SCHOOL OF COMPUTATION,
INFORMATION AND TECHNOLOGY —
INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Bachelor's Thesis, Master's Thesis, ... in Informatics

Thesis title

Author

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I confirm that this bachelor's thesis, master's thesis, ... is my own work and I have documented all sources and material used.

Munich, Submission date   Author

Acknowledgments

Abstract

Contents

1 Introduction

1.1 Motivation

Micro air vehicles (MAVs) with efficient autonomous navigation can strengthen applications such as search-and-rescue and last-mile delivery, where safety, robustness, and endurance are critical. Conventional quadrotors offer agility and precise control but are power-inefficient in sustained forward flight. Fixed-wing platforms are efficient but cannot hover and are less maneuverable in confined spaces. Hybrid vertical take-off and landing (VTOL) concepts improve mission versatility but increase mechanical and control complexity. This thesis investigates an intermediate design: a multirotor augmented with fixed aerodynamic surfaces to harvest passive lift during horizontal motion while keeping multirotor agility.

1.2 Problem statement and scope

In the presence of aerodynamic surfaces, hard-to-model aerodynamic forces become significant and challenge controller design. We aim to develop a platform and control strategy that:

- preserves quadrotor agility while improving forward-flight efficiency via passive lift,
- tracks agile trajectories accurately without requiring aerodynamic parameter identification, and
- remains robust to modeling errors and disturbances.

The central question is whether an Incremental Nonlinear Dynamic Inversion (INDI)-based controller can achieve accurate trajectory tracking on an aerodynamic surface-enhanced quadrotor without an explicit aerodynamic model.

1.3 Contributions

This thesis presents:

- a design of an aerodynamic surface-enhanced quadrotor in X-wing configuration,
- a dynamics model combining a standard quadrotor 6-DoF model with simplified quadratic lift/drag,
- a trajectory-tracking controller based on geometric control and INDI, including a coordinated-turn option, and
- an experimental evaluation: thrust-map identification, agility/controllability, aerodynamic disturbance characterization, and efficiency assessment.

1.4 Thesis organization

Chapter 3 reviews related work and motivates the chosen design. Chapter 4 details the platform. Chapter 5 derives the model. Chapter 6 presents the controller. Chapters 7 and 8 describe the setup and experiments. Chapter 9 concludes.

2 Background

This chapter introduces foundational concepts relevant to agile and efficient autonomous flight with aerodynamic surface-enhanced multirotors. It briefly covers flight vehicle classes, 6-DoF rigid-body kinematics and dynamics, and aerodynamic fundamentals (lift, drag, moments) used later in the modeling and control chapters.

2.1 Aerial vehicle classes

We distinguish multirotors, fixed-wing aircraft, tailsitters, and general VTOL hybrids. Key trade-offs include agility, efficiency, range, and controllability. Hybrids aim to combine vertical take-off and landing with efficient forward flight.

2.2 Rigid-body frames and notation

We use an inertial/world frame $\{\mathcal{I}\}$ and a body frame $\{\mathcal{B}\}$. Position $\mathbf{p} \in \mathbb{R}^3$, velocity $\mathbf{v}$, orientation $R \in SO(3)$, angular velocity $\boldsymbol{\omega} \in \mathbb{R}^3$. Standard hat/vee maps and skew operator $[\cdot]_\times$ are adopted.

2.3 Aerodynamic preliminaries

Lift $L = \frac{1}{2}\rho V^2 S C_L(\alpha)$ and drag $D = \frac{1}{2}\rho V^2 S C_D(\alpha)$, with α the angle of attack, reference area S, and air density ρ. For small angles or thin-airfoil approximations, $C_L \approx a_\alpha \alpha$, $C_D \approx C_{D0} + kC_L^2$. These models motivate the simplified quadratic lift/drag used in Chapter 5.

3 Related Work

We review UAV archetypes and control approaches with emphasis on agility, efficiency, and controllability, motivating our X-wing multirotor with passive aerodynamic lift and an INDI-based controller.

3.1 UAV archetypes and trade-offs

- Quadrotors: highly agile and controllable, hover capable, but power-inefficient in high-speed flight. - Fixed-wing: efficient at speed and range, but poor agility in confined spaces; requires runway/launch. - Tailsitters/tilt-rotors (VTOL): combine hover and efficient cruise; transitions and cross-couplings complicate control. - Aerodynamic-surface-enhanced multirotors: retain quad agility while harvesting passive lift in forward flight.

3.2 Control approaches

- Geometric control on SE(3) and differential flatness-based planners for agile trajectory tracking. - Disturbance observers, incremental (nonlinear) dynamic inversion, and adaptive methods for model uncertainties. - INDI in particular achieves robustness by leveraging incremental relations between actuator changes and measured accelerations/ang. rates, reducing dependence on aerodynamic models.

3.3 Positioning our work

We target accurate tracking during agile maneuvers without modeling aerodynamic coefficients, enabled by INDI, while leveraging passive lift for efficiency during forward flight. This guides design choices in Chapters 4 and 6.

4 Platform Design

We design an aerodynamic surface-enhanced quadrotor in X-wing configuration to preserve multirotor agility while benefiting from passive lift in forward flight.

4.1 Configuration and layout

- Quadrotor X configuration with integrated fixed wings (X-shaped planform) aligned with the rotor arms. - Structural considerations: wing aspect ratio, sweep/dihedral, stiffness, and mounting relative to CoG and rotor thrust lines. - Sensors and avionics: IMU, FC/ESCs, Jetson companion, motion capture (Vicon) for ground-truth.

4.2 Wing and aerodynamic surface choices

- Select planform and airfoil balancing lift at operational Reynolds numbers with low added mass. - Wing area and placement trade-offs: lift vs. added drag and control cross-coupling; ensure propeller inflow interactions are manageable.

4.3 Propulsion and actuation

- Motor-propeller pair sized for required thrust-to-weight and agility margins (e.g., 3g lateral load tracking). - Thrust and torque maps: throttle-to-RPM and RPM-to-thrust/torque characterization to support control allocation.

5 Dynamics Model

We derive a 6-DoF rigid-body model of the platform with rotor thrust/torque and simplified aerodynamic forces/moments from the integrated wings.

5.1 Frames, states, and inputs

States: $(\mathbf{p}, \mathbf{v}, R, \boldsymbol{\omega}) \in \mathbb{R}^3 \times \mathbb{R}^3 \times SO(3) \times \mathbb{R}^3$. Inputs: rotor thrusts $\mathbf{u} = [f_1, \ldots, f_4]^\top$ (or RPM), combined into total thrust f_T and body torques $\boldsymbol{\tau}$ by allocation matrix G.

5.2 Forces and moments

- Gravity: $m\mathbf{g}$. - Rotor thrust in body z: $\mathbf{F}_T = -f_T\, R\mathbf{e}_3$ (world frame). - Aerodynamics (simplified): wing lift and drag quadratic in body-frame airspeed $\mathbf{v}_a = \mathbf{v} - \mathbf{v}_w$ transformed to the body.

$$L = \tfrac{1}{2}\rho S C_L(\alpha)\|\mathbf{v}_a\|^2, \qquad D = \tfrac{1}{2}\rho S C_D(\alpha)\|\mathbf{v}_a\|^2. \tag{5.1}$$

We use $C_L = a_\alpha \alpha$, $C_D = C_{D0} + kC_L^2$ or the compact quadratic form $\mathbf{F}_{\text{aero}} = -k_D\,\|\mathbf{v}_a\|\,\mathbf{v}_a + k_L\,\|\mathbf{v}_a\|\,\mathbf{v}_\perp$ with $\mathbf{v}_\perp$ orthogonal to the surface.

Moments from aerodynamic center offset and rotor torques are aggregated into $\boldsymbol{\tau} = G_\tau\,\mathbf{u} + \boldsymbol{\tau}_{\text{aero}}$.

5.3 Equations of motion

$$\dot{\mathbf{p}} = \mathbf{v}, \tag{5.2}$$

$$\dot{\mathbf{v}} = \tfrac{1}{m}\big(m\mathbf{g} + \mathbf{F}_T + R\,\mathbf{F}_{\text{aero}}\big), \tag{5.3}$$

$$\dot{R} = R\,[\boldsymbol{\omega}]_\times, \tag{5.4}$$

$$J\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega} \times J\boldsymbol{\omega} + \boldsymbol{\tau}. \tag{5.5}$$

Assumptions: quasi-steady aerodynamics, negligible prop-wash coupling in first-order model, parameter lumping for identification.

6 Control Architecture

We design a trajectory-tracking controller combining geometric position/attitude control with Incremental Nonlinear Dynamic Inversion (INDI). Differential flatness provides reference generation. INDI reduces dependence on aerodynamic modeling and handles unmodeled disturbances.

6.1 Reference generation

Trajectory references $(\mathbf{p}_d, \dot{\mathbf{p}}_d, \ddot{\mathbf{p}}_d, \psi_d)$ from a flatness-based planner or minimum-snap polynomial, optionally enforcing coordinated-turn constraints in forward flight to bound sideslip.

6.2 Outer-loop (geometric SE(3))

Compute desired body z-axis from force command $\mathbf{f}_d = m(\ddot{\mathbf{p}}_d + \mathbf{k}_p\tilde{\mathbf{p}} + \mathbf{k}_v\tilde{\mathbf{v}} - \mathbf{g})$ and yaw ψ_d, yielding desired attitude R_d and thrust f_T.

6.3 Inner-loop INDI

Using measured specific force and angular rates, INDI updates actuator commands incrementally:

$$\Delta\mathbf{u} = G^{-1}\left(\mathbf{y}_d - \mathbf{y}\right), \tag{6.1}$$

where $\mathbf{y}$ are directly measurable accelerations/attitude-rate related outputs. The key insight is that unmodeled aerodynamics cancel in the increment under small sampling intervals, leaving a local input-output mapping identified online via control effectiveness. See [SCC16; Oos+17; Kam+18] and [Tzo+21] for agile INDI on aerial platforms.

6.3.1 Aerodynamic cancellation argument

Let $\dot{\mathbf{y}} = f(\cdot) + B\,\mathbf{u} + \mathbf{d}$ with disturbance/aerodynamics $\mathbf{d}$. Over short intervals Δt, the change satisfies $\Delta\mathbf{y} \approx B\,\Delta\mathbf{u}$ as $\Delta\mathbf{d}$ is second-order. Thus the incremental control law does not require explicit aerodynamic parameters.

6.4 Coordinated turn option

Impose sideslip $\beta \approx 0$ by aligning drag with body-x projected velocity and setting a yaw rate command consistent with lateral acceleration: $\dot{\psi} \approx a_y/(V\cos\theta)$ at moderate bank angles.

7 Experimental Setup

We briefly document the hardware, software stack, and facilities enabling reproducible experiments.

7.1 Hardware

- Airframe: X-wing aerodynamic surface-enhanced quadrotor. - Propulsion: motors, ESCs, props; thrust-to-weight and voltage. - Avionics: Flight Controller (Betaflight/Agilicious/Pilot), Jetson companion, IMU, telemetry.

7.1.1 Bill of Materials (BOM)

Table 7.1 lists the main components. Replace the placeholders with the exact models you used; include part numbers where helpful.

7.2 Software

- Estimation and control pipeline on FC/companion; logging. - Vicon motion capture integration for ground truth and state feedback.

7.3 Facilities

- Flight arena for agility tests (3g circles), AIDA hall for efficiency trials.

Table 7.1: Bill of materials for the platform.

Category	Component	Model / Key specs
Airframe	Frame	X-wing custom frame; integrated fixed wings with Bambu Lab PLA Aero skins and dual 10 mm OD carbon tube spars; wing area $S \approx$ [..] m^2, span [..] m
Propulsion	Motor ($\times 4$)	T-MOTORHOBBY VELOX V2808
Propulsion	Propeller ($\times 4$)	HQProp $7 \times 3.5 \times 3$ Racing Prop, 3-blade, 7" (Light Grey)
Avionics	FC+ESC Stack	Kakute H7 v1.5 Stack (Flight Controller + 4-in-1 ESC)
Wiring	Motor power	12 AWG wire (FC/ESC to motors)
Power	Battery ($\times 2$, parallel)	Tattu R-Line V5.0 LiPo, 6S, 1400 mAh, 150C, XT60; effective 6S, 2800 mAh (parallel)
Companion	NVIDIA Jetson Orin	Orin Nano 8GB (specify exact variant), CUDA 12, 8GB LPDDR5; JetPack 6 (Ubuntu 22.04)
Companion power	Battery	Tattu R-Line Version 3.0, 1800 mAh, 4S, 14.8 V, 120C, XT60 (via buck regulator to Jetson input)
Avionics	IMU	[IMU chip], gyro rate [..] Hz, accel range [..] g
Motion capture	Vicon markers	[Marker size], placement scheme
Comms	RC/Telemetry	[RC link], [telemetry radio]
Bench (lab)	PSU / Load cell	[PSU model], [load cell model], ranges [..]

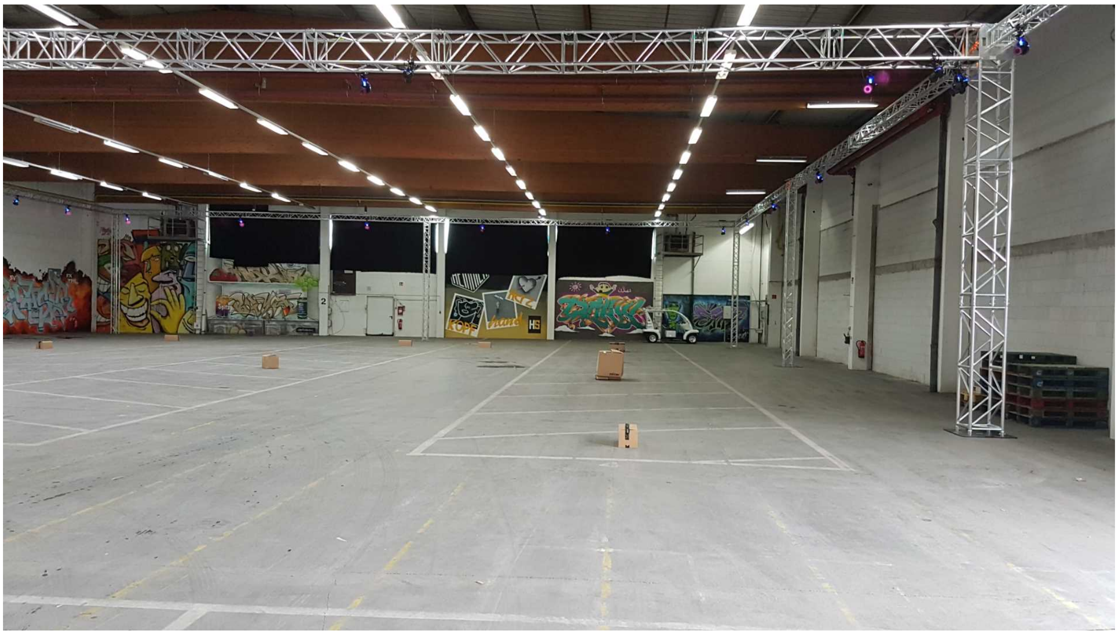

Figure 7.1: AIDA Hall test facility used for efficiency trials (image credit: Reutlingen University AIDA [Reu24]).

8 Experiments and Evaluation

We design experiments to validate thrust mapping, agility/controllability, aerodynamic disturbance characterization, and efficiency gains.

8.1 Thrust map identification

- Throttle-to-thrust and RPM-to-thrust mapping; present identified curves and fitted models.

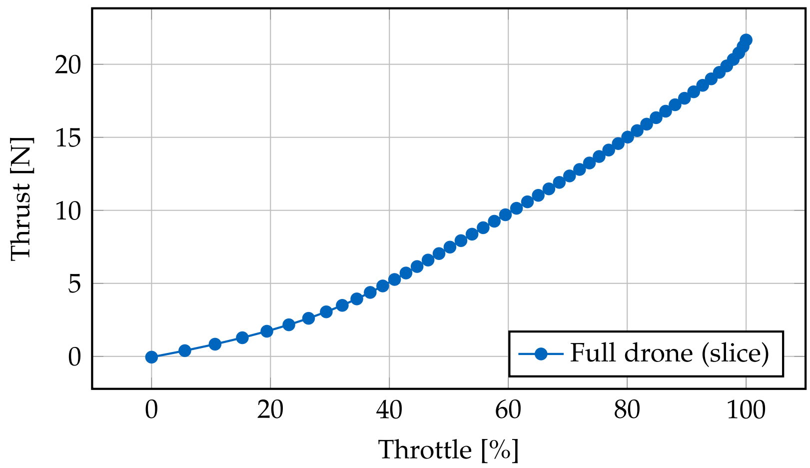

Figure 8.1: Throttle–thrust curve derived from the thrust lookup at a fixed voltage slice.

8.2 Agility and tracking

- 3g circles in flight arena; metrics: RMS position/attitude tracking error, control effort.

8.3 Aerodynamic forces/moments quantification

- Identify equivalent k_D, k_L or $C_L(\alpha), C_D(\alpha)$ from maneuvering flight data; discuss sensitivity.

8.4 Efficiency assessment

- Compare theoretical quad thrust input vs. measured thrust input in AIDA hall flights; quantify energy savings due to passive lift.

8.5 Baseline comparison

- Compare against baseline quadrotor controller without INDI or without wings.

9 Conclusion

We summarize contributions: design of an aerodynamic surface-enhanced quadrotor, a robust INDI-based tracking controller, and experimental validation demonstrating accurate agile tracking and improved forward-flight efficiency. We outline future work, including refined aerodynamic modeling, coordinated-turn guidance integration, and extended outdoor testing.

Abbreviations

UAV Unmanned Aerial Vehicle
MAV Micro Air Vehicle
VTOL Vertical Take-Off and Landing
INDI Incremental Nonlinear Dynamic Inversion
EoM Equations of Motion
DoF Degrees of Freedom
CoG Center of Gravity
CoP Center of Pressure
IMU Inertial Measurement Unit
Vicon Vicon Motion Capture System
FC Flight Controller
ESC Electronic Speed Controller
RPM Revolutions per Minute

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