



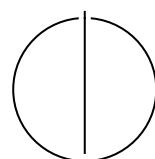
SCHOOL OF COMPUTATION,
INFORMATION AND TECHNOLOGY —
INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics

**Design and Control of an Aerodynamic
Surface-Enhanced Multirotor**

William Constantin Rosenhahn





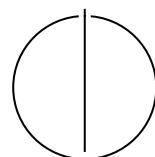
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**Design and Control of an Aerodynamic
Surface-Enhanced Multirotor**

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Submission Date: 01.12.2025



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

Munich, 01.12.2025

William Constantin Rosenhahn

Acknowledgments

Abstract

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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 derives the model. Chapter 5 details the platform. 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, $C_L \approx a_\alpha \alpha$, $C_D \approx C_{D0} + k C_L^2$. These models motivate the simplified quadratic lift/drag used in Chapter 4.

3 Related Work

Designing a UAV that is both agile (e.g., sustained $\geq 3g$ banked turns on meter-scale radii with low tracking error) and energy-efficient (low Wh/km or J/m at cruise), while remaining controllable across hover and forward flight, robust to aerodynamic disturbances, and implementable with moderate complexity, requires weighing trade-offs across canonical configurations: multirotors, fixed-wing, tailsitters, tiltrotors/tilt-wings, and quadplane VTOLs. We additionally review “aerodynamically augmented” multicopters—i.e., quadrotors with small fixed lifting surfaces or shrouds—because they can mitigate the multirotor’s forward-flight inefficiency without incurring the full complexity of morphing hybrids.

3.1 Baselines: Agility vs. Efficiency

Pure multirotors Pure multirotors excel in agility and controllability in hover and low-speed flight. State-of-the-art quadrotors routinely track aggressive trajectories at 2–5 g and 40–70 km/h with centimeter-level RMS errors using differential-flatness feedforward plus robust inner loops—often incremental nonlinear dynamic inversion (INDI) [TK18; TK21a; FKa22]. For example, Tal and Karaman report tracking at 12.9 m/s with up to 2.1 g and 6.6 cm RMS error, and explicit robustness to added drag and rope pulls due to INDI’s disturbance-rejection properties [TK18]. Foehn et al.’s Agilicious platform demonstrates up to ~ 5 g and ~ 70 km/h autonomous tracking with modern model-predictive and differential-flatness-based controllers, again emphasizing agility and controllability [FKa22]. However, multirotors are energetically inefficient in forward flight because thrust must be tilted to produce lift and drag grows quickly with speed.

Fixed-wing aircraft By contrast, fixed-wing aircraft achieve much lower J/m at cruise because wings supply lift with high L/D , but they cannot hover.

Hybrids: tailsitters, tiltrotors, and quadplanes Tailsitters and tiltrotor/tilt-wing hybrids attempt to combine both: hover on rotors, then transition to wing-borne flight

for efficiency. Recent tailsitter work shows promising agility and envelope coverage—e.g., Lu et al. report 10–20 m/s trajectories with ~ 2.5 g agile maneuvers using a flatness-based planner and robust tracking [LGa22], and Tal and Karaman demonstrate global trajectory-tracking and agile uncoordinated flight (e.g., sideways/knife-edge) using a global INDI framework [TK21b; TK22]. Tilt-wing/tilt-rotor concepts have matured in modeling and flight-dynamics/transitions (e.g., Daud Filho et al. present dynamic models and simulated transition trajectories for a canard-plus-wing tilt concept) but remain mechanically and algorithmically complex, with challenging cross-couplings during transitions [Da24; MJa22]. Quadplanes (fixed wing + vertical-lift rotors) offer practical VTOL with cruise efficiency; experimental examples (e.g., a tandem-wing quadplane) target long-range VTOL with simpler mechanisms than tilting actuators, though added mass/drag can degrade hover agility and gust robustness [OŁ22].

3.2 Controller Classes Used Across the Spectrum

Geometric SE(3) control established a rigorous foundation for aggressive multirotor tracking with global attitude representations [LLM10] and geometric adaptive variants handle parametric uncertainties [GLL15]. Differential-flatness-based planning/control (e.g., minimum-snap) is ubiquitous for trajectory generation and feedforward tracking [MK11; TK18]. INDI has become a go-to inner-loop choice for robustness to unmodeled aero forces/torques at high speed and in gusts [SCM10; SCC17]. A direct empirical comparison on agile quadrotor flight found that both NMPC and differential-flatness-based controllers benefit markedly ($\approx 78\%$ error reduction) from coupling to an INDI inner loop and drag modeling at speeds up to 20 m/s [Sun+21]. These results are important because the proposed quad-with-small-wings concept aims to keep a multirotor control stack (differential-flatness/geometric + INDI) while adding lightweight aerodynamics.

3.3 Aerodynamic Augmentation on Multicopters

The most directly relevant evidence comes from micro-to-small UAVs that add fixed lifting surfaces to multirotors:

Small wings Dawkins and DeVries integrated small wings on a micro-quad and quantified the trade-off: $\sim 35\%$ energy saving in forward flight, but $\sim 45\%$ extra power in hover due to added mass/drag; the wing “pays off” beyond $\sim 3\text{--}5$ m/s depending on angle-of-attack and prop wash interaction [DD18]. They report smoother tracking

and reduced pitch angles at speed, indicating improved controllability in forward flight, but some hover agility penalty.

Xiao et al. designed a “lifting-wing fixed on multirotor” with a decoupled wing mount. On a 1.2 kg quad, they measured 50.14% less electrical power at 15 m/s compared with the bare quad; optimal cruise power shifted from \approx 200–250 W down to \approx 100–125 W with the wing, without major changes to the multirotor controller [XQa20]. This is a strong, quantitative demonstration that small fixed aerodynamic surfaces can more than halve J/m at moderate forward speeds while preserving conventional quad control.

Airfoiled arms Freitas et al. systematically tested airfoiled arms on a quad (DJI F450 class). Arm airfoils reduced arm drag and delivered \sim 19–31% less electrical power in forward flight at 10–15 m/s (depending on angle) and modest improvements to top speed, with negligible hover penalty and no controller change [FDF25]. This is especially attractive for “agility-first” designs where we seek free forward-flight efficiency.

Summary These works collectively show that adding small lifting/streamlining surfaces to a quad yields measured cruise efficiency gains (\approx 20–50% power reduction at \approx 10–15 m/s) at minimal implementation cost: no tilting mechanisms, no transitions, and only modest or negligible changes to hover agility if the surfaces are small and decoupled from rotor flows. Importantly, the canonical quadrotor controller stack (geometric/differential-flatness + INDI inner loop) remains applicable, maintaining excellent tracking (\sim few-cm RMS) and high gust robustness documented for agile quads [TK18; FKa22; Sun+21].

3.4 Shrouds and Ducts as Augmentation

Shrouding improves hover power loading and can protect the rotors. MDPI Drones studies report \sim 15–28% improvements in lift and “FM efficiency” for optimized ducted multi-propeller configurations in hover [Li+21]. Classic MAV shroud experiments show up to \sim 30% power-loading gains at small scales [HBC14], and broader surveys note up to $>50\%$ thrust gains or equivalent power reductions in hover for well-designed ducts, but performance degrades at higher advance ratios (forward flight) due to inlet losses and added frontal area [Ca21; Per08]. Thus, shrouds are advantageous for hover/low-speed efficiency and safety but can hurt high-speed efficiency and cross-wind agility—less aligned with our “agile forward-flight efficiency” goal.

3.5 Quantitative Comparison Across Criteria

From the studies above:

Agility Pure multirotors: $\geq 3 g$, $\leq 0.1 \text{ m RMS}$ tracking demonstrated [TK18; FKa22]. Tailsitters: agile aerobatics and 2–3 g transitions are feasible [LGa22; TK22], but hover control surfaces may be saturation-limited in gusts. Quadplanes/tilt designs: agility is generally lower in hover due to added inertia and interference; transitions add constraints [OL22; MJa22].

Efficiency (forward flight) Small fixed wings/airfoils on quads reduce cruise power by $\sim 20\text{--}50\%$ at 10–15 m/s [DD18; XQa20; FDF25]. Shrouds: +15–30% hover power loading, but often worse at higher advance ratios [Li+21; HBC14; Ca21]. Hybrids (tilt/quadplane/tailsitter) achieve fixed-wing-like J/m at cruise but pay complexity/weight penalties.

Controllability & transitions Multirotors and “quad + small wings” avoid mode transitions entirely—hover/forward authority comes from the same actuators; differential-flatness/geometric + INDI covers both regimes [LLM10; TK18]. Hybrids require transition path planning and mode-dependent control allocation [Da24; MJa22].

Robustness to aero disturbances INDI-based quads show strong disturbance rejection without precise aero models [SCM10; SCC17; Sun+21]. Hybrids can be robust, but robustness proofs and quantitative gust testing during transition remain sparse.

Implementation complexity Adding small fixed surfaces is mechanically trivial and controller-agnostic; shrouds add structure and possible crosswind penalties; hybrids add mechanisms, sensors, and software complexity (e.g., NMPC with switching and detailed aerodynamics).

3.6 Gaps and Open Issues

Despite progress, three gaps remain:

1. There are few quantitative studies of small, fixed wings on quads that explicitly preserve aggressive maneuverability ($\geq 3 g$, meter-scale turns) while reporting cruise Wh/km (or J/m) and closed-loop tracking error; most report % power savings at one speed [DD18; XQa20].

2. Disturbance modeling for augmented quads is incomplete, particularly interactions between rotor wakes and small wings across the speed envelope and in crosswinds; robust INDI masks some deficiencies, but better disturbance observers/models would inform design trade-offs [Sun+21].
3. For hybrid VTOLs, coordinated-turn performance (load factors, radius, sideslip limits) with full transition dynamics is under-reported; Daud Filho et al. detail transitions but not coordinated turns with quantitative lateral-acceleration margins [Da24].

These gaps motivate a design that seeks measured efficiency gains with minimal impact on agility and low complexity.

3.7 Why a Quadrotor with Small Fixed Aerodynamic Surfaces?

The literature supports a clear argument:

1. **Preserve hover agility and controllability:** no transitions, mature differential-flatness/geometric + INDI stack with proven centimeter-level tracking and multi-g maneuvers [LLM10; TK18; FKa22].
2. **Capture meaningful cruise-efficiency gains:** $\sim 20\text{--}50\%$ power reduction around 10–15 m/s using small wings or airfoiled arms [DD18; XQa20; FDF25], directly lowering J/m and extending range/mission time without complex mechanisms.
3. **Maintain robustness to disturbances via INDI** without high-fidelity aero models [SCM10; SCC17; Sun+21].
4. **Keep implementation complexity low:** fixed surfaces; unchanged propulsion and control allocation, avoiding the mass, moving parts, and software overhead of tilt/transition systems [MJa22; OŁ22].

Given the target criteria—agility, efficiency at cruise, controllability across the envelope, gust robustness, and modest complexity—the evidence favors a quadrotor with small fixed aerodynamic surfaces over more complex hybrids.

4 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.

4.1 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 $\mathbf{u} = [f_1, \dots, f_4]^\top$ (or RPM), combined into total thrust f_T and body torques $\boldsymbol{\tau}$ by allocation matrix G .

4.2 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.

$$L = \frac{1}{2}\rho S C_L(\alpha) \|\mathbf{v}_a\|^2, \quad D = \frac{1}{2}\rho S C_D(\alpha) \|\mathbf{v}_a\|^2. \quad (4.1)$$

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 $\boldsymbol{\tau} = G_\tau \mathbf{u} + \boldsymbol{\tau}_{\text{aero}}$.

4.3 Equations of motion

$$\dot{\mathbf{p}} = \mathbf{v}, \quad (4.2)$$

$$\dot{\mathbf{v}} = \frac{1}{m}(m\mathbf{g} + \mathbf{F}_T + R \mathbf{F}_{\text{aero}}), \quad (4.3)$$

$$\dot{R} = R [\boldsymbol{\omega}]_\times, \quad (4.4)$$

$$J\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega} \times J\boldsymbol{\omega} + \boldsymbol{\tau}. \quad (4.5)$$

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

5 Platform Design

5.1 Platform Design

We design an aerodynamic surface-enhanced quadrotor in an X-wing configuration to preserve the agility of a conventional multirotor while benefiting from passive lift in forward flight. The design objective was to create a platform that remains fully compatible with existing quadrotor control architectures while achieving improved aerodynamic efficiency in the moderate-speed regime of 5 m s^{-1} to 15 m s^{-1} . This range was chosen to match the operational envelope of modern visual-inertial odometry and path-planning algorithms, which rely on sufficient feature persistence and computation time when traversing complex environments. The platform maintains full hover capability and allows seamless transition between flight regimes, including the ability to come to a complete stop in the case of unexpected obstacles or path-planning delays.

5.1.1 Configuration and Layout

The overall configuration follows a conventional X-shaped quadrotor layout in which each rotor arm is extended into a fixed aerodynamic lifting surface, forming an “X-wing” planform. This choice leverages the inherent structural arrangement of a quadrotor—four arms symmetrically distributed around the center of gravity—while enabling these arms to generate lift instead of purely supporting the motors. Alternative configurations such as a “plus” (+) layout or biplane arrangements were considered less favorable: in a + configuration, two wings would be vertically oriented and thus unable to generate lift, while a biplane would require additional structural connections between the upper and lower planes, adding mass and complexity. The X-wing approach allows a single compact central frame with minimal added mass.

Each of the four wings has a span of 0.45 m and a chord of 0.25 m, resulting in an aspect ratio of approximately 1.8. The wing span was chosen to accommodate readily available 0.5 m carbon rods used as internal spars, simplifying construction while placing the platform in the target cruise speed range of approximately 10 m s^{-1} , where full aerodynamic lift would support the vehicle weight. The chord length was constrained by the available 3D printer build volume of just over 250 mm; longer chords would have exceeded printability limits. The motor mounting legs, which

position the motors in front of the wings and provide landing feet to avoid landing directly on the wing trailing edges, were printed diagonally within the build volume, further informing the final chord dimension. This value provides a balance between aerodynamic efficiency and structural stiffness; higher aspect ratios would improve lift–drag performance but increase bending inertia and reduce agility. The total diagonal motor-to-motor distance is 1.1 m. All wings are mounted with alternating dihedral and anhedral angles of $\pm 45^\circ$, creating a fully symmetric configuration independent of flight direction. This symmetry enables the same controller gains to be used in roll and pitch and allows the yaw heading to be freely adjusted depending on which orientation minimizes control effort.

The wings are untwisted and employ a NACA 0015 symmetric airfoil. The choice of a symmetric section was motivated by the requirement for bidirectional flight and simple aerodynamic modeling. The thickness ratio of 15% conveniently accommodates the two internal carbon spars used for stiffness and assembly. The NACA 0015 profile also exhibits a delayed stall and smooth lift curve, beneficial during transition and moderate-angle flight conditions. The chord line of each wing is aligned with the average rotor thrust axis (noting that the motors are tilted $\pm 5^\circ$ for yaw authority, as discussed below), such that the average motor thrust is directed vertically downward in hover without inducing horizontal force components. This alignment prioritizes hover efficiency, though tilting the wings relative to the motor thrust could improve forward-flight performance by allowing the motors to contribute a greater vertical component while the wings operate at reduced angles of attack.

The wings are printed from PLA Aero filament and contribute a total of approximately 440 g to the vehicle mass. All non-propulsive components (flight controller, companion computer, and batteries) are mounted near the geometric center, at $x = y = 0$, distributed symmetrically about the $z = 0$ plane to ensure balanced inertia. The complete airframe, including center hub and motor mounts, is fully 3D-printed. No structural asymmetries or significant vibrations were observed during geometric control experiments. However, when using the INDI controller, elastic wing vibrations appeared in the IMU data. To mitigate this, thin lines were tensioned between neighboring wings to increase stiffness and shift the dominant resonance frequency upward, improving signal filtering and control stability.

5.1.2 Wing Aerodynamics

The aerodynamic surfaces were designed for efficient lift generation in the cruise speed range of 5 m s^{-1} to 15 m s^{-1} . At a nominal flight velocity of 10 m s^{-1} and chord length of 0.25 m, the expected Reynolds number is on the order of 1×10^5 – 2×10^5 , placing the operation in the low-Reynolds transitional regime. At these conditions, the NACA 0015

profile provides a lift coefficient slightly below unity ($C_L \approx 0.9$) and a drag coefficient of approximately $C_D = 0.08$. The target angle of attack in steady cruise was set to around 10° . Lift and drag forces were estimated using the analytical model introduced earlier,

$$L = \frac{1}{2}\rho S C_L(\alpha) \|v_a\|^2, \quad D = \frac{1}{2}\rho S C_D(\alpha) \|v_a\|^2,$$

with ρ denoting air density, S the total projected wing area, and v_a the airspeed relative to the body. These analytical estimates guided the sizing of the vehicle and the placement of the aerodynamic surfaces relative to the center of gravity.

Quantitative estimate at 12 m/s. Using $\rho = 1.225 \text{ kg/m}^3$, total projected wing area $S \approx 0.318 \text{ m}^2$, $C_L \approx 0.9$ at $\alpha \approx 10^\circ$, and $C_D \approx 0.18$, we obtain

$$L = \frac{1}{2}\rho S C_L V^2 \approx \frac{1}{2} \cdot 1.225 \cdot 0.318 \cdot 0.9 \cdot (12)^2 \approx 25.25 \text{ N},$$

$$D = \frac{1}{2}\rho S C_D V^2 \approx \frac{1}{2} \cdot 1.225 \cdot 0.318 \cdot 0.18 \cdot (12)^2 \approx 5.05 \text{ N}.$$

For the 2.5 kg platform ($W \approx 24.53 \text{ N}$), the wings supply $\approx 103\%$ of the weight at 12 m/s, meaning the rotors can reduce thrust significantly and primarily need to overcome aerodynamic drag and provide control authority. The wing-induced drag corresponds to $\approx 60.6 \text{ W}$ of propulsive power at 12 m/s ($P_D = DV$), not accounting for additional parasite/induced drag from the fuselage, rotors, and interference effects. These values are first-order estimates in the low- Re regime and neglect propeller-wing interaction; they nonetheless quantify the expected forward-flight relief on rotor-induced power.

Propeller-wing interaction effects were not explicitly studied in this work. Since the wings are aligned with the rotor arms, partial overlap between the propeller wake and wing surface occurs, but its contribution to performance is assumed to be secondary compared to the main aerodynamic lift of the forward wings. Future investigations could employ CFD or wind-tunnel testing to quantify this coupling.

5.1.3 Propulsion and Actuation

The propulsion system was designed to maintain high agility while achieving efficient cruise performance. A thrust-to-weight ratio exceeding 3 was selected as a design target, enabling the vehicle to perform aggressive maneuvers and sustain up to 3 g lateral acceleration, consistent with agility metrics reported in the multirotor literature. To meet this target, high-response racing-grade components were chosen: T-MOTOR VELOX V2808 motors combined with HQProp 7×3.5×3 three-blade propellers. The resulting hover throttle is approximately 30%, leaving sufficient control margin for disturbance rejection and attitude stabilization.

Motor and propeller performance were characterized experimentally to obtain both thrust and torque mappings. The measurements were performed using a single motor mounted on a six-axis force–torque sensor, with forces and torques recorded over a range of command inputs. The empirical relations between motor command, thrust, and torque were used to map the controller outputs into corresponding DShot commands for the flight controller. These mappings also served to estimate instantaneous energy consumption and mechanical efficiency during flight trials.

The motors are tilted outward by 5° to increase effective yaw torque authority. In the control model, this tilt is represented as a small rotation of the individual thrust vectors, effectively increasing the available moment around the vertical axis. No DShot timing modifications were required, and no direct RPM feedback control was implemented. Instead, the INDI controller integrates motor speed responses and compensates for small deviations, ensuring smooth dynamic performance.

Although the addition of wings increases the total inertia of the platform, particularly in yaw, the resulting damping improved stability and reduced sensitivity to high-frequency disturbances. No significant cross-coupling between roll and pitch dynamics was observed. Overall, the X-wing configuration provides a good compromise between efficiency and agility, maintaining the control simplicity of a quadrotor while offering measurable lift benefits in forward flight. Performance gains were compared analytically against a non-winged reference quadrotor of comparable size and propulsion, confirming a theoretical reduction in power consumption at moderate forward velocities.

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:

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

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

7.1 Experimental Setup

This section documents the hardware configuration, software stack, and test facilities that enabled the experimental evaluation of the aerodynamic surface-enhanced quadrotor. The setup was designed to be fully reproducible, with all control and estimation software running on open frameworks and all data recorded for subsequent analysis.

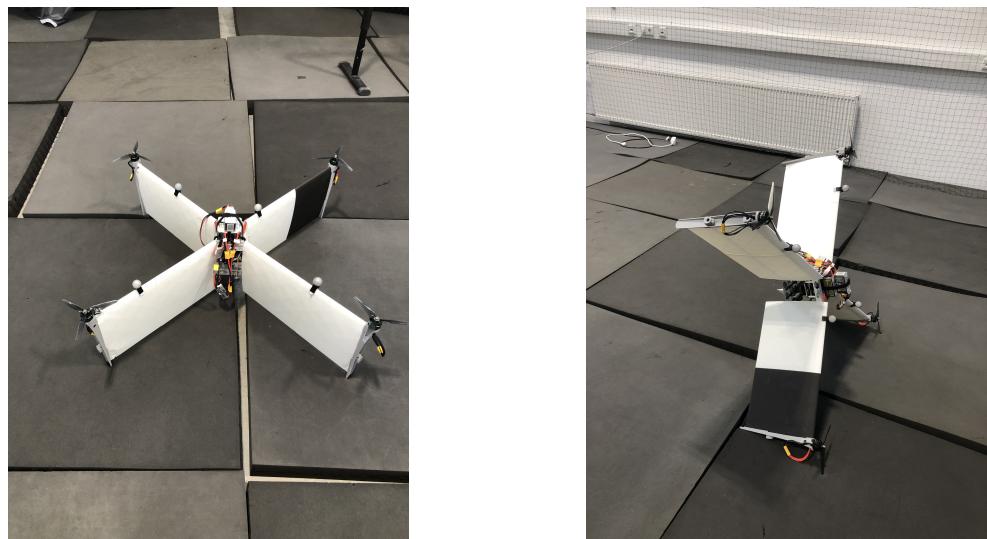
7.1.1 Hardware

Airframe and Propulsion

The experimental platform consists of an X-wing aerodynamic surface-enhanced quadrotor (Fig. 7.1) with a total mass of 2.5 kg (without batteries: 1.75 kg). Each of the four T-MOTOR VELOX V2808 motors produces a maximum static thrust of approximately 22 N, resulting in a total available thrust of 88 N and a thrust-to-weight ratio of 3.59 at nominal 22.2 V (6S LiPo). The propulsion system employs HQProp 7×3.5×3 three-blade racing propellers optimized for medium–high efficiency in the forward-flight regime.

The wings feature a NACA 0015 airfoil with a span of 450 mm and a chord of 250 mm. Four identical fixed wings are arranged orthogonally (90° between adjacent wings) and mounted with alternating dihedral and anhedral angles of $\pm 45^\circ$. The wings are attached to the central frame using two carbon spars (10 mm outer diameter) clamped into the core structure, allowing for fast removal. The center frame and motor mounts are 3D-printed from standard PLA, while the wing surfaces are printed from lightweight PLA Aero. The total projected horizontal area of all wings is approximately $S_t = 0.318 \text{ m}^2$.

Each motor is mounted with a 5° tilt to improve yaw authority. The center of gravity is located at the geometric center of the vehicle, aligned with the midpoint between all four motors, and approximately at one quarter of the wing chord length from the leading edge.



(a) Top view showing X-wing configuration with orthogonal wing arrangement.

(b) Side view showing alternating dihedral/anhedral wing angles.

Figure 7.1: The experimental X-wing aerodynamic surface-enhanced quadrotor platform.

Thrust Characterization and Command Mapping

To accurately relate motor command inputs to generated thrust, a static thrust characterization was performed for the chosen motor–propeller configuration. A single T-MOTOR VELOX V2808 motor equipped with an HQProp 7×3.5×3 propeller was mounted on a six-axis force–torque sensor (Rokubi Mini) using a custom 3D-printed fixture. The setup allowed precise measurement of the vertical force while commanding the motor through the same DShot interface used in flight (Fig. 7.2).

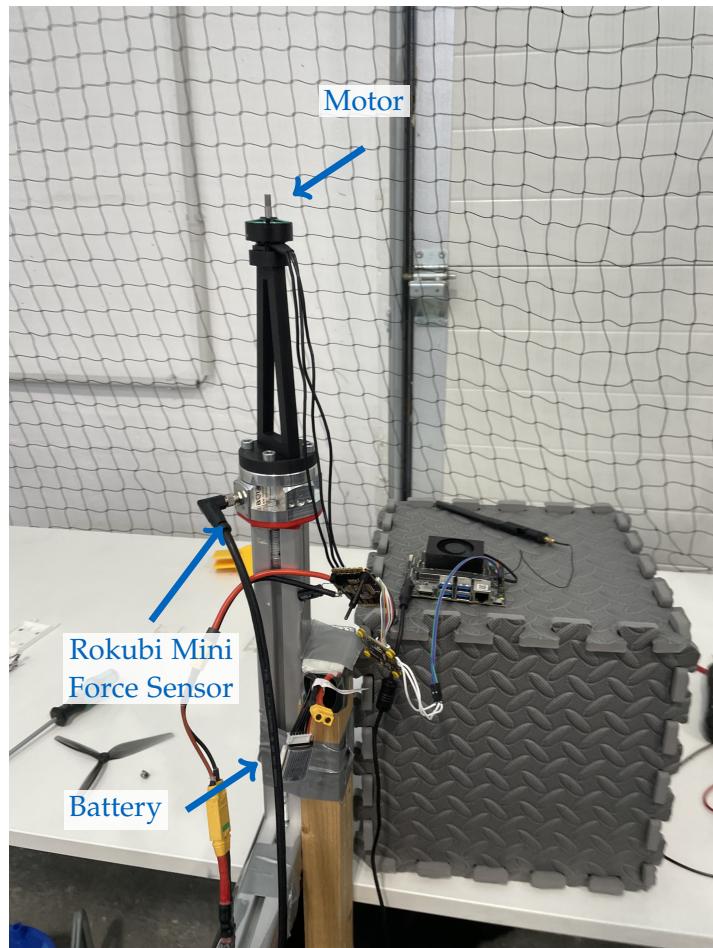


Figure 7.2: Static thrust characterization test stand with motor mounted on Rokubi Mini force–torque sensor.

Motor command values were swept across the full throttle range in incremental steps, and the resulting thrust was recorded. Each command level was averaged over a

2 s window to mitigate transient effects. The measurements yielded a nonlinear but monotonic mapping between normalized command input $u \in [0, 1]$ and thrust output T , which was fitted with a second-order polynomial of the form

$$T(u) = a_2 u^2 + a_1 u + a_0, \quad (7.1)$$

where the coefficients a_i were obtained via least-squares regression.

This empirical mapping was subsequently integrated into the control pipeline to convert desired thrust values from the INDI controller into per-motor DShot commands. The calibrated relationship improved the accuracy of total thrust estimation and allowed for energy-based efficiency analysis during flight tests.

Power configuration considerations. During the bench tests, one motor was mounted on the force sensor while the remaining four motors stayed on the vehicle and were kept fixed. We observed that the command-to-thrust relationship depends on how many motors are simultaneously powered from the battery due to load-dependent voltage sag and internal resistance effects. In particular, running only a single motor from a single 6S pack produced a slightly different mapping than powering all four motors from the flight-representative configuration with two 6S packs in parallel (6S 2P). Unless stated otherwise, the mapping used for control in flight was calibrated under the latter 6S 2P, four-motor-powered condition, and all subsequent thrust conversions refer to this configuration.

Avionics and Electrical System

The avionics stack is based on a *Kakute H7 v1.5* flight controller paired with a 4-in-1 ESC. Two 1400 mA h 6S Tattu R-Line batteries are connected in parallel to power the propulsion and avionics subsystems, resulting in an effective 2800 mA h capacity. The onboard computer, an NVIDIA Jetson Orin Nano (8 GB), is powered independently from a 1800 mA h 4S LiPo battery.

A custom-modified version of *Betaflight* firmware was employed on the flight controller to extract motor RPM and battery voltage data from the DShot interface and stream them over MAVLink. This modification was necessary because the stock Betaflight implementation does not support publishing these telemetry values via MAVLink. The onboard IMU integrated into the Kakute H7 was used for all experiments; no external IMUs were installed. Vicon markers were arranged asymmetrically to ensure unambiguous pose tracking.

Table 7.1: Bill of Materials (BOM) for the experimental platform.

Category	Component	Model / Key Specs
Airframe	Frame	X-wing center frame with carbon wing spars
Airframe	Wings	Four fixed wings (each 450×250 mm; NACA 0015 airfoil), orthogonal layout (90° between adjacent wings); skins: Bambu Lab PLA Aero; spars: 10 mm OD carbon tubes; total projected horizontal area $S_t \approx 0.318 \text{ m}^2$
Propulsion	Motors ($\times 4$)	T-MOTOR VELOX V2808, max 22 N each
Propulsion	Propellers ($\times 4$)	HQProp 7 \times 3.5 \times 3, 3-blade racing propeller (7", light grey)
Avionics	FC+ESC	Kakute H7 v1.5 Stack (4-in-1 ESC)
Power	Battery ($\times 2$, parallel)	Tattu R-Line V5.0 6S 1400 mAh 150C, XT60; effective 6S 2800 mAh (parallel)
Companion	Computer	Jetson Orin Nano 8 GB (Ubuntu 20.04)
Companion	Power	Tattu R-Line V3.0 4S 1800 mAh 120C, XT60
Motion Capture	Markers	Four 2 cm markers arranged in an asymmetric constellation

7.1.2 Software

Architecture and Communication

The onboard software stack consists of *ROS 1 Noetic* running on the Jetson companion. The geometric controller with inner and outer INDI (Incremental Nonlinear Dynamic Inversion) loops was implemented in ROS and executed on the companion, which sent individual motor speed commands directly to the flight controller over MAVLink via UART. The flight controller, in turn, only relayed the received motor commands to the ESCs while providing IMU, motor RPM, and battery telemetry back to the companion.

A ROS master node was hosted on a ground station computer, while the Jetson ran a ROS node for flight control and data logging. Communication between the two systems was established via Wi-Fi. The ground station handled trajectory loading, arming, and manual control interfaces. All experiment data, including position, velocity, attitude, thrust commands, and battery voltage, were logged in *rosbag* format for offline analysis in Python.

Estimation and Control

The state estimation pipeline used the Vicon motion capture system to provide real-time position and attitude feedback to the controller. In some experiments, an onboard

Extended Kalman Filter (EKF) fused IMU data for state estimation. The Vicon system and onboard IMU operated in a consistent right-handed coordinate convention (front-left-up), with roll about the x -axis, pitch about y , and yaw about z .

All flight maneuvers, including point-to-point transitions and trajectory tracking, were executed fully autonomously from predefined setpoints. No separate failsafe was implemented for Vicon loss, but trajectories could be manually stopped and the vehicle landed or disarmed from the base station.

7.1.3 Facilities

Motion Capture Systems

Two different Vicon systems were employed for data acquisition and feedback. The smaller test arena in Munich measured approximately $7\text{ m} \times 8\text{ m}$ and was used primarily for agility experiments, such as 3 g circle maneuvers. The larger *AIDA Hall* at Reutlingen University provided a volume of about $60\text{ m} \times 45\text{ m}$, enabling steady forward-flight efficiency trials (see Fig. 7.3). Both systems operated at a sampling rate of 200 Hz . Vicon data were used both as ground truth and as feedback for the control loop.



Figure 7.3: AIDA Hall test facility used for efficiency trials (image credit: Reutlingen University [Reu24]).

Test Protocols

Agility tests were performed in the Munich indoor arena equipped with safety nets and a soft landing surface. Efficiency tests were conducted in the AIDA Hall under still-air indoor conditions, with no wind sources or obstacles. Energy consumption was estimated from measured voltage, current draw, and propeller rotational speed data. Typical flight durations were approximately five minutes per run.

Documentation

All experiments were recorded through *rosbag* logs and video footage to facilitate data visualization and reproducibility. Post-processing and analysis were conducted in Python, using custom scripts for trajectory evaluation, energy estimation, and control performance comparison.

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.

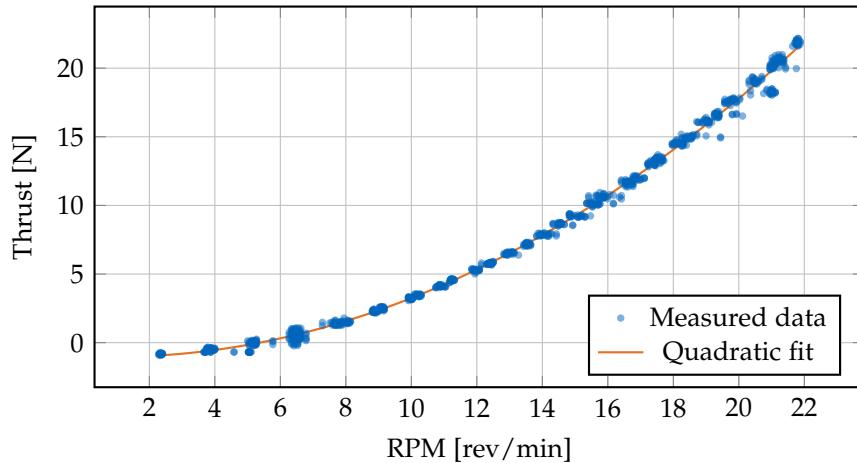


Figure 8.1: Thrust vs RPM with quadratic fit: $T = 0.0515 \cdot \text{RPM}^2 - 0.0902 \cdot \text{RPM} - 0.996$ (N). $R^2 = 0.997$.

8.2 Agility and tracking

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

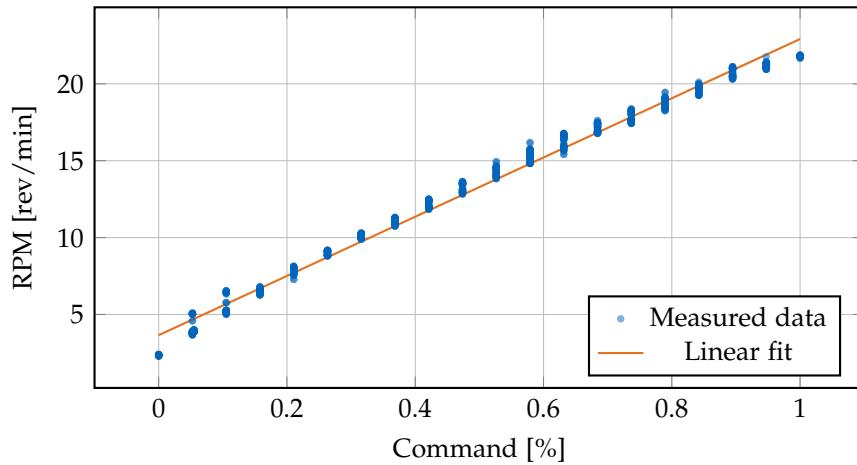


Figure 8.2: RPM vs Command with linear fit: $\text{RPM} = 19.26 \cdot \text{cmd} + 3.65 (rev/min). $R^2 = 0.991$.$

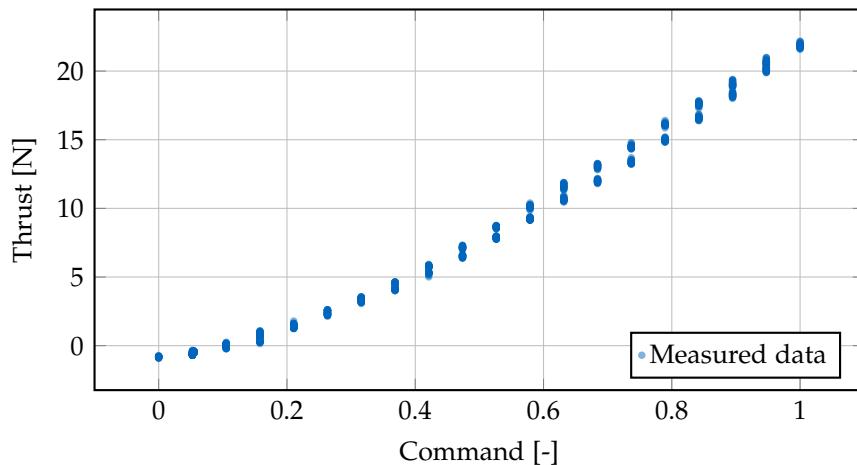


Figure 8.3: Thrust vs Command showing the direct relationship between motor command and thrust force.

8.3 Aerodynamic forces/moment 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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