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VSTOL FCS Using Nonlinear Dynamic Inversion and Scheduled Fixed Wing Controllers.

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***Abstract*— *This paper describes the application of input-output Nonlinear Dynamic Inversion (NDI) to flight control of a tilt-rotor actuated Vertical Short Take Off and Landing (VSTOL) platform. The NDI formulation is performed in the inertial reference frame resulting in a decoupled and linearised set of integrator virtual plants controlled using Linear Quadratic Integral (LQI) control. The NDI controller is continuously enabled along with a conventional fixed wing controller with the latter scheduled in and out of control authority as a function of the wing tilt/vector angle control input generated by the NDI controller.**

NOMENCLATURE

AoA, Angle of Attack.
FCS, Flight Control System.
INDI Incremental Nonlinear Dynamic Inversion.
PVTOL Planar Vertical Take Off and Landing.
QCAT, Quadratic Control Allocation Tool.
SISO, Single Input Single Output.

I. INTRODUCTION

VSTOL controlled flight is challenging because it involves both the allocation of thrust between the longitudinal and powered/aerodynamic lift together with the nonlinearities of the aerodynamic coefficients beyond the usual AoA seen in fixed wing flight. Conventional scheduled linear control for VSTOL control whilst feasible requires extensive numerical and empirical gain scheduling, see [1]. Therefore, NDI has increasingly been seen as an alternative to scheduled approaches because of its inherent ability to linearise and uncouple non-linear systems before applying linear control to the resulting virtual plant, see [2]. For NDI to be applicable to a plant it is required that a set of outputs equal to the number of inputs can be evaluated such that all states and inputs can be determined from these outputs without integration. VSTOL platforms are such a differentially flat system [3].

However, NDI alone without some form of robust controller included has the drawback that an accurate model is required for the state feedback law to be derived which is challenging given the previously mentioned aerodynamic non-linearities and the action of disturbances on the system [4, 5]. Hence, INDI has been proposed, see [6], which has the advantage that the aerodynamics can be excluded for the hover but taken into account with fixed wing controllers classically designed that are blended in and out of control authority based on some scheduling criteria.

Both the approach taken in [6] and this work deal with disturbance rejection by the scheduling of the hover and fixed wing controllers and allocation of the vertical and longitudinal thrust. The difference is that NDI not INDI is used and the NDI formulation is performed in the inertial reference frame. Further, the tilt/vector angle is a control input from the NDI and is used both as the scheduling variable in the allocation of classical fixed wing controller authority **and** tilt/vector angle control demand where needed.

II. CONTROL DESIGN

This scheme combines nonlinear control for the hover with scheduled linear control for the fixed wing.

A. Hover NDI

The 'xz' (vertical plane) longitudinal *hover* dynamics of the rigid body aircraft reduced to PVTOL form using vectored thrust actuation are shown in Fig. 1. With the assumption that by design the closed loop tilt actuation (rotor tilt relative to the fuselage) is a stable first order response with negligible transients the overall PVTOL system can be stated in the inertial reference frame as:

$$\begin{aligned} m\ddot{x} &= u_1 \cos\Psi, \\ m\ddot{z} &= -u_1 \sin\Psi + mg, \\ \dot{\Gamma} = u_2, \quad I_\theta \ddot{\theta} &= u_3. \end{aligned} \tag{1}$$

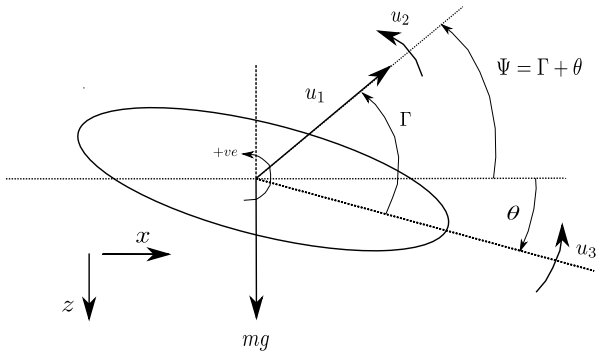


Fig. 1. PVTOL *hover* schematic.

where:

- u_1 is the net thrust force from the rotors.

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- u_2 is the tilt actuation moment.
- u_3 is the pitch actuation moment.
- Γ is the wing tilt relative to the fuselage.
- θ is the pitch of the aircraft.
- Ψ is the thrust incidence angle.
- I_θ is the pitch inertia.

Using input output NDI theory a state feedback law can be derived that reduces the nonlinear system represented by Eq. 1 into a uncoupled linear system with no unobservable unstable dynamics as follows:

$$x^{(3)} = v_1, \quad z^{(3)} = v_2, \quad \theta^{(2)} = v_3. \tag{2}$$

Therefore, we can track an arbitrary state trajectory and guarantee that the system will be stable. The application of the NDI VSTOL controller to the various VSTOL platform architectures described in [7] can be allocated directly from the tilt angle Γ NDI control input or from the sine and cosine of the tilt angle Γ NDI control input respectively.

1) LQI servo control: The uncoupled linearised plants resulting from the NDI are controlled with deterministically designed LQI controllers using the pole placement technique detailed in [8].

B. Fixed wing altitude control

The cascaded outer fixed wing loop takes an altitude rate of change demand and generates a control input of pitch angle which is the demand in turn for the inner loop which generates a control input of elevator angle. Both inner and outer bandwidth separated fixed wing controllers are SISO linear and therefore gain scheduled.

III. VSTOL CONTROL ALLOCATION

The flight control is unified in that the control architecture is fixed throughout the flight envelope [9] with the control authority being allocated by means of the VSTOL vector tilt/angle Γ between the powered lift and the control surfaces as shown in Fig. 2.

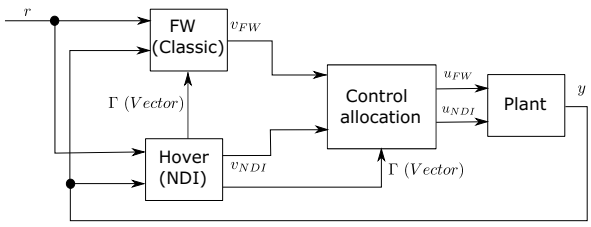


Fig. 2. Unified VSTOL control scheme schematic.

In particular, the fixed wing controllers are blended in and out of control authority by scaling the saturation limits as a function of the vector tilt/angle, Γ, as:

$$f(\Gamma) = \frac{1}{2}\left(1 + \tanh\left[\frac{\Gamma - c}{h}\right]\right), \tag{3}$$

where the parameters c and h shift and smooth the transition respectively [10]. The vector tilt/angle, Γ, is obtained on-line from the NDI state feedback law (see Fig. 2).

A. Multi-rotor control allocation

From Eq. 1 the vertical and horizontal allocation of thrust u_1 and pitch moment actuation u_3 from the NDI hover controller require further control allocation into the equivalent multi-rotor speed actuation units. The allocation to derive the rotor speeds equivalent to the virtual forces and moments used a non-linear control allocation matrix and the QCAT solver [11].

IV. CONCLUSION

The NDI VSTOL scheme formulated in the inertial reference frame using the tilt angle Γ control input to schedule between the NDI hover and fixed wing control discussed in this paper has been shown by simulation to provide a simple VSTOL FCS architecture. In particular, **the core originality of this work in that the NDI state feedback law provides the VSTOL tilt corridor** on-line without the need for a reference model or calibration has been demonstrated. It is also the case that the stated VSTOL NDI scheme is compatible with the now established 'two-stick' inceptor principle for VSTOL flight as detailed in [9, 12].

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