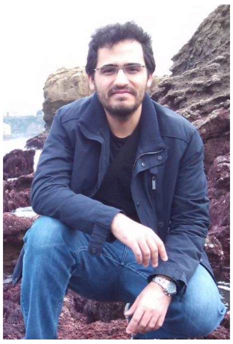

The ϕ-theory approach to flight control design of tail-sitting vehicles

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Context: Remote building intrusion missions in complex urban environments call for micro air vehicles (MAVs) capable of switching between long-endurance and hover flight modes. Traditionally, long-endurance missions are performed by fixed-wing architectures which advantage from lift generation due to aerodynamic surfaces. This yields high-speed stable flight even under adverse wind conditions. On the other hand, hovering platforms (e.g., multi-rotor platforms, helicopters) cannot benefit from air to vehicle relative movement and calls for energetically expensive propulsion methods that precludes long-distance missions but allows for sustained low-speed unstable indoor flight. This thesis is built around a hybrid architecture based on the tilt-body tail-sitting concept, called *MAVion* (see Figure 1), that is capable of balancing aerodynamic and propulsion design parameters to deliver a solution to the remote building intrusion problem.

Figure 1: (a) *MAVion* under wind tunnel testing. (b) *MAVion* Roll & Fly [5] variant.

Since their debut in the 50s, vertical take-off and landing (VTOL) aircraft would only be flown by the most experienced pilots. Recent advances on low-cost inertial sensors, embedded computing and control technology, on the other hand, support stability augmentation systems (SAS) in mitigating unstable dynamic modes and allowing for inexperienced (or even autonomous) flight. Nearly all autopilot design techniques, however, rely on accurate mathematical descriptions of novel and thus unfamiliar architectures (e.g., number and positioning of propellers, number and positioning of fixed/variable aerodynamic surfaces). While a large and growing body of literature has investigated underlying modeling, control and planning issues to specific hybrid vehicles, an unified approach to addressing arbitrary architectures is practically non-existent. The present thesis establishes an unified framework, namely the ϕ-theory, for assessing hybrid vehicles handling qualities and, moreover, designing appropriate stabilizing control laws.

Problem statement: Find a $\{\alpha, \beta\}$-free mathematical description of tail-sitter dynamics in the nonlinear form $\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u})$ such that (i) $f(\cdot)$ is polynomial-like and thus **singularity-free** over all configuration space $\boldsymbol{x} \in \mathbb{U}$; (ii) $f(\cdot)$ parameters identification requires **no wind tunnel nor computer fluid dynamics** computations for designing a preliminary stable autopilot; (iii) $f(\cdot)$ simple structure encourages nonlinear control design; (iv) provides **insight** into the vehicle qualitative dynamics and (v) can be **validated by means of wind tunnel campaigns and outdoor flight experiments**.

Motivation: The $\{\alpha, \beta\}$-free parametrization requirement simplifies modeling of wing sections not covered by propeller slipstream since there tail-sitters encounter near-zero freestream velocities that call for near-zero algebraic divisions in α and β computation. Although *if-else* statements with appropriate *ad hoc* thresholds would solve this issue, notice that $\nabla\alpha(\boldsymbol{v}_\infty)$ is not continuous at $\boldsymbol{v}_\infty = \mathbf{0}$ and yields a nondifferentiable mapping regardless of the value one defines for α at the singularity. This property hinders linearization-based techniques employment for control analysis during hover flight. On the other hand, requirement (i) is motivated by recent efforts in semidefinite programming (SDP) and sums-of-squares optimization (SOS) that allow for efficient trajectory optimization and control in models governed by polynomial differential equations. ϕ-theory provides an alternative SDP-friendly formulation. The remaining requirements (ii)-(v) are self-explanatory.

Theoretical methodology: The ϕ-theory framework is proposed for hybrid vehicles modeling. Its mathematical properties and features are thoroughly studied. The present thesis shows that ϕ-theory-based models concur with (i)-(iv). **Experimental methodology:** This thesis contrasts wind tunnel data to theoretical findings to assess ϕ-theory suitability in real world. Finally, experimental flights call for state estimators that rely on low-cost navigation sensors. Accordingly, the present thesis proposes a **novel state estimator architecture** [4] that lays the foundation for aided inertial navigation that employs complementary filtering for attitude estimation by means of a magnetometer as an external aid, and an EKF for additional sensors integration. Finally, a *Paparazzi*-based MAVion prototype is integrated, programmed and flown to thoroughly illustrate a complete ϕ-theory-based tail-sitter control design case-study.

Overview of my contribution: This study set out to establish a tractable model for tail-sitting vehicles in view of control design and qualitative dynamics analysis. The proposed ϕ-theory not only yields a numerically advantageous model but also extends our comprehension of tail-sitting vehicles. In sharp contrast with existent literature, the proposed model is globally non-singular, polynomial-like and bypasses the use of aerodynamic angles α and β (both free-stream and propwash-induced!).

Even if mathematically elegant, a mathematical model has practical use only if consistent with reality. This thesis shows this is the case by means of wind tunnel data and flight experiments. I strongly believe ϕ-theory provides a fitting balance between model complexity and controller design simplicity. I prove this point by tuning MAVion's controller in simulation and test-flying it in reality – with a novel aided inertial navigation technique – without resorting to further exhausting experimental tuning campaigns.

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