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Unmanned Aircraft Systems

EPRL Sliding Mode Flight Controller with Model-based Switching Manifold of a Quad-Rotor UAV

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Agenda

01 - INTRODUCTION

Context, Motivation and Contributions

02 – PRELIMINARIES

Quad-Rotor Model and Problem Formulation

03 – PROPOSED CONTROLLER

Concept and Design

04 – NUMERICAL SIMULATIONS

Results and Comparative Study

05 – CONCLUSIONS

Summary and Ideas

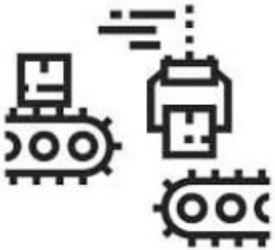
01 - Introduction

FROM INDUSTRY 1.0 TO INDUSTRY 4.0

1st Revolution

Mechanization, water and steam power

2nd Revolution

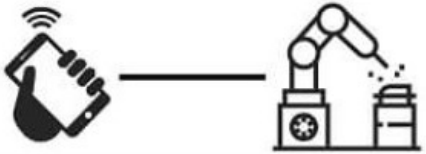


Mass production, assemply line and electrical energy

3rd Revolution

Electronics, computers and automation

4th Revolution



Cyber-physical systems and big-data

Late 18th century

Early 20th century

Early 70s

Today

01 - Introduction

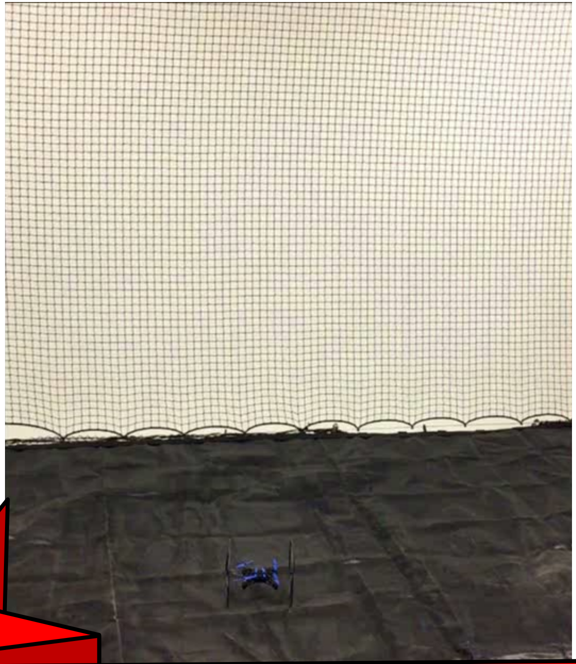
Advantages

- Vertical take-off and landing
- *Flying in low speed*
- High maneuverability
- Small 4-rotors, less kinetic energy
- *Simple design and easy maintenance*
- Several possible applications

Disadvantages

- underactuated system
- Presence of hard nonlinearities
- highly coupled dynamics
- Requires precise & accurate rotor-speed control
- It is sensitive to perturbation

01 - Introduction



ACCURATE FLIGHT
AND STABILIZATION !!!

01 - Introduction

Technique	Advantages	Drawbacks
Feedback Linearization	• Full linearization of the drone model • Application of linear control methods	• Holds higher order Lie derivatives • States become noisy • Parametric changes not handled • Requires precise model
Integral Backstepping	• Steady state error elimination • Augmented robustness • Finite-time convergence	• Complexity in coefficient selection • Increase the control effort
Conventional SMC	• Insensitive to external disturbances • Robustness against model uncertainties • Controller structure is simple and easily tunable • Removes steady state error by adding integral action	• Chattering phenomenon • Sensor drift.

01 - Introduction

• High Order SMC	• Reduces the chattering while preserving the SMC invariance property • Insensitive to matched uncertainties • Asymptotic convergence	• Sliding surface selection is tedious • Difficult implementation
Model Predictive Control (MPC)	• Optimal control input • Desired state and input constraints can be defined • Ability to predict future control moves	• Additional computational power needed and storage required • Hard to obtain a reliable prediction model which can lead to instability • No robustness is ensured
Artificial Neural Networks (ANN) based control	• Learning ability • Rejects disturbances and estimates uncertain model parameters • No need of exact model • Can be trained to provide tolerance against the cyber threats, injected faulty data, wireless communication attacks...	• Offline learning may fail under unknown environment • Learning process is clumsy • Requires larger computational effort due to stochastic learning policies

01 - Introduction

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01 - Introduction

Original Contributions:

Exponential Power Reaching Law (EPRL) SMC with model-based sliding surfaces.

- Simplicity of the control law: A complete control decoupling is ensured since the proposed approach is not a model-based one.

- Chattering reduction and finite-time reaching convergence: The decoupled controller ensures chattering decoulping. In addition, the combination of the ERL and the PRRL ensures a faster finite-time convergence of the model-based sliding surfaces to zero and a chattering reduction since the switching gains are adapted according to the sliding surfaces' values.

- Better tracking performance: An augmented integral term in the proposed model-based sliding surfaces helps removing the steady state error and helps rejecting the effects of unmatched uncertainties that acts on the systems' states.

02 - Preliminaries

System description

Quad-rotor UAV model has 6-DOF: i) $P = [x, y, z]^T$ is the vector of position (x, y) and altitude (z) states and ii) $\Theta = [\phi, \theta, \psi]^T$ is the vector of attitude or orientation or Euler angles (roll, pitch and yaw).

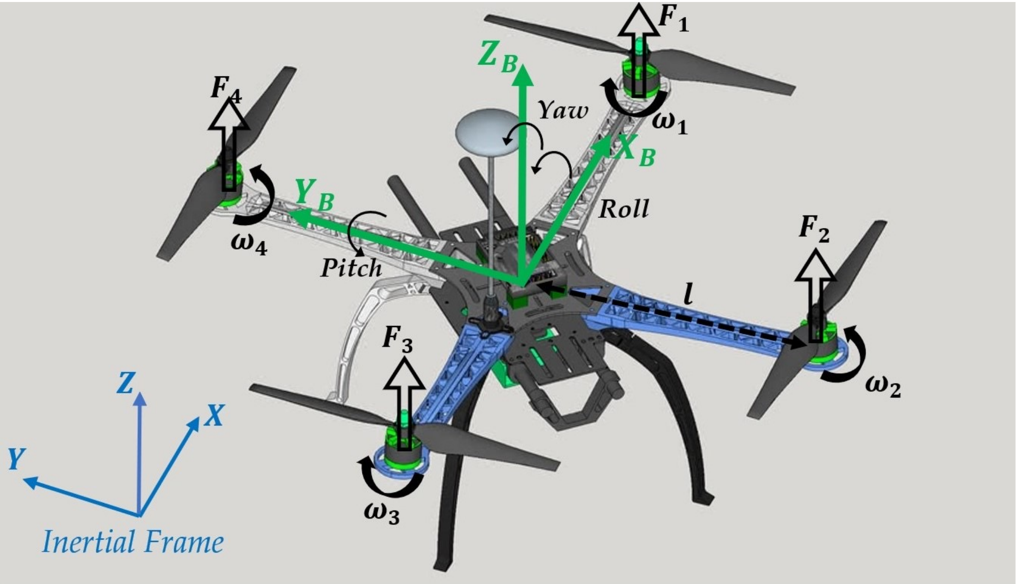


Figure 1: *quad-rotor structure, forces, angles and frames*

02 - Preliminaries

System description

Take off:

To take off the ground, the drone needs a net upward force. The motors generate lift that is greater than the force of gravity, making the drone take off.

Hovering:

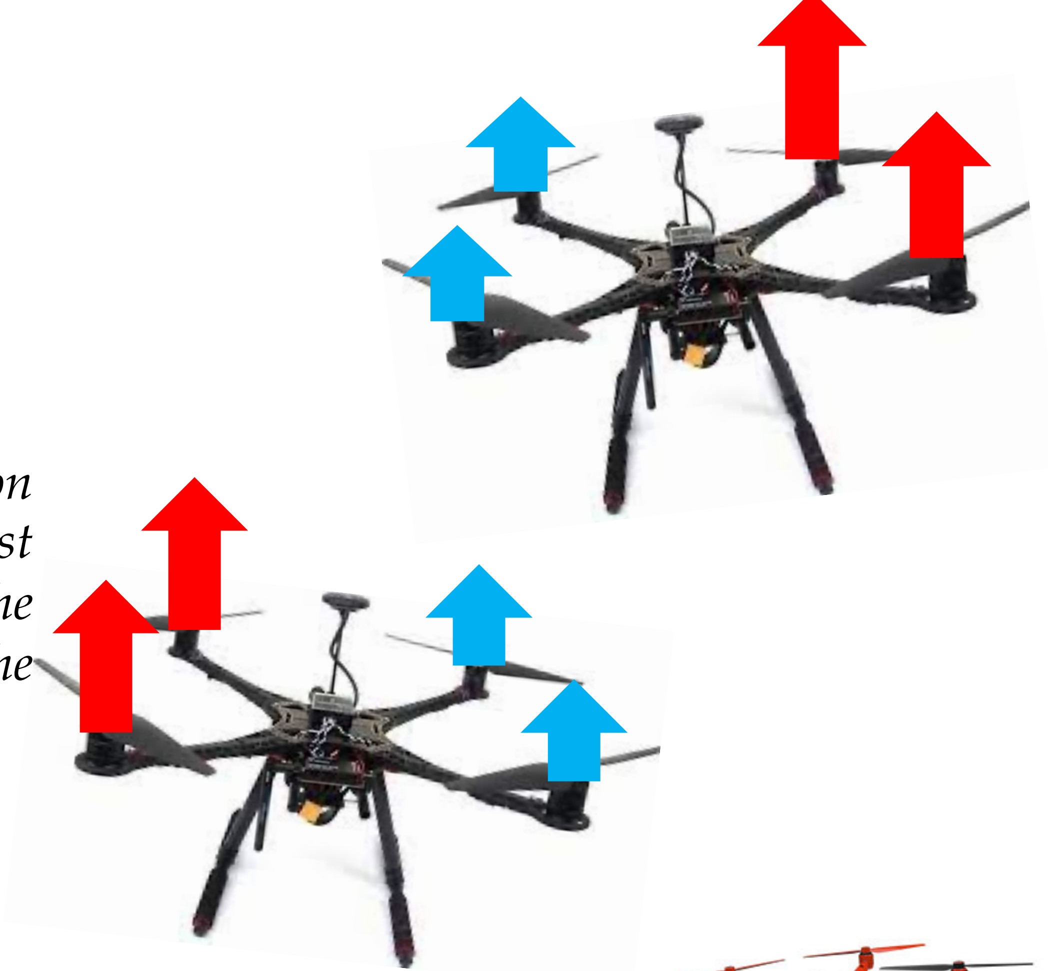
Here, the motors create lift that is equal to the force of gravity on the system. Therefore, the lift and force of gravity cancel out and makes the drone hover in mid-air.

02 - Preliminaries

System description

Roll:

To Roll to the left, the lift is increased on the motors on the right. The drone must also decrease the lift on the motors on the left. Otherwise, to roll to the right, the drone must do the exact opposite.

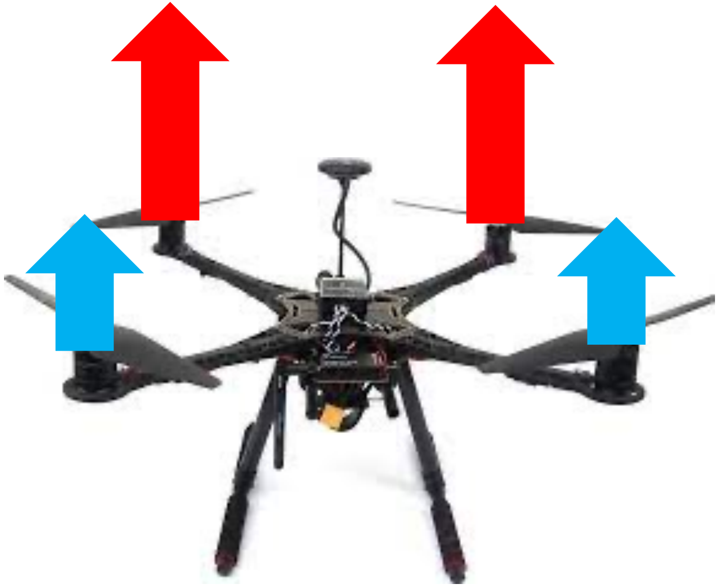


02 - Preliminaries

System description

Pitch:

To make the drone pitch forwards (move towards) to you. The power applied to the rear motors is increased. This generates a forward net force which makes the drone's nose to pitch downward. The drone also have to decrease the power applied to the two front motors to keep the angular momentum conserved. The exact opposite is done to make the drone pitch backwards (move away) from you.

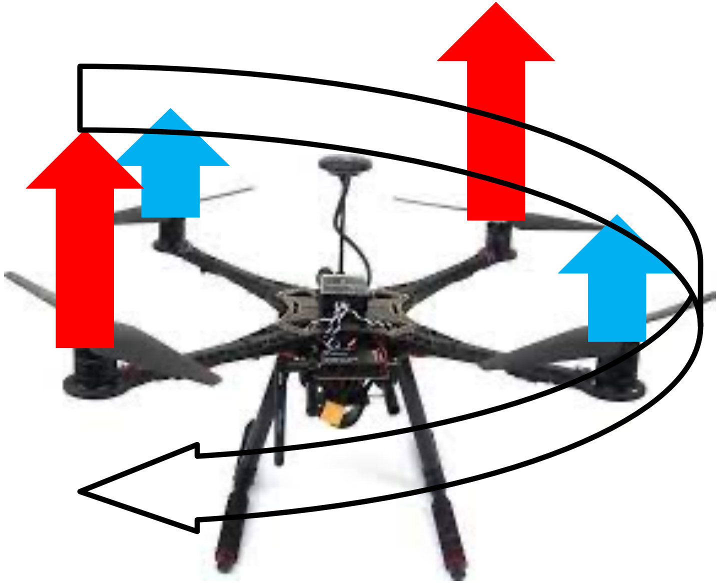


02 - Preliminaries

System description

Yaw:

To make the drone Yaw (rotate) clockwise. The drone must increase the lift on the anti-clockwise moving motors and also have to decrease the lift on clockwise rotating motors. The reason behind this is to keep the upward and downward net force equal to zero. There is also a resulting anti-clockwise torque. The drone rotates clockwise to conserve the angular momentum.



02 - Preliminaries

Dynamic model

Position and altitude model:

$$M\ddot{P} + K_P\dot{P} = \tau_P$$

- M *: quad-rotor's mass;*
- K_P*: diagonal matrix where the elements are the drag coefficients of translation;*
- τ_P *: virtual input vector that is linked to the total thrust by the following formula:*

$$\tau_T = \sqrt{\tau_{P1}^2 + \tau_{P2}^2 + (Mg + \tau_{P3})^2}$$

Attitude model:

$$I(\Theta)\ddot{\Theta} + C(\Theta,\dot{\Theta})\dot{\Theta} = \tau_\Theta$$

- $I(\Theta)$ *: inertia matrix;*
- $C(\Theta,\dot{\Theta})$*: Coriolis forces matrix;*
- τ_Θ *: vector of roll, pitch and yaw torques.*

02 - Preliminaries

Problem formulation

Let $\tilde{P} = P - P^d \in \mathbb{R}^3$ *be the position and altitude error vector with* $P^d \in R^3$ *is the desired known position and altitude vector and let* $\tilde{\Theta} = \Theta - \Theta^d \in \mathbb{R}^3$ *be the attitude error vector with* $\Theta^d \in \mathbb{R}^3$ *is the known desired attitude vector.*

Assuming that the roll ϕ *and the pitch* θ *are different from* $\pm\pi/2$ *to avoid singular configuration, the control objective is to design two cascade robust nonlinear controllers using EPRL SM fligh control with model-based sliding surfaces to ensure the convergence of both* $\tilde{P}$ *and* $\tilde{\Theta}$ *to zero.*

03 – Proposed Controller

Global structure

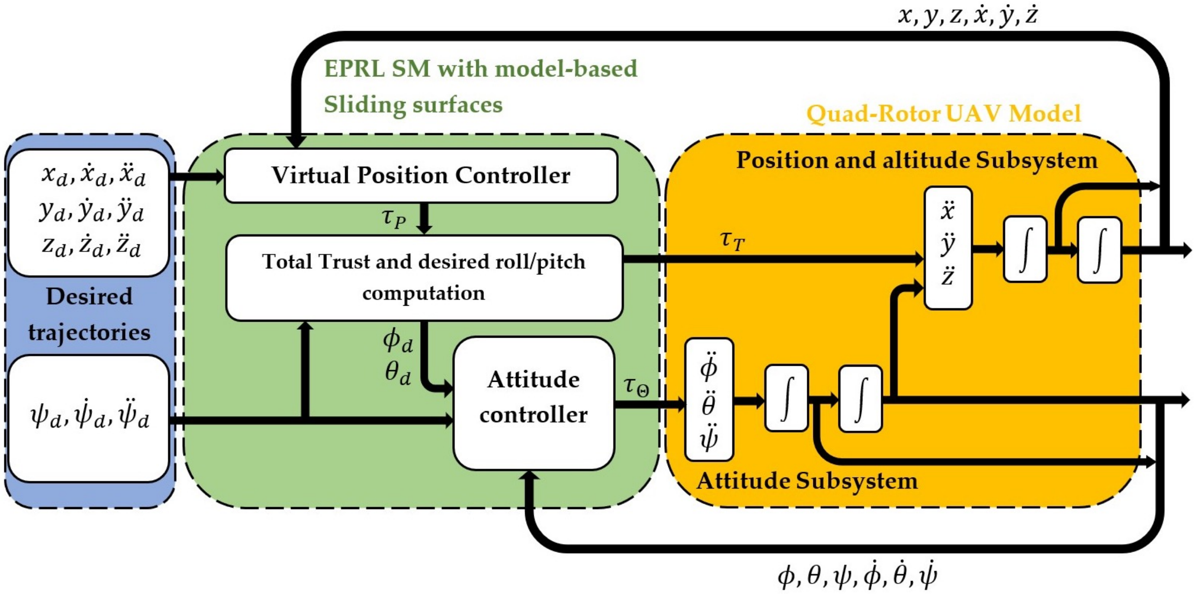


Figure 2: *Closed-loop block diagram of the proposed flight controller*

03 – Proposed Controller

Outer control loop

The proposed approach design consists of two steps:

- ***First Step:*** *Design of the model-based sliding surfaces and compute its first-time derivative:*

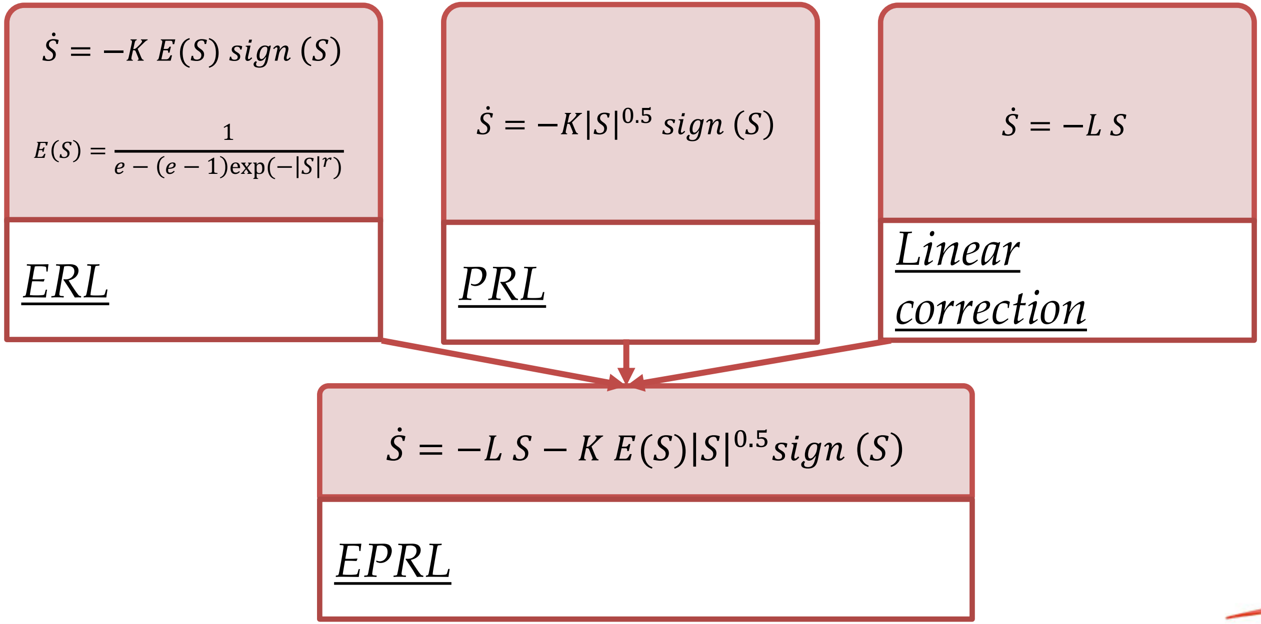
$$S_P = M\dot{\tilde{P}} + (K_P + \Lambda_1)\tilde{P} + \Lambda_2 \int_0^t \tilde{P}\, dt$$

$$\dot{S}_P = M\left(\ddot{P} - \ddot{P}^d\right) + (K_P + \Lambda_1)\left(\dot{P} - \dot{P}^d\right) + \Lambda_2\tilde{P}$$

03 – Proposed Controller

Outer control loop

- ***Second step:*** *Design of the control law:*



$$\dot{S} = -K\,E(S)\,sign\,(S)$$

$$E(S) = \frac{1}{e-(e-1)\exp(-|S|^{r})}$$

ERL

$$\dot{S} = -K|S|^{0.5}\,sign\,(S)$$

PRL

$$\dot{S} = -L\,S$$

Linear correction

$$\dot{S} = -L\,S - K\,E(S)|S|^{0.5}sign\,(S)$$

EPRL

03 – Proposed Controller

Outer control loop

Theorem 1:

Consider the position model of the quad-rotor UAV system, the computed total force:

$$\tau_T = \sqrt{\tau_{P1}^2 + \tau_{P2}^2 + (Mg + \tau_{P3})^2}$$

$$\tau_p = \left[\tau_{p1}, \tau_{p2}, \tau_{p3}\right]^T = M\ddot{P}^d + K_d\dot{P}^d - \Lambda_1\dot{\tilde{P}} - \Lambda_2\tilde{P} - L_P S_P - K_P E_P(S_P)|S_P|^{0.5} sign\,(S_P)$$

ensures the convergence of S_{Pi} *to zero in a finite-time smaller than:*

$$T_{Pi}^c \leq \frac{-2}{L_{Pi}}\, ln\left(\frac{K_{Pi} + L_{Pi}|S_{Pi}(t_0)|^{0.5}}{K_{Pi}}\right)$$

03 – Proposed Controller

Inner control loop

Let us first compute the desired roll and pitch trajectories:

$$\phi^d = arcsin\left(\frac{sin(\psi^d)\tau_{P1} - cos(\psi^d)\tau_{P2}}{\tau_T}\right)$$

$$\theta^d = arctan\left(\frac{cos(\psi^d)\tau_{P1} + sin(\psi^d)\tau_{P2}}{\tau_{P3} + \mathrm{g}M}\right)$$

03 – Proposed Controller

Inner control loop

- **First Step:** *Design of the model-based sliding surfaces and compute its first-time derivative:*

$$S_\Theta = I(\Theta)\dot{\Theta} - I(\Theta^d)\dot{\Theta}^d + \Gamma_1\tilde{\Theta} + \Gamma_2\int_0^t \left(\tilde{\Theta} - \left(W(\Theta,\dot{\Theta}) + C(\Theta,\dot{\Theta})\right)\dot{\Theta} + \left(W(\Theta^d,\dot{\Theta}^d) + C(\Theta^d,\dot{\Theta}^d)\right)\dot{\Theta}^d\right) dt$$

$$W(\Theta,\dot{\Theta}) = \dot{I}(\Theta) - 2C(\Theta,\dot{\Theta}), \qquad W(\Theta^d,\dot{\Theta}^d) = \dot{I}(\Theta^d) - 2C(\Theta^d,\dot{\Theta}^d)$$

$$\dot{S}_\Theta = I(\Theta)\ddot{\Theta} + C(\Theta,\dot{\Theta})\dot{\Theta} - \left(\underbrace{I(\Theta^d)\ddot{\Theta}^d + C(\Theta^d,\dot{\Theta}^d)\dot{\Theta}^d}_{\tau_\Theta^d}\right) + \Gamma_1\dot{\tilde{\Theta}} + \Gamma_2\tilde{\Theta}$$

- **Second step:** *Compute the control law:*

$$\dot{S}_\Theta = -L_\Theta\, S_\Theta - K_\Theta\, E_\Theta(S_\Theta)|S_\Theta|^{0.5} sign\,(S_\Theta)$$

03 – Proposed Controller

Inner control loop

Theorem 2:

Consider the attitude model of the quad-rotor system, the computed control input vector:

$$\tau_{\Theta} = \tau_{\Theta}^{d} - \Gamma_1 \dot{\tilde{\Theta}} - \Gamma_2 \tilde{\Theta} - L_{\Theta}\, S_{\Theta} - K_{\Theta}\, E_{\Theta}(S_{\Theta})|S_{\Theta}|^{0.5} sign\,(S_{\Theta})$$

ensures the convergence of S_{Pi} *to zero in a finite-time smaller than:*

$$T_{\Theta i}^{c} \leq \frac{-2}{L_{\Theta i}}\, ln\left(\frac{K_{\Theta i} + L_{\Theta i}|S_{\Theta i}(t_0)|^{0.5}}{K_{\Theta i}}\right)$$

04 – Numerical Simulations

Results

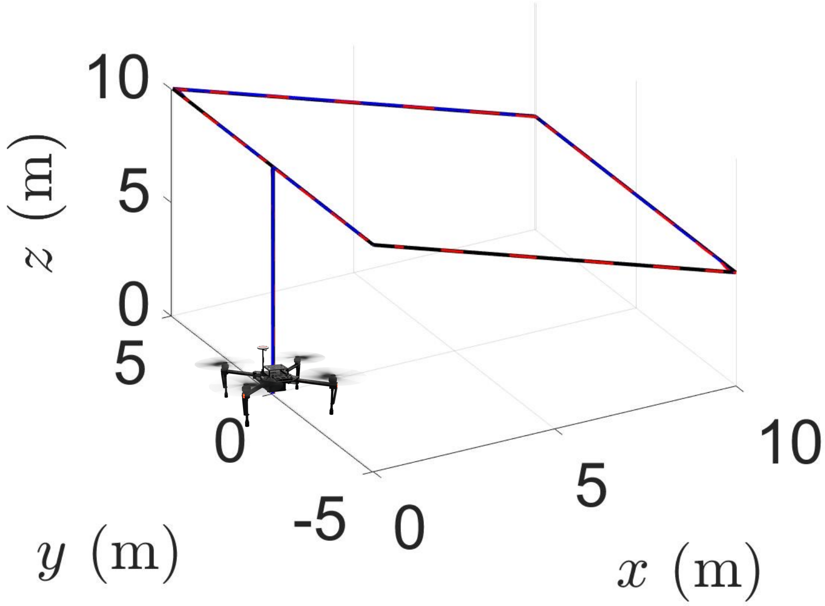


Figure 3: *3D cartesian space tracking*

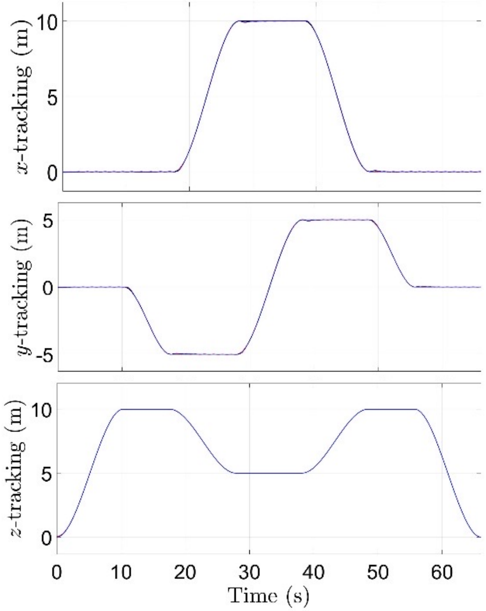


Figure 4: *Position and altitude tracking*

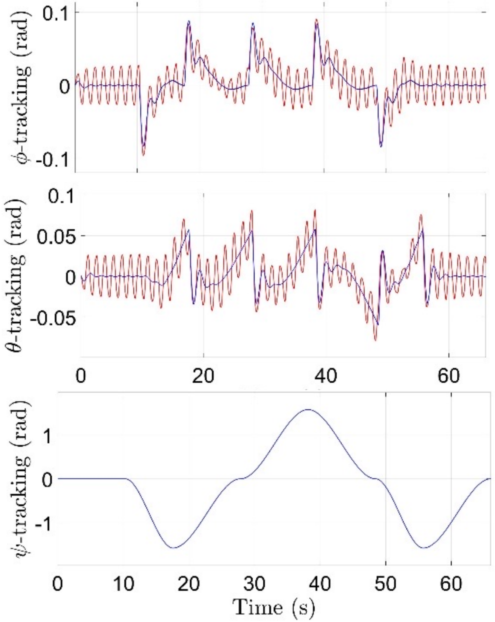


Figure 5: *Attitude tracking*

04 – Numerical Simulations

Results

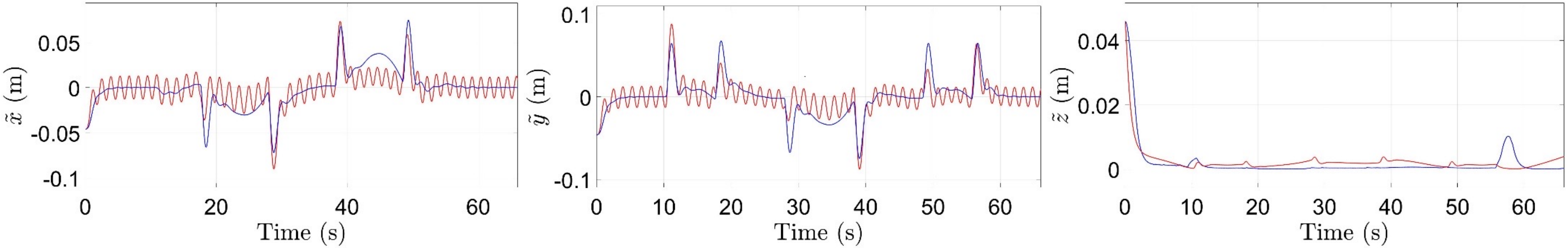


Figure 6: *Position and altitude tracking error*

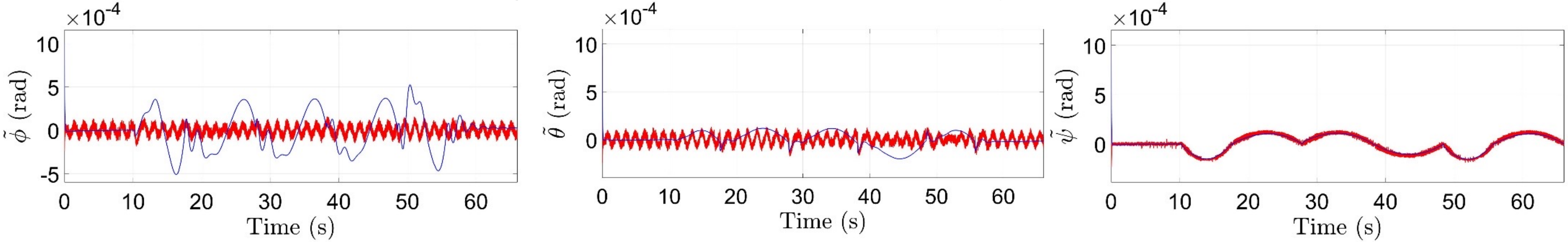


Figure 7: *Attitude tracking error*

04 – Numerical Simulations

Results

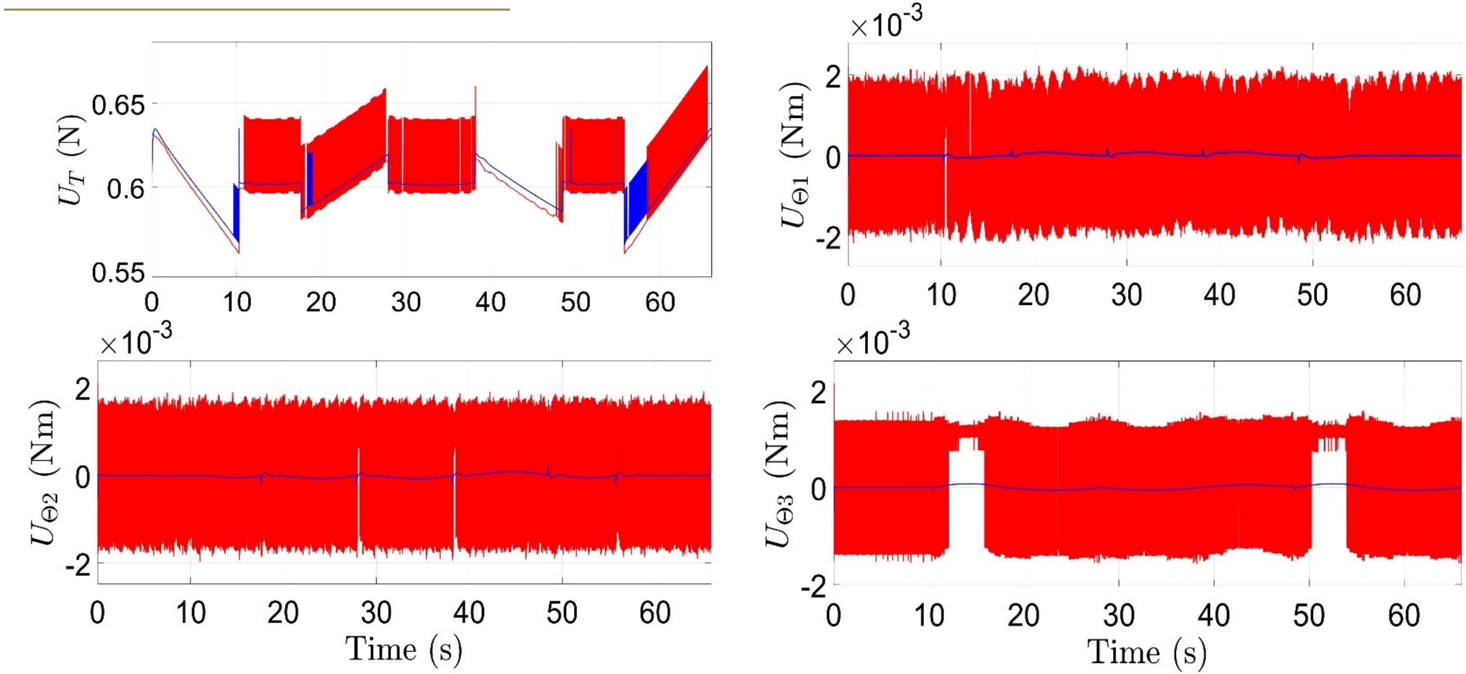
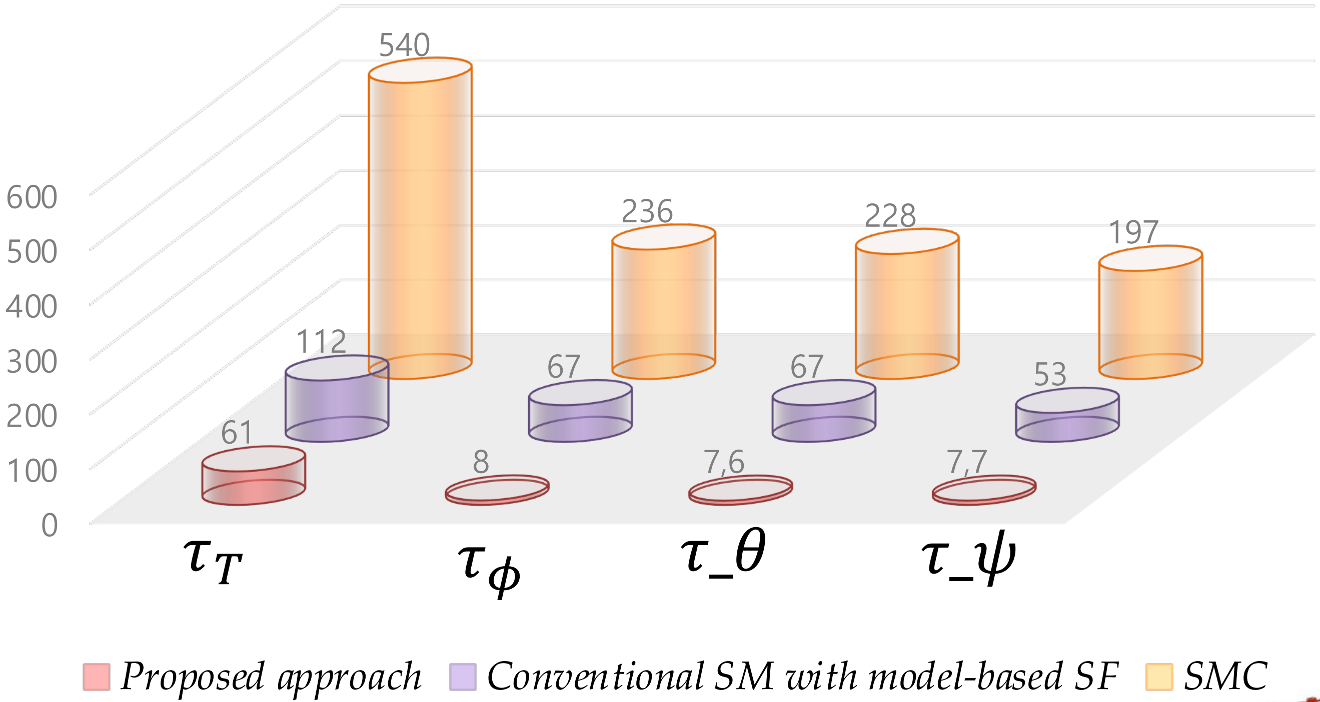


Figure 8: *Computed control inputs*

04 – Numerical Simulations

Comparative study



05 – Conclusions

Summary

- *Development of EPRL SM flight control with model-based switching surfaces for quad-rotor UAV systems;*
- *Simulation results and quantitative comparison of the enhanced method with the conventional SM with model-based switching surfaces.*

Future works

- *Real-time implementation of the proposed approach on a real quad-rotor system and on other second-order nonlinear systems.*

THANK YOU!

Hope you like this presentation