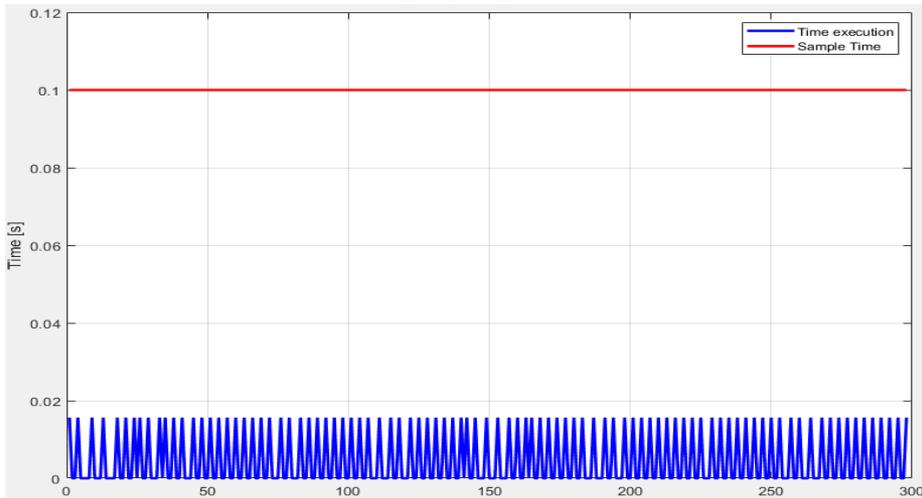


Debido al aumento del Horizonte de predicción, se observa que no existen picos en el arranque del UAV hacia la trayectoria deseada, cuidando así las características físicas de los motores del mismo.

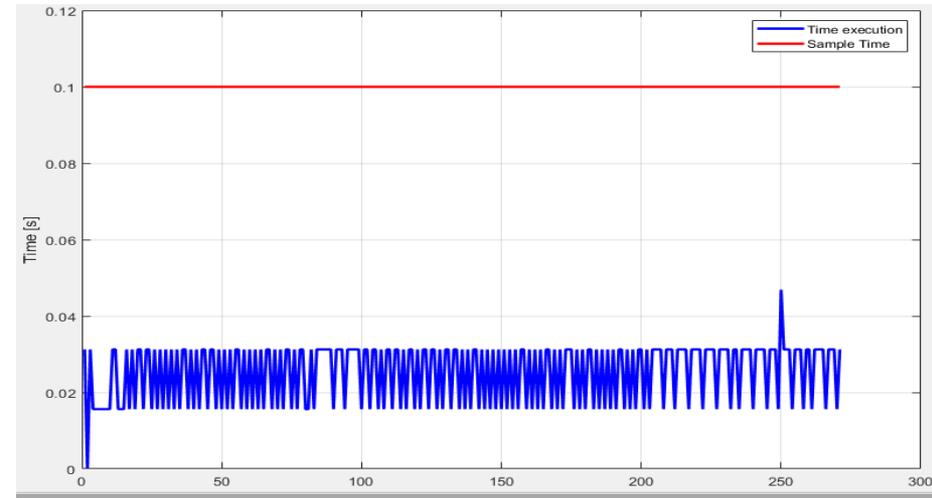
5. RESULTADOS

5.7 TIEMPO DE MUESTREO VS TIEMPO DE COMPUTO

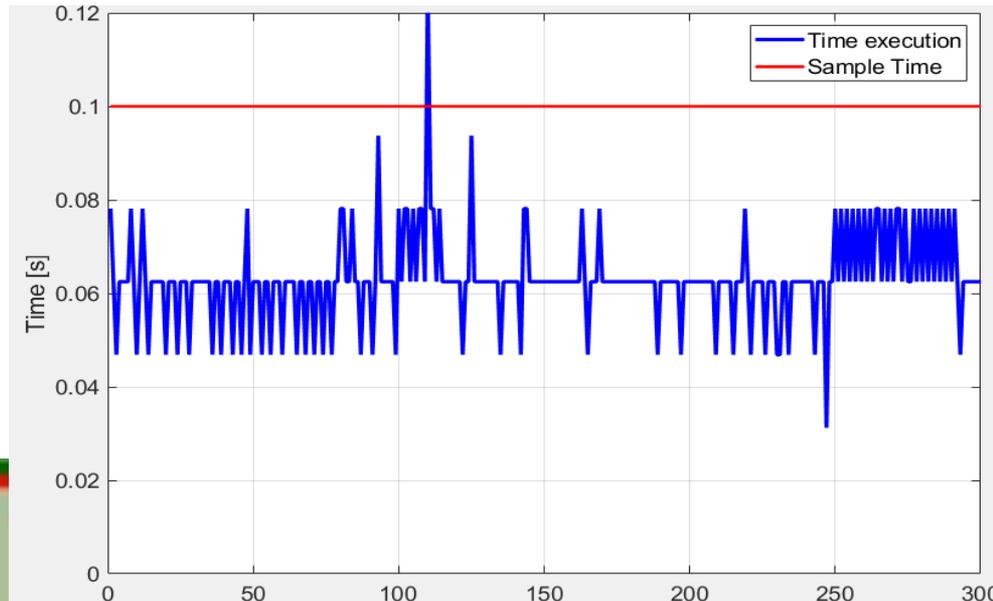
Para N=3



Para N=5

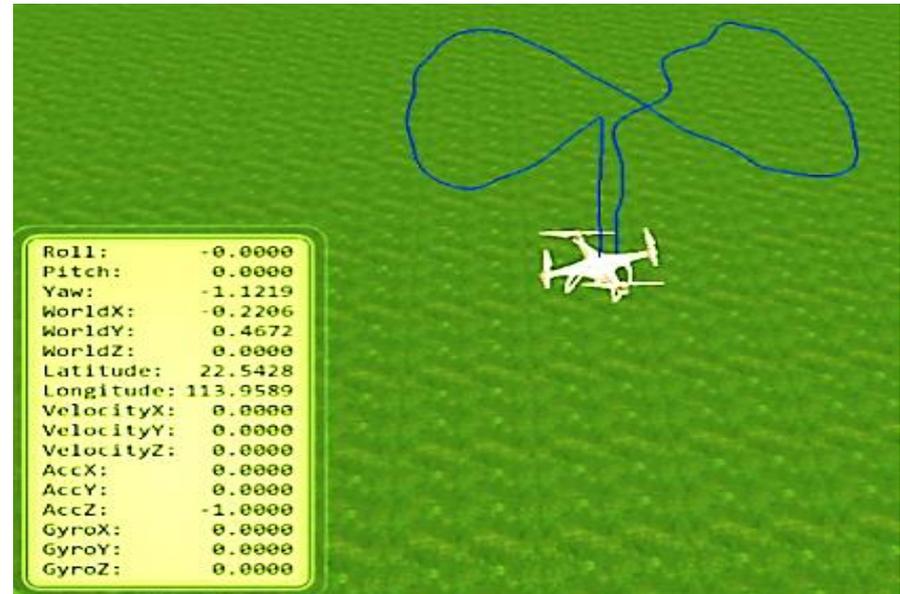
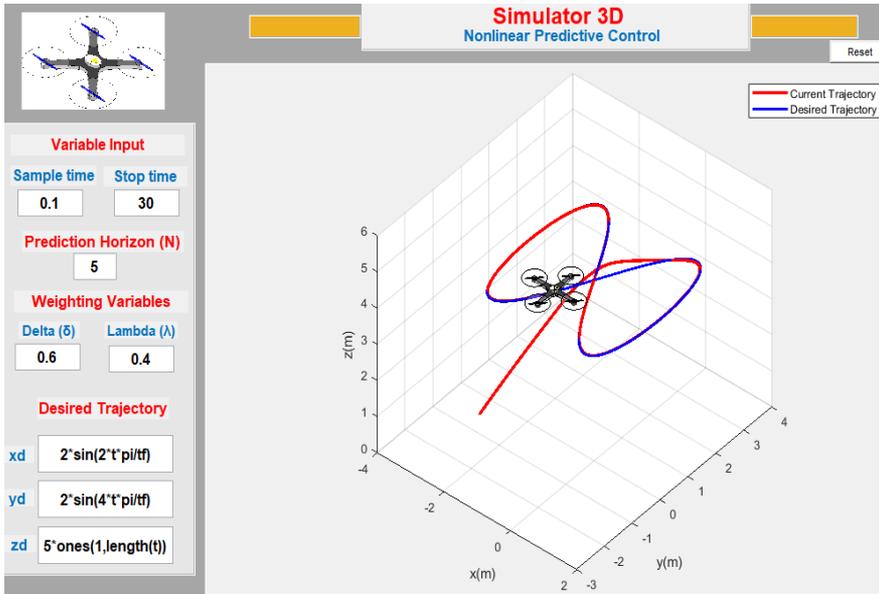


Para N=8



5. RESULTADOS

5.8 PRUEBAS EXPERIMENTALES

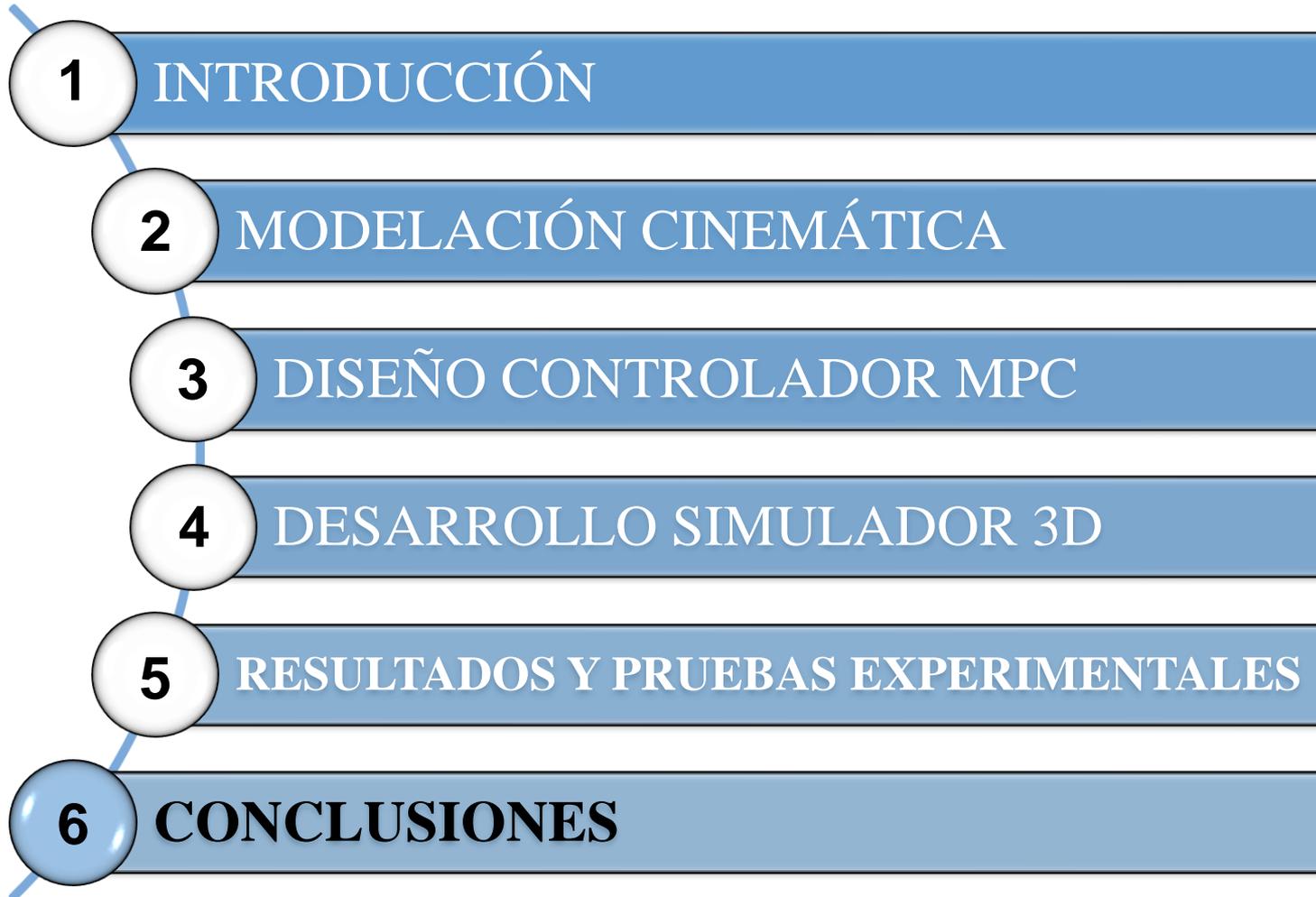




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**Sede
Latacunga**



6. CONCLUSIONES

- ✓ El control predictivo basado en modelo se basa en la búsqueda de una serie de múltiples referencias en distintos instantes de tiempo, cuyo número depende del horizonte de predicción.
- ✓ El modelo cinemático permite determinar las características de movimiento y maniobrabilidad que puede tener el sistema robótico, para ser utilizado con diferentes algoritmos de control avanzado.
- ✓ Se implementa un esquema de control predictivo que considera un funcional de coste en función a los errores de control y de la variación de las velocidades de maniobrabilidad del UAV, prediciendo una trayectoria o evento.
- ✓ Se determina que para un horizonte de predicción mayor a 8, se corre el riesgo de que el tiempo de ejecución sea mayor al tiempo de muestreo, teniendo como resultado inestabilidad en el sistema.
- ✓ El simulador 3d desarrollado es intuitivo para el usuario y permite realizar simulaciones previas a las pruebas experimentales y así evaluar el comportamiento del controlador propuesto, de tal manera que ayuda a evitar fallas en las pruebas de vuelo.



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DEPARTAMENTO DE ELÉCTRICA Y ELECTRÓNICA

CARRERA DE INGENIERÍA EN ELECTRÓNICA E INSTRUMENTACIÓN

**Artículo Académico Previo a la Obtención del Título de Ingeniería en Electrónica E
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**“CONTROL PREDICTIVO NO LINEAL PARA EL SEGUIMIENTO DE TRAYECTORIA DE VEHÍCULOS AÉREOS NO
TRIPULADOS”**

NONLINEAR PREDICTIVE CONTROL FOR THE TRACKING OF UNMANNED AERIAL VEHICLES

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