

Control of an Over-actuated Fixed-wing Vectored Thrust eVTOL

Emmanuel Enenakpogbe^{†*}, James F. Whidborne^{‡*}, Linghai Lu^{§*}

Abstract—A novel full-envelope controller for an over-actuated fixed-wing vectored thrust eVTOL aircraft is presented. It proposes a generic control architecture applicable to piloted, semi-automatic and fully-automated flight consisting of an aircraft-level controller (high-level controller) and a control allocation scheme. The aircraft-level controller consists of a main inner-loop non-linear dynamic inversion controller and an outer-loop proportional-integral linear controller. The inner-loop classical non-linear dynamic inversion controller is used for forward cruise flight while the outer-loop proportional-integral linear controller is used for hover/low speed control and position control. The control allocation scheme uses a novel architecture which transfers the non-linearity in the vectored thrust effector model formulation to the computation of the actuator limits by converting the effector model from polar to rectangular form thus allowing the use of a linear optimisation technique. The linear optimisation technique is an Active Set Linear Quadratic Programming constrained optimisation algorithm with a weighted least squares formulation. The control allocation allocates the overall control demand (virtual controls) to individual redundant effectors while performing control error minimisation, control channel prioritization and control effort minimization. Simulation results shows forward transition from hover to cruise and clearly demonstrates that the controller can handle saturation (position or rate). The proposed controller can also handle actuator failures.

Index Terms—NDI, INDI, Transition, over-actuated, virtual controls, Full Envelope, easy-to-fly, effector model, VTOL, control allocation, Active Set, Weighted least squares, optimal, high level controller, unified control framework, real-time, online, constrained optimisation, linear quadratic programming.

I. INTRODUCTION

One of the control challenges of vectored thrust and tilt-rotor eVTOLs is the interaction and coupling between the aeromechanical and dynamic forces and moments potentially depleting the natural aerodynamic damping or stiffness tending to drive an aircraft unstable [1]. One particularly challenging eVTOL configuration is the Lilium Jet [2], an early version of which is the 7-seater light sports aircraft with 36 all-electric engines (six on each of the two front canards and twelve on each rear main wings).

The Electric Ducted Fans (EDFs) are located on top of the control surfaces, which provides vectored thrust simultaneously with aerodynamic control. However its canard configuration can destabilize the short-period mode [3], [4] requiring

fly-by-wire stability augmented flight control systems. The configuration is also challenging because the coupling between the aerodynamic surface control and the vectored thrust make control allocation during transition very difficult. This paper proposes an easy-to-fly, simple and unified control framework with real-time control allocation for the Lilium-style eVTOL planform shown in Figure 1, which also shows the EDF arrangement whereby the fans are ganged together in sets of three.

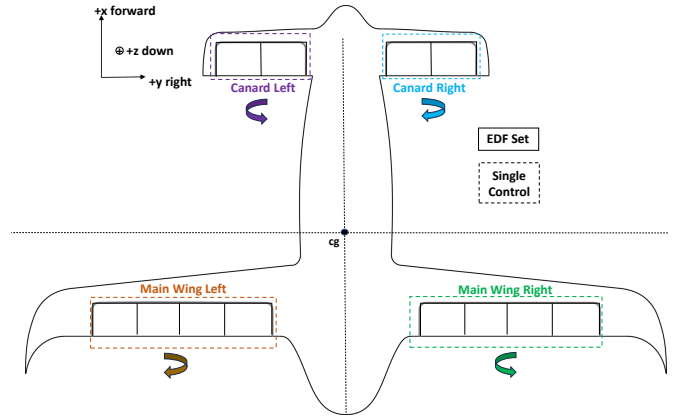


Fig. 1: Aircraft planform showing EDF sets distribution

II. MODELLING, CONTROL AND METHODOLOGY

The cruise aerodynamic model is derived from [5] and [6] while the hover aerodynamic model is a flat plate resistance force model from [6]. The geometric information, moment of inertia, mass and effector distribution as indicated in Figure 1 are based on [5]. Nonlinear Dynamic Inversion (NDI) is a well-established nonlinear control approach which has been combined with control allocation for the full envelope control of several limited special class of eVTOL tilt-rotor configurations [6]–[9] because it can deal with the nonlinearities and wide operating envelope. NDI [7] is used as the high-level controller (aircraft-level controller) for the eVTOL configuration in this paper rather than incremental NDI (INDI) of [6] because although it has some drawbacks (poor external disturbances rejection and robustness to model uncertainties), it is well established and has proven stability analysis.

There are several control allocation approaches and techniques used for motion control of over-actuated mechanical

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systems [10]–[13]. This paper builds on [7] by including lateral-directional controls and control effector model, and proposes a constrained optimal control allocation for full-envelope control of a Lilium-styled aircraft [2].

The control allocation (CA) approach taken is to transfer the non-linearity in the effector model due to polar thrust formulation to the computation of actuator saturation and rate limit constraints by decomposing its thrust components on the body axes and treating them as elements of the control input. The non-linear computation of the actuator limits is computed and updated dynamically based on the unconstrained actuator demands and real physical limits. This formulation of a linear effector model allows the use of a real-time linear constrained optimisation algorithm. An online constrained optimisation linear control allocation scheme is proposed incorporating the Active Set Linear quadratic programming (QP) algorithm [14], [15] of a weighted least squares (WLS) formulation with a novel functional architecture generic for piloted, semi-automatic and automated flight [7].

III. SIMULATION RESULTS

The full mission profile has been tested in simulation. An example of a forward transition from hover to cruise is shown in Figures 3 and 2. Starting at an altitude of $h = 3000\text{m}$ in hover. At time $t = 5\text{s}$, a forward transition was commanded from hover to a cruise speed $u = 78\text{m/s}$ and $\alpha = 2.83^\circ$ over a 45s duration. During the forward transition, the altitude was maintained within $\pm 2\text{m}$ due to the height hold outer linear control loop. the canard EDFs tilted from $\Gamma = 91^\circ$ to $\Gamma = 15^\circ$ while the main wing EDFs tilted from $\Gamma = 89^\circ$ to $\Gamma = 0^\circ$ ensuring low rotor-induced drag and power consumption. The EDF thrust at cruise speed for the all EDFs reduced to about 25% compared to hover since the lift is primarily provided by the wings and canards leaving the EDF to only provide forward thrust.

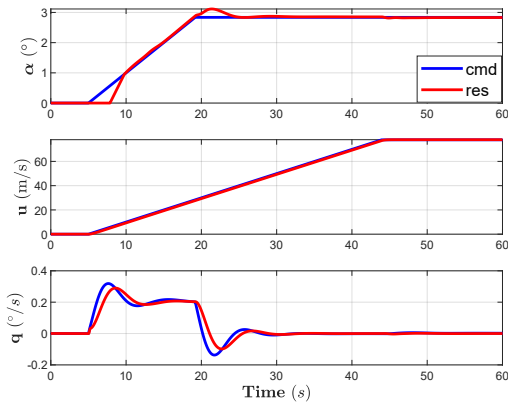


Fig. 2: Forward Transition from Hover to Cruise - States

IV. CONCLUSIONS

The simulation results demonstrates the control of an over-actuated Lilium-styled VTOL aircraft during the critical forward transition flight from hover to cruise using a controller

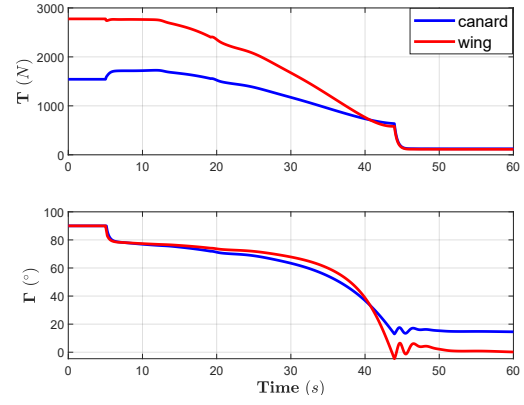


Fig. 3: Forward Transition from Hover to Cruise - actuators

functional architecture consisting of classical NDI high-level controller and the Active Set Linear QP WLS control allocation algorithm. The control allocation scheme handles the EDF actuator thrust and tilting mechanism dynamics and limits during the forward transition phase preventing any loss or limitation of control authority during actuator saturation.

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2024-05-22

Institute of Electrical and Electronics Engineers (IEEE)

<https://doi.org/10.1109/CONTROL60310.2024.10531934>

Enenakpogbe E, Whidborne JF, Lu L. (2024) Control of an over-actuated fixed-wing vectored thrust eVTOL. In: 2024 UKACC, 14th International Conference on Control (CONTROL), 10-12 April 2024, Winchester, UK, pp. 315-316