Deutscher Akademischer Austauschdienst Dienst

RESEARCH PROJECT

MODELLING AND CONTROL OF AN OVERACTUATED HEXACOPTER TILT-ROTOR UNMANNED AERIAL VEHICLE

AREA: Electrical Engineering
SUB-AREAS: Robotics and Control Systems

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Contents

Abstract

Flying robots with directional thrusters are typically over-actuated systems delivering safety, versatility, and cost reduction in inspections. Taking this into account, this project aims to design and develop a novel light-weight Unmanned Aerial Vehicle (UAV) prototype, an overactuated Hexacopter Tilt-Rotor (HTR). It has 2 of the 6 actuators that can be independently tilted, also presenting high manoeuvrability. In this arrangement, every propulsion motor has its command signal embedded in traditional control boards. Also, the aircraft enhances its yawing capability and increases one more actuation domain: forward/backward velocity.

I. Introduction

A. *Background Global Scenario*

The acronym UAV means Unmanned Aerial Vehicle which has been showing considerable growth in recent years, leveraged by technological developments, mainly in the areas of electronics and military automation [1].

This consequently generates a large market to emerge from potential applications and services to be offered by UAVs. When considered in civil applications, there is a wide range of possible scenarios for its use, such as remote environmental research, pollution monitoring and certification, fire management, security, border monitoring, oceanography, agriculture and fisheries applications [2].

Each application may demand a specific UAV topology, fixed wings (airplanes, for example), rotating wings (helicopters and multicopters, for example) and those of Hybrid categories (balloons and airships, for example).

Recent literature shows several traditional UAVs designs with good stability and reliable flight conditions, such as multicopters [3], [4], [5], [6], fixed wings [7], [8], [9] and hybrids [10], [11], [12], [13].

However, the vehicle displacement in three-dimensional space may face some limitations related to its performance since most of the UAVs are underactuated mechanical systems; that is, they have fewer actuators than Degrees of Freedom (DoF). This is, for example, the case with traditional helicopters and quadrotors, where only the aircraft's angular positions (roll, pitch, and yaw) and altitude can be independently controlled. At the same time, the behavior in the vehicle's inertial frame is determined by the consequent performance in these 4 DoFs.

This brings to light a wide variety of control techniques to deal with these underactuated UAV limitations to perform a more effective and robust flight, as can be seen in the works of [14], [15] and [16].

Taking these limitations into account, Tilt-rotors were created. Projects were proposed with different tilting procedures, such as fixed wings UAVs with tilting mechanisms [17], [18] and UAVs with non-parallel propulsion directions, even when they are fixed [19].

These Tilt-rotors can operate through different flight modes, such as hover flight, forward flight (with cruising speed), and the respective transition between them (just by tilting from engines "helicopter" mode to "fixed-wing" mode) [20].

As an example, the work of [21] shows the combination of several underactuated and directed propulsion vehicle modules to achieve the full DoF performance. Its main objective was based on the optimal allocation of available (redundant) control variables.

In [22] it was considered the possibility of a Tilt-rotors vehicle driving the main propulsion in 2 fully controlled DoFs. A trajectory tracking control strategy was then proposed, where a limited range of thrust angles was adopted.

Another example of a vehicle was presented in [23], consisting of two main coaxial propellers surrounded by three tilting thrusters. The prototype is capable of flying in two flight modes: a fixed configuration in which it behaves like a traditional underactuated UAV; and a configuration of variable thruster angles that ensure a satisfactory performance, according to the authors.

Other works also stand out regarding Tilt-rotors topologies, both with fixed wings [24], [25], [26], [27], [28] or rotating [29], [30], [31]. A great advantage of these topologies is the possibility of taking off and landing vertically, dispensing landing strips and increasing versatility.

Comparing these 2 Tilt-rotors configurations, those with fixed wings generally have a more extensive flight range than those without them, as the wings generate lift during flight, allowing to attenuate the thrusters rotations, which leads to battery savings and increased autonomy.

On the other hand, it is more challenging to obtain fixed-wing Tilt-rotors with control characteristics considerably robust to atmospheric disturbances when compared to Tilt-rotors without fixed wings (rotating wings). This difficulty can make its application unfeasible, for example, in detailed inspections of transmission lines, where flights hovering close to the cables are needed.

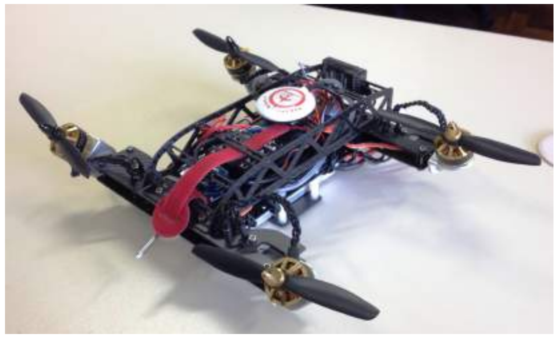
Mathematically, this complexity is explained by the presence of aerodynamic surfaces that increase the system nonlinearity, bringing with them drag forces and torques as atmospheric disturbances arise. In addition, they also lead to a decrease in maneuverability and robustness in hover flights through sudden maneuvers, which can limit the perception of details during monitoring, and even generate instability.

Therefore, this project aims to design and develop a Tilt-rotor with Hexacopter topology, where 2 of the 6 actuators can be tilted. To accomplish this, there is the necessity to expand the control allocation technique developed in [1], [32], where was considered to break the non-linear allocation system with a non-unique solution into 2 linear subsystems.

The QTR control system developed in the respective works had efficient results in the control performance of its global position and angular attitude, with the ability to take-off and land vertically on the ground, as well as hovering mode. This vehicle also exhibited autonomous flying abilities with linear velocity by changing the vehicle's 4 propulsion motors tilting angles. Above all, the control techniques implemented in this closed-loop system could track reference trajectories with null steady-state errors.

Regarding the implemented control allocation technique, the authors proposed to break the Control Effectiveness Matrix (CEM) (5x4 dimension) into 2 subsystems, 1 with CEM dimensions of 2x5 and

Fig. 1: Illustration picture of the Quadrotor Tilt-Rotor (QTR) developed in [1], [32].



the other one with 5x4, where the virtual control actions were divided according to the real control actions according to the system's control needs.

B. Objectives

The general objective of this research project is to design and develop a prototype with HTR topology, where 2 of the 6 actuators have the possibility to be independently tilted, i.e., this UAV will also be overactuated.

Consequently, this research project aims at achieving the following goals:

- Development of a model that encompasses the UAV aerodynamic forces, as well as its CEM, which directly reflects on the control allocation technique to be expanded, presented in the doctoral thesis of [1];
- Simulate and create the designed HTR project;
- Implement all the control loops necessary for the development of autonomous missions, as well as the tuning of the respective controllers;
- Expand the control allocation technique proposed in [1], including the mitigation of a new subset combinations of the new UAV CEMs;
- Assure the minimum stability requirements for the new proposed subset combinations from the full CEM.

C. Joint Works

The partnership between the Candidate and the Host produced publications in different subareas of control techniques. These will be explored in the following 3 subsections. The first one (Section I-C1) depicts production in subareas of control techniques applied to UAVs, that is, into the area of this research project. The second one (Section I-C2) shows other common publications out of UAVs but still covered by control techniques. The last one (Section I-C3) presents a common publications of UAVs still under review.

It is important to mention other results of this partnership. The Candidate performed a lecture on Leuphana University of Lüneburg (invited by the Host) titled by (*Aspects and Different Views of Control Allocation Techniques for Over-Actuated UAVs*) on February 25th 2019.

*1) **Related Works - Published**:* The following publications are from International Conferences sponsored by IEEE:

- SANTOS, M. F.; HONORIO, L. M.; COSTA, E. B.; SILVA, M. F.; VIDAL, V. F.; SANTOS NETO, A. F.; REZENDE, H. B.; MERCORELLI, P.; N. PANCOTI, A. A.. Detection Time Analysis of Propulsion System Fault Effects in a Hexacopter. In: 20th International Carpathian Control Conference (ICCC), Krakow-Wieliczka, 2019. p. 1;

- C. SILVA, D. H.; SANTOS, M. F.; SILVA, M. F.; S. NETO, A. F.; MERCORELLI, P.. Design of Controllers Applied to Autonomous Unmanned Aerial Vehicles Using Software In The Loop. In: 20th International Carpathian Control Conference (ICCC), Krakow-Wieliczka, 2019. p. 1.

2) ***Other Works - Published****:* Here are some publications in International Conferences sponsored by IEEE:

- COSTA, K. C.; MACHARETH, G. A.; SANTOS, M. F.; MERCORELLI, P.. Classical PI Controllers with Anti-Windup Techniques Applied on Level Systems: An Interesting Case Study. In: International Conference on Mathematics and Computers in Science and Engineering (MACISE), Madrid, 2020. p. 163-166;
- MUNIZ, L. M.; CARMO, M. J.; SANTOS, M. F.; SANTOS NETO, A. F.; MERCORELLI, P.. Case Study: Aspects of Fuzzy Controller Implementation in Embedded Systems. In: International Conference on Mathematics and Computers in Science and Engineering (MACISE), Madrid, 2020. p. 155-158;
- RIBEIRO, J. M. S.; SILVA, M. F.; SANTOS, M. F.; VIDAL, V. F.; HONORIO, L. M.; SILVA, L. A. Z.; REZENDE, H. B.; SANTOS NETO, A. F.; MERCORELLI, P.; PANCOTI, A. A. N.. Ant Colony Optimization Algorithm and Artificial Immune System Applied to a Robot Route. In: 20th International Carpathian Control Conference (ICCC), Krakow-Wieliczka, 2019. p. 1;
- MACHADO, C. M.; SANTOS, M. F.; CARVALHO, J. R.; MERCORELLI, P.. PI and Fuzzy Controllers for Non-Linear Systems: A Case Study. In: 3rd European Conference on Electrical Engineering and Computer Science (EECS), Athens, 2019. p. 11;
- SANTOS NETO, A. F.; SANTOS, M. F.; SANTIAGO, A. C.; VIDAL, V. F.; MERCORELLI, P.. Case Study: Application of NNARX Networks in the Identification of a Small-Scale Level System. In: 3rd European Conference on Electrical Engineering and Computer Science (EECS), Athens, 2019. p. 15.

Here are some publications in International Journals:

- MARIQUITO, K. C. C.; MACHARETH, G. A.; SANTOS, M. F.; MERCORELLI, P.; ROCHA, L. G.. Analysis of PI Controllers with Anti-Windup Techniques on Level Systems. WSEAS Transactions on Environment and Development, v. 16, p. 243-249, 2020;
- MUNIZ, L. M.; CARMO, M. J.; SANTOS, M. F.; SANTOS NETO, A. F.; MERCORELLI, P.. Study of Fuzzy Controllers Performance: Application on Embedded Systems. WSEAS TRANSACTIONS ON POWER SYSTEMS, v. 15, p. 87-93, 2020;
- MACHADO, C. M.; SANTOS, M. F.; CARVALHO, J. R.; MERCORELLI, P.. Study of Non-Linear Systems: PI and Fuzzy Controllers Performances. WSEAS TRANSACTIONS ON POWER SYSTEMS, v. 15, p. 79-86, 2020;
- SANTOS NETO, A. F.; SANTOS, M. F.; CERQUEIRA, A. S.; VIDAL, V. F.; MERCORELLI, P.. NNARX Networks on Didactic Level System Identification. WSEAS TRANSACTIONS ON SYSTEMS AND CONTROL, v. 15, p. 184-190, 2020.

3) ***Related Works - Under Review****:* At this time, we (Candidate and Host) have 1 paper submitted to the Journal of Control, Automation and Electrical Systems from Springer publisher. The name of the paper is *Influence of a Nonlinear Control Allocation Frequency Variation on a QTR* and was submitted in October 5^{th} 2021. We also have 2 papers to the Journal of Applied Physics, System Science and Computer, from the 5^{th} International Conference on Applied Physics, Simulation and Computing: *PI Control Applied to a Small-Scale Thermal Plant System with Heating and Cooling Sources* and *Development of a Didactic Graphical Simulation Interface on MATLAB for Systems Control*.

II. UAV Modelling and Control

For effective control over an HTR with the a deterministic controller, a model of the system is necessary [33]. Such a model must describe both the dynamics and kinematics of the vehicle.

Kinematics requires the use of two coordinate or reference systems simultaneously[1], one of them inertial (associated with planet Earth) and the other non-inertial (fixed on HTR, typically on the Center of Gravity (CG) of the vehicle).

Therefore, the non-inertial coordinate system moves relative to the inertial coordinate system. From a practical point of view, the model needs to be able to accurately describe the position and orientation of the controlled HTR in relation to a fixed point on the Earth, for example, the location of the control station on the ground or takeoff point.

Two coordinate systems are used due to:

- Vehicle dynamics, typically described through Newtonian mechanics, must be expressed by differential equations whose variables are referenced in an inertial coordinate system;
- Information associated with maps, in addition to certain mission requirements, are georeferenced and, therefore, referenced in the inertial coordinate system;
- The aerodynamic and propulsion forces and torques must be referenced in a coordinate system that is fixed on the vehicle in order to facilitate the modeling process, as well as simplify the obtained model.

A. Kinematics

The linear and angular velocities of the HTR, which are presented below, are naturally referenced in the $\mathcal{F}^v$ coordinate system. It is simple to obtain them referenced in the $\mathcal{F}^i$ coordinate system, to implement the control techniques through the kinematic transformation:

$$\dot{\boldsymbol{\eta}} = \begin{bmatrix} \dot{\boldsymbol{\eta}}_{\mathbf{1}} \\ \dot{\boldsymbol{\eta}}_{\mathbf{2}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J_L}(\boldsymbol{\eta_2}) & \mathbf{0_{3\times 3}} \\ \mathbf{0_{3\times 3}} & \boldsymbol{J_A}(\boldsymbol{\eta_2}) \end{bmatrix} \begin{bmatrix} \boldsymbol{\nu_1} \\ \boldsymbol{\nu_2} \end{bmatrix} = \boldsymbol{J}(\boldsymbol{\eta_2})\,\boldsymbol{\nu} \tag{1}$$

where the linear and angular velocity vectors $\boldsymbol{\nu} \in \mathbb{R}^6$, referenced in the coordinate system $\mathcal{F}^v$, is composed by the components $\boldsymbol{\nu_1} = [\,u, v, w\,]^T$ [m/s], whose components are respectively the forward linear, lateral and vertical velocities along the respective axes, and $\boldsymbol{\nu_2} = [\,p, q, r\,]^T$ [rad/s], whose components are respectively the angular rolling, pitching and yawing velocities also about the respective X, Y and Z axes. The position and attitude vectors $\boldsymbol{\eta} \in \mathbb{R}^6$, referenced in the $\mathcal{F}^i$ coordinate system, is composed by the components $\boldsymbol{\eta_1} = [\,n, e, d\,]^T$ [m], whose components are respectively the (linear) displacements along the axes $\boldsymbol{i^i}$, $\boldsymbol{j^i}$ and $\boldsymbol{k^i}$, and the vector $\boldsymbol{\eta_2}$, whose components are respectively the angular displacements about these same 3 axes.

Hence, in the $\mathcal{F}^i$ coordinate system, the vector of linear and angular velocities $\dot{\boldsymbol{\eta}} = \dot{\boldsymbol{\eta}}(t) = \frac{\mathrm{d}}{\mathrm{dt}}[\boldsymbol{\eta}(t)]$ is composed of the components $\dot{\boldsymbol{\eta}}_{\mathbf{1}} = [\,\dot{n}, \dot{e}, \dot{d}\,]^T$ [m/s] e $\dot{\boldsymbol{\eta}}_{\mathbf{2}} = [\,\dot{\phi}, \dot{\theta}, \dot{\psi}\,]^T$ [rad/s], where $\boldsymbol{\eta}(t) = \boldsymbol{\eta}$ and $t \in \mathbb{R}_{\geqslant 0}$ [s] is the time parameter. Thus, we obtain the two relations established in (1), that is, $\dot{\boldsymbol{\eta}}_{\mathbf{1}} = \boldsymbol{J_L}(\boldsymbol{\eta_2})\,\boldsymbol{\nu_1}$ and $\dot{\boldsymbol{\eta}}_{\mathbf{2}} = \boldsymbol{J_A}(\boldsymbol{\eta_2})\,\boldsymbol{\nu_2}$.

The opposite direction of the $\boldsymbol{k^i}$ axis is commonly adopted in modeling because it is more intuitive to work with the UAV notion of altitude. For this reason, the vector $\boldsymbol{\eta_1}$ is replaced by the vector $\boldsymbol{\eta_1^\star} := [\,n, e, h\,]^T$, where $h := -d$ denotes the HTR altitude. Therefore, the vector $\boldsymbol{\eta^\star} = [\,(\boldsymbol{\eta_1^\star})^T, \boldsymbol{\eta_2}^T\,]^T$ replaces the vector $\boldsymbol{\eta}$, and the matrix $\boldsymbol{J^\star}(\boldsymbol{\eta_2}) := \mathrm{diag}(\boldsymbol{H}\,\boldsymbol{J_L}(\boldsymbol{\eta_2}), \boldsymbol{J_A}(\boldsymbol{\eta_2}))$ replaces the original coordinate system transformation matrix $\boldsymbol{J}(\boldsymbol{\eta_2})$. Then,

$$\dot{\boldsymbol{\eta}}^\star = \begin{bmatrix} \dot{\boldsymbol{\eta}}_{\mathbf{1}}^\star \\ \dot{\boldsymbol{\eta}}_{\mathbf{2}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}\,\boldsymbol{J_L}(\boldsymbol{\eta_2}) & \mathbf{0_{3\times 3}} \\ \mathbf{0_{3\times 3}} & \boldsymbol{J_A}(\boldsymbol{\eta_2}) \end{bmatrix} \begin{bmatrix} \boldsymbol{\nu_1} \\ \boldsymbol{\nu_2} \end{bmatrix} = \boldsymbol{J^\star}(\boldsymbol{\eta_2})\,\boldsymbol{\nu} \tag{2}$$

where $\boldsymbol{H} \in \mathbb{R}^{3\times 3} \,|\, \boldsymbol{H} = \boldsymbol{H}^T = \boldsymbol{H}^{-1} := \mathrm{diag}(1, 1, -1)$ is a sign inversion matrix that implements this inversion $\boldsymbol{k^i}$.

[1]This occurs in all cases where you want to implement automatic motion control, regardless of the particular fact that the controlled vehicle is aerial [34], [35], [36], [33].

B. Dynamics

The HTR dynamics modeling as a rigid body is based on Newton's second law (classical mechanics), and, for this reason, it is naturally referenced in the $\mathcal{F}^i$ coordinate system. However, aerodynamic and propulsion forces and torques, in addition to disturbances, are described more naturally when referenced in the $\mathcal{F}^v$ coordinate system. This simplifies the resulting dynamic model but requires the inclusion of Coriolis pseudo-forces in the model.

Thus, the HTR dynamics for motion control purposes is given by:

$$\boldsymbol{M^b}\dot{\boldsymbol{\nu}} + \boldsymbol{C^b}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau_p^b} + \boldsymbol{\tau_a^b} + \boldsymbol{\tau_g^b} \tag{3}$$

where $\boldsymbol{M^b} \in \mathbb{R}^{6\times6}$ is the system Jacobian matrix, $\boldsymbol{C^b}(\boldsymbol{\nu}) \in \mathbb{R}^{6\times6}$ is the centripetal Coriolis matrix on the vehicle body-fixed $\mathcal{F}^b$, and $\boldsymbol{\tau_a^b}, \boldsymbol{\tau_g^b}, \boldsymbol{\tau_p^b} \in \mathbb{R}^6$ are the resulting aerodynamic, gravitational and propulsion forces, respectively, composed of forces and torques, both in the $\mathcal{F}^b$ frame.

In addition, it is possible to manipulate the equation above and present it already in closed-loop form, with the insertion of the control action:

$$\left[\boldsymbol{\eta_d} - \left(\underbrace{\boldsymbol{M^b}\dot{\boldsymbol{\nu}} + \boldsymbol{C^b}(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{\tau_a^b} - \boldsymbol{\tau_g^b}}_{\text{HTR Model}}\right)\right] \cdot \underbrace{\boldsymbol{K^b}}_{\boldsymbol{\tau_c}} = \boldsymbol{\tau_p^b} \tag{4}$$

where $\boldsymbol{\eta_d} \in \mathbb{R}^6$ is the vector of setpoints, $\boldsymbol{K^b} \in \mathbb{R}^6$ are control actions of a given controller in the frame $\mathcal{F}^b$, and $\boldsymbol{\tau_c} \in \mathbb{R}^6$ is the resulting vector in the frame $\mathcal{F}^b$, representing the virtual control actions, used in the control allocation step.

C. Overall Control System

The topology of the hybrid HTR control system to be developed is defined below. It is based on the P-PID controller, where there are 2 cascaded feedback loops for all 5 controlled DoFs. Its block diagram is shown in Figure 2.

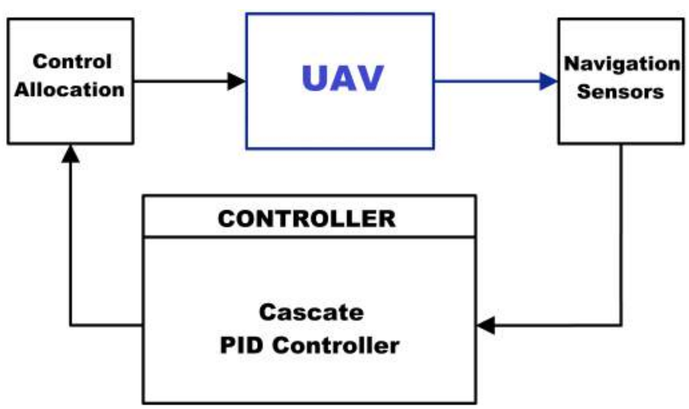


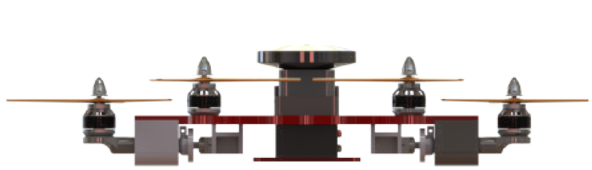
Fig. 2: Block diagram for the UAV control system.

A similar control system was successfully used by the Candidate ([1], [32]) to control a quadrotor in open-field tests, where a new control allocation methodology was implemented.

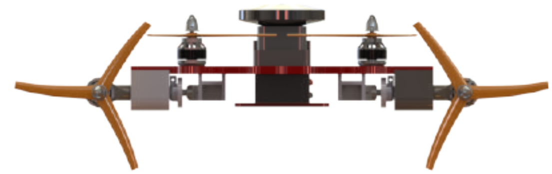
D. HTR Prototype

This section is created to present the desired HTR prototype, designed in SolidWorks software. Figure 3 illustrate the front and isometric views with 2 distinct servomotor positions to better show its tilt ability:

Fig. 3: HTR project illustration.



(a) HTR front view: servomotors with 0 degrees.



(b) HTR front view: servomotors with 90 degrees.

(c) HTR isometric view: servomotors with 0 degrees.

(d) HTR isometric view: servomotors with 90 degrees.

Figures 4(a) and 4(c) show the HTR with 0 degrees for the 2 servomotors. With these characteristics, the vehicle flies as a traditional hexacopter for rolling, pitching, and altitude maneuvers. Figures 4(b) and 4(d) present the HTR with 90 degrees for the 2 servomotors, in forward direction. Then, the vehicle flies in a fixed-wing mode, where forward/backward maneuvers are performed. With 90 degrees servomotor angle, the HTR flies in the forwarding direction. If it is -90 degrees, the HTR flies in backward direction. Now, if the 2 servomotors have opposite directions with the same magnitude, the HTR performs yawing maneuvers.

III. Research Methodology

The methodology of this project is basically divided into 8 steps, as shown in Figure 4:

The green markings represent steps developed at the Leuphana University of Lüneburg. The stages in red will be developed after staying in Germany, at the Candidate's University, in Brazil.

The first step is based on the design and development of the proposed overactuated vehicle, still in the SolidWorks software, considering all material parameters to be used.

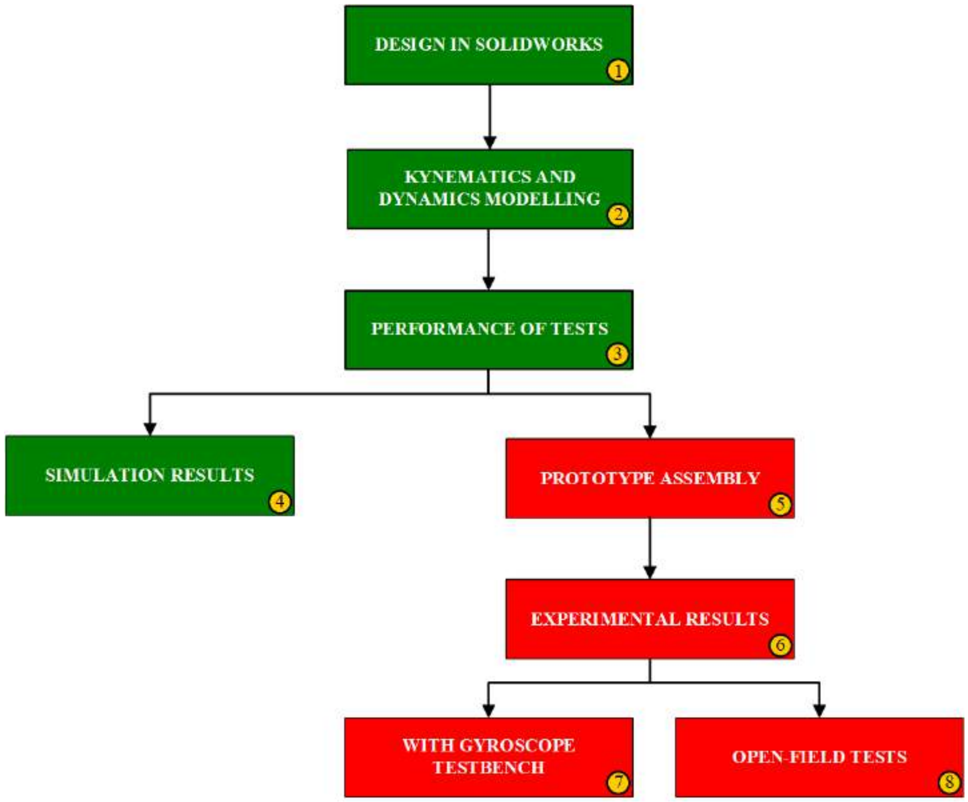
Continuing, the second stage will develop the entire mathematical formulation of the vehicle's kinematic and dynamic model, encompassing the controller with the whole tuning.

The third stage will take place in 2 ways: simulation tests and experimental tests. The first one will take some simulation tests into account, considering several flight scenarios. Right after this step, we would start building an article for an international journal.

After staying in Germany, the fifth stage will be the construction of the HTR prototype, where all the preliminary testbench analyses will be created. After that, experimental tests will start in the sixth stage, carried out in a gyroscopic testbench (3 DoFs will be used: rolling, pitching, and yawing) and in the open field (all 5 DoFs will be evaluated).

After the eighth stage, the second article for an international journal will be created, always in partnership and in line with the Host.

Fig. 4: Steps of the project's methodology.



To complete, the Candidate works on control and modelling of UAVs, also covering the controller tuning and control allocation tasks. Regarding the Host's work, it has a widespread and vast area of research, including many different systems. At this point, his experience in the distinct area will improve this project idea not only for UAV application but in other overactuated control systems. The publication done by this partnership shows the possibility of the project's success not only for this research project but also after it.

The complementarity between the Candidate and the Host has built a solid base for the project and partnership success. They wish to continue researching in this area after finishing the Candidate's stay in Germany. The expected success of this project will present a new control allocation technique applied not only on UAVs but in other overactuated systems. Then, the methodology presented in [1], [32] will be expanded for different possibilities of breaking the control allocation into an overlapped subsystem, always assuring stability and convergence.

At the end of this 8-week project as a visitant and research professor in Leuphana University, we also expect to develop at least 1 (one) high-impact journal paper, 1 (one) low-impact journal paper, and 1 international conference paper.

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