PhD thesis: Design of an innovative urban air mobility vehicle (UAMV) - A control-oriented study

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Summary

This Ph.D. thesis addresses the problem of designing a Vertical Take-Off and Landing (VTOL) aircraft for Urban Air Mobility with special emphasis on the control system design and tuning problem. This thesis is divided into two main parts. The first part focuses on the design of an innovative Vertical Take-Off and Landing (VTOL) aircraft for Urban Air Mobility, featuring a novel ThrustPod propulsion system patented by the Polytechnic University of Turin. The ThrustPod's patent is based on extractable and retractable modules containing the rotors to guarantee the thrust for the vertical flight phases, such as take-off and landing. The ThrustPod's main advantages comprise reduced aerodynamic drag during cruise and the capability of converting a conventional fixed-wing aircraft to a VTOL configuration with minimal effort. An optimal aircraft configuration for a passenger transportation VTOL aircraft was identified through a custom MATLAB® algorithm, optimizing the maximum take-off weight and the disposition of the ThrustPod modules and the rotors inside. A comparison with market competitors demonstrated that the passenger aircraft ThrustPod configuration achieves better performance in terms of range, passenger capacity, and energy efficiency. To rapidly validate the ThrustPod's capabilities, two scaled prototypes based on this configuration were developed, resulting in a quadcopter-like arrangement with four ducted-fan rotors for VTOL operations. Control strategies for quadcopter VTOL hover operations were developed, highlighting a Model Reference Adaptive Controller (MRAC) combined with a PID controller and dynamic inversion as the most effective solution.

A prototype UAV can experience uncontrolled damage and crashes during flight; hence, the need for a safe and controlled environment is crucial for the

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UAV controller's testing. These considerations motivate the second part of the thesis, where specialized test benches were designed, in independent collaborations with SELT Aerospace & Defence company (Italy) and Virginia Tech (USA). These test benches allow testing the inner loop dynamics of a multi-rotor autonomous uncrewed aerial vehicle (UAV) in a safe environment. The test bench developed at Virginia Tech, the ThrustStand, is analyzed in further detail since it overcomes several limitations of alternative commercial-off-the-shelf and custom-made test benches.

The main objective for the ThrustStand is to apply torques via three motors aligned with the roll, pitch, and yaw axes that cancel the inertial forces of the structure, effectively enabling the emulation of free-flight conditions for the UAV. The ThrustStand can also be employed to experimentally estimate the inertia tensor of a UAV. To this goal, an algorithm is proposed and validated through case study simulations using MATLAB® software.

To enable the ThrustStand, this thesis devotes considerable effort to deriving the equations of motion of this multi-body system. Special emphasis is given to the problem of modeling unavoidable realization errors, such as offsets in the centering of the ThrustStand components. Leveraging these dynamical models, we present two control techniques to ensure satisfactory test results. The first control technique is a classical proportional-integral controller with dynamic inversion. As expected, this technique proved to be effective only for small error margins in the mass, tensor of inertia, and positional offset parameters. The second control technique considered in this thesis leverages the first one as a baseline and improves its limitations. In particular, this second technique includes the e-modification of model reference adaptive control (MRAC). Simulation results in a very high fidelity environment based on Project:Chrono demonstrate how the proposed control architecture based on adaptive control effectively cancels the inertial effect of the ThrustStand and allows the UAV's inner loop controller to operate as if it were in actual free flight conditions.

This thesis is a component of broad, partly overlapping, efforts in the areas of large UAV design for UAM operations and the design of high-fidelity simulation and experiment setups for testing advanced control systems on Class 2 and larger UAVs. Future work will be devoted on extending the validation of the ThrustStand through Hardware-in-the-Loop experiments, exploring alternative control strategies for both the test-bench and the ThrustPod prototypes, and studying advanced control approaches to enable flights in complex mission scenarios in the presence of uncertain or varying payloads.