Adaptive and Autonomous Aerospace Systems

School of Industrial and Information Engineering - Aeronautical Engineering

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Project exam 2025/2026

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Introduction

The first time you take the exam, it consists in the development of a **project** and an individual **oral exam**.

- The project consists in the solution of a problem formulated in multiple tasks, described in the next slides.

- The individual oral part consists in the development of a presentation about one of the topics covered in the third part of the course (autonomous aerospace systems).

Rules

Rules for the project

- You can work individually or work in a small group (max 3 people).
- The project must be delivered in the form of an **oral presentation** (supported by slides) given by the group together with the **code** used for obtaining the results.

Rules for the individual oral exam

- You must prepare a short presentation on the topic that you liked the most on autonomous systems (third part of the course).
- Maximum 15 slides and 15 minutes for the talk.

The individual oral exam must be taken jointly with the project presentation.

Evaluation

The design project gives up to 32 points.

- Lack of clarity or a not thorough enough analysis of the results are penalized with the 10% of the points for each task.
- Conceptual errors are penalized with 2 up to 5 points for each error, depending on the severity.

The individual presentation will give or remove points to the project grade [-5; +2]

The work will be evaluated based on

1. Methodological correctness and mathematical rigor.
2. Completeness of the results.
3. Clarity of presentation.
4. Original contributions.

Rules

- The exam can be taken whenever ready during the year from the first exam date to the end of September 2026.

- To fix the date for the exam, you must **send an email** to davide.invernizzi@polimi.it, I will then give you some options.
  - The slides and the code for the project must be sent to me at least three days before the exam.
  - The presentation for the individual part can be handed over on the day of the exam.

- If:
  - you do not pass the exam, or
  - you decide to refuse the proposed mark,

then in the next attempts the exam will consist of an **oral interview** covering **all the topics** of the course.

- If you request to schedule a group exam date but one or more members of the group do not present the project, the exam will be considered **failed**.

Project description

The project concerns the development of an adaptive controller to support package delivery missions.

The tasks are intended to address the control system development in an incremental manner, starting from the design model up to the testing in a representative simulation environment.

All the data for the development of the control system and the simulation are available in the zip file uploaded on weebep.

Project description

Task 1: simulation model implementation (6 pts – 8 pts with task 1.3)

Model dynamics (see Part 1 lectures for the derivation of the model)

UAV dynamics

$$\dot{p} = R v_b$$
$$\dot{R} = R S(\omega_b)$$
$$M \dot{\nu}_b + \nu_b^\times M \nu_b = -D \nu_b + w_g + F u$$

$$\nu_b := \begin{bmatrix} v_b \\ \omega_b \end{bmatrix} \quad M := \begin{bmatrix} m I_3 & S^\top \\ S & J \end{bmatrix} \quad w_g := -\begin{bmatrix} m g R^\top e_3 \\ g S R^\top e_3 \end{bmatrix}$$

$$F := \begin{bmatrix} n_1 & \cdots & n_N \\ (p_1^\times - \xi_1 \sigma_1 I_3) n_1 & \cdots & (p_N^\times - \xi_N \sigma_N I_3) n_N \end{bmatrix}$$

Propeller dynamics (closed loop)

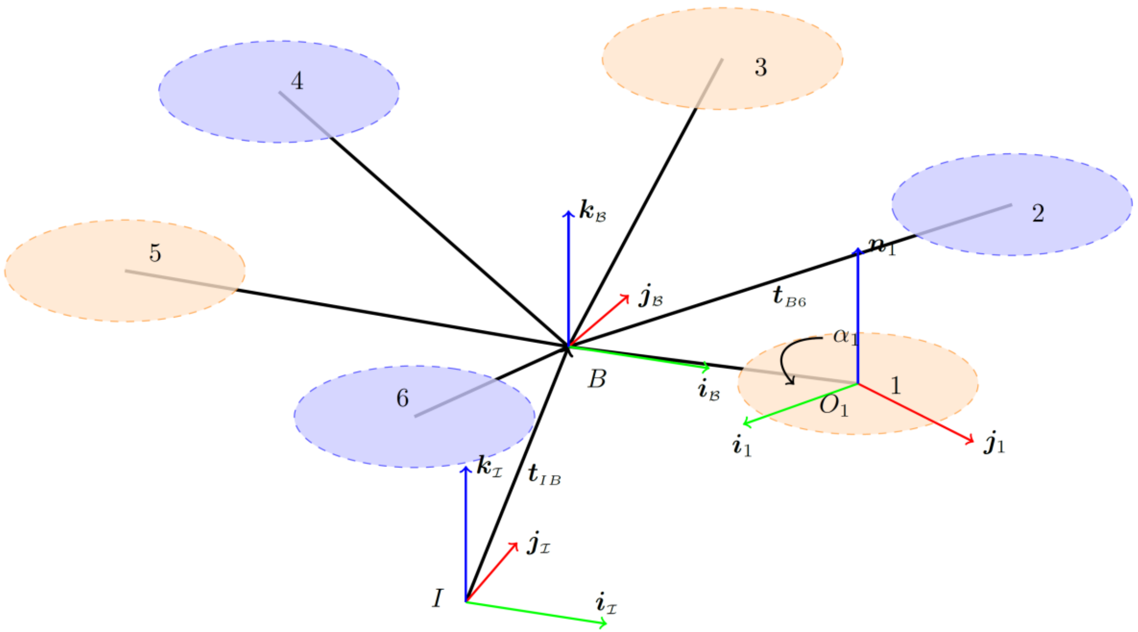
$$\dot{\Omega}_r = -k_{r,m}(\Omega_r - \Omega_{r,cmd})$$
$$T_r = \mathrm{sat}_{T_m}^{T_M}(\lambda_r k_f \Omega_r^2)$$
$$u = \begin{bmatrix} T_1 & \cdots & T_N \end{bmatrix}^\top$$

$$r = 1, \ldots, N$$

The nominal values for the parameters are reported in the MATLAB script *MAIN_exam.m* available on weebep in the exam folder.

1.1 Implement in Simulink the dynamics of a hexacopter UAV with the geometric and inertial data in the provided MATLAB script.

The six propellers are evenly placed in the plane of the body frame according to the following figure



Project description

1.2 Given the nominal model of the UAV, compute analytically the commands $\Omega_{r,cmd}, r = 1, \dots, 6$ to trim the UAV at

$$p = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^\top m$$

where p is the inertial position.

Project description

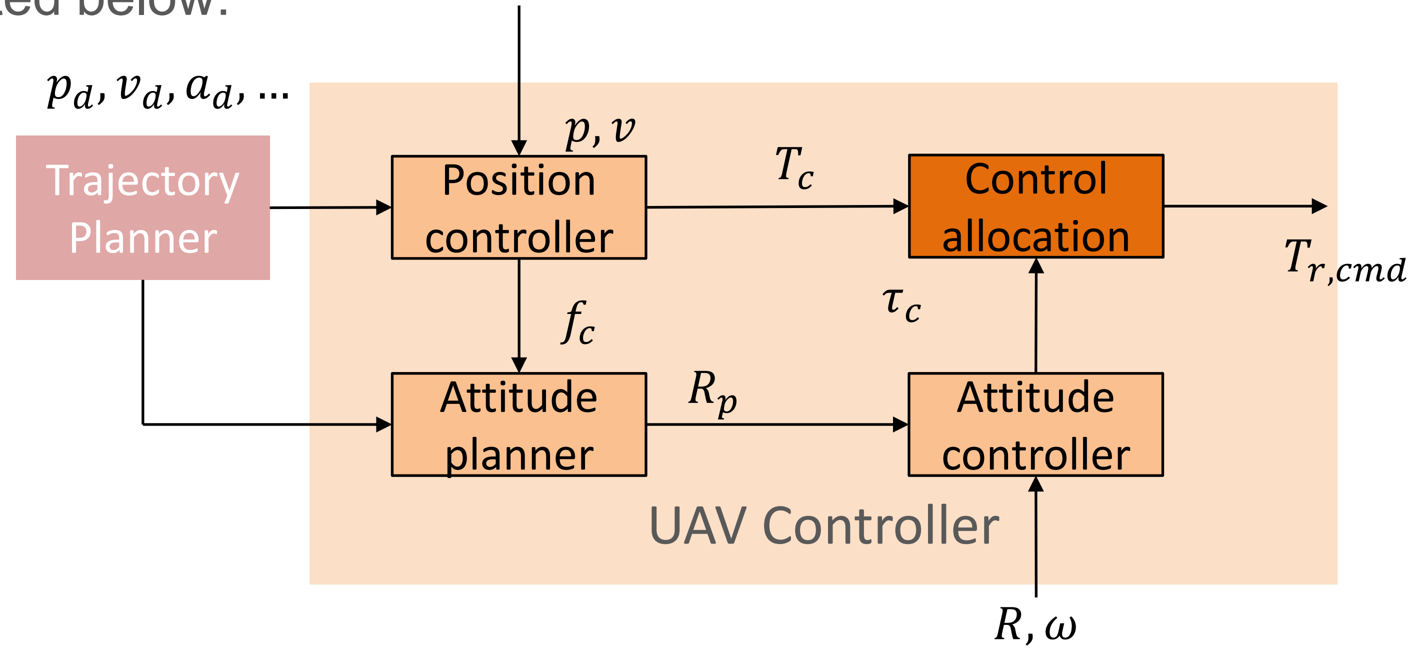
1.3 Given the nominal model of the UAV, compute (analytically or numerically) the commands $\Omega_{r,cmd}, r = 1, \dots, N_R$ to trim the UAV at

$$v_i = \begin{bmatrix} 2 & 0 & 0 \end{bmatrix}^\top m/s$$

where v_i is the inertial velocity.

Task 2: Baseline controller implementation, tuning and testing (8pts)

2.1 Implement in Simulink the control architecture for position-heading tracking control presented in P2CS1 and reported below:



- Select suitable **motion control laws** for the position and attitude blocks capable of ensuring position and heading direction control.
- **Control allocation** can be performed using the pseudo inverse method, as discussed in P2CS1.

Project description

2.2 Baseline controller design tuning: tune the motion controllers to have a desired behavior with respect to a setpoint tracking case.

To tune the gains, you must properly specify control objectives (e.g., overshoot, settling time, disturbance rejection capabilities, ...) that the controller should provide in design conditions.

Consider working on simplified/linearized models when performing the tuning and taking into account constraints from actuator and sensor dynamics (e.g., bandwidth, saturation, delays).

Project description

2.3 Test the control design on the full nonlinear simulation model developed in Task 1.

2.3.1 Verify the behavior for

- the setpoint tracking case used to tune the controller
  - Retune the controller if needed
- a trajectory tracking scenario (specify a suitable trajectory considering speed no larger than 4-5m/s and a suitable metric to evaluate the tracking performance).

2.3.2 Simulate a reduction of the propellers' effectiveness during the trajectory tracking scenario and assess the impact on the tracking capabilities of the baseline control system.

Task 3: Adaptive augmentation (10 pts – 12 pts with task 3.4)

3.1 Assume a scenario where the hexacopter UAV is used for package delivery.

Considering the package as a rigid body attached at the bottom with of the UAV at a distance $r_c \in \mathbb{R}^3$ from the origin of the body.

- Specify suitable inertial properties for the package and then properly modify the UAV simulator.
- Verify the behavior of the baseline control system in a representative scenario, assuming that the inertial properties of the package are completely unknown to the baseline controller.

Project description

3.2 Consider the following approximation of the uncertain UAV dynamics for position control augmentation

$$m\dot{v}_i = -mge_3 + f_e + \Lambda_f f_c$$

where Λ_f is a diagonal control effectiveness matrix and f_e represents an exogenous disturbance force.

- Derive the corresponding predictor dynamics and the corresponding update laws for the development of a Predictor-Based MRAC design assuming f_e be constant.

<u>Remark</u>: You are not asked to augment the attitude baseline controller. Under which assumptions is this reasonable?

3.3 Adaptive control law implementation and testing

- Based on the uncertain dynamics derived in point 3.2, implement in Simulink the PBMRAC controller, in augmentation to the baseline position controller developed in Task 2.

- Test the control law in a <u>representative</u> scenario. What is the effect of the added package mass on the control effectiveness?

3.4 (Alternative to Task 1.3) Monte Carlo analysis

- Implement a Monte Carlo procedure accounting for:
- uncertain mass of the package
- uncertain efficiency of the propellers

Parametric uncertainties can be modeled as random distributions (assume as mean values the numbers provided in the MATLAB script and reasonable values for their deviation – they should be physically consistent and reasonable).

- Define suitable metrics to evaluate the performance of the control law with respect to nominal conditions for a representative scenario.
- Analyze and discuss the obtained results in terms of statistics of the considered metrics (e.g., collect data in histograms – select a reasonable number of simulation runs).

Task 4: test in delivery scenario (6pt)

Consider developing a suitable delivery scenario where the hexacopter must deliver a package in an urban like environment (consider at least three buildings with suitable dimensions).

Specify take off and landing locations and set up a mission for the UAV splitting the delivery in **take off**, **cruise** and **landing phases**.

Assume the landing location to be in front of a building and consider the environment and the map to be known.

Test the behavior of the adaptive control system in the presence of reasonable unforeseen events (wind gusts/degradation of the actuation capabilities).

NB: You can use MATLAB built-in functions to generate the environment and the trajectory (seen in the LAB on planning).