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L_1 Adaptive Dynamic Inversion Controller for an X-Wing Tail-Sitter MAV in Hover Flight

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Abstract

This paper presents a hover flight attitude controller for a tail-sitter vertical take-off and landing (VTOL) micro aerial vehicle (MAV). The MAV named Novlit-3 combines a novel non-orthogonal X shaped wing layout with a single propeller, which is capable for high efficient cruise and prop-hang hover. Considering the nonlinear unstable dynamics and disturbance sensitivity of the VTOL MAV, we apply the L_1 adaptive control theory to augment the baseline dynamic inversion controller. The L_1 adaptive augmentation acts on the angular dynamics, estimating and compensating the time-varying uncertainty with fast adaptation rate and appropriate time-delay margin. The flight validation is executed on the Novlit-3 VTOL MAV.

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Keywords: $\mathcal{L}_1$ adaptive control; Dynamic inversion; Tail-sitter MAV; Hover

1. Introduction

The capability of vertical take-off and landing (VTOL) enables Micro Aerial Vehicle (MAV) to execute low-speed search in limited space or even stare surveillance. Tail-sitter configuration tends to be an appropriate solution for VTOL MAV since it achieves transition flight between high efficient cruise and prop-hang hover without involving additional tilting mechanism. Novlit-3 (Figure 1) is a tail-sitter VTOL MAV with 60cm wing span and 700g take-off weight, which has a novel X shaped wing layout with a single propeller. Its non-orthogonal wing layout and the corresponding control surfaces arrangement provide extra lateral-directional stability in cruise and

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preferable controllability in hover. The hover flight of the Novlit-3 has tightly inertial coupling, high bandwidth, unstable and disturbance sensitive dynamics. In this paper, the authors view these factors as time-varying uncertainties and the L_1 adaptive control theory is applied in the hover flight attitude controller for the Novlit-3.

Fig. 1 Novlit-3 tail-sitter VTOL MAV

The L_1 adaptive control theory is a revision of model reference adaptive control (MRAC). By integrating a well-designed low-pass filter to the adaptive control output, it achieves fast estimation of time-varying uncertainty and robust compensation of the estimated uncertainty within the bandwidth of the control channel. Taking advantages of its decoupled fast adaptation and guaranteed robustness, various types of L_1 adaptive controllers have been developed and validated for helicopters and multirotors hover attitude control [1-3]. In this paper, we proposed a L_1 augmented dynamic inversion control architecture. The proportional-integral kinematic inversion controller generates the desired angular rate for the inner-loop dynamic inversion controller with proportional angular rate error feedback, according to the attitude command. As the L_1 augmentation is applied in the inner-loop angular dynamics to compensate the time-varying uncertainty, the inner-loop controller has small phase lag so that the L_1 augmentation could be more sensitive to angular rate response error. Thus environmental disturbance and modeling errors can be identified and compensated with less time-delay and acceptable robustness. The proposed control architecture has been validated on the Novlit-3.

Nomenclature

J	Moment of inertia of MAV
M_{total}	Overall control moment
M_{DI}	Control moment of dynamic inversion
M_{AD}	Control moment of L_1 adaptive augmentation
σ	Uncertainty in angular dynamics
ω	$[p \quad q \quad r]^T$ Vector of roll rate, pitch rate and yaw rate
Ω	$[\phi \quad \theta \quad \psi]^T$ Vector of roll angle, pitch angle and yaw angle
ω_{des}	Desired ω
Ω_{des}	Desired Ω

2. Baseline dynamic inversion controller

2.1. Outer-loop kinematic inversion

The outer-loop kinematic inversion generates ω_{des} according to the error between Ω_{des} and Ω.

$$\omega_{des} = G^{-1}(K_{PE} + K_{IE}\frac{1}{s})(\Omega_{des} - \Omega) \tag{1}$$

Where K_{PE} and K_{IE} are proportional and integral gains of the attitude angle error, the nonlinear kinematic transform matrix G is defined as follows

$$G = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \tag{2}$$

2.2. Inner-loop dynamic inversion

The inner-loop dynamic inversion determines M_{DI} based on the error between ω_{des} and ω. The key idea of the dynamic inversion control theory is transforming a nonlinear system into a chain of integrators, then using the corresponding dynamic inversion control signal to drive the pseudo control variable to follow the desired value [2]. For the angular dynamics of MAV, we take angular acceleration as pseudo control variable, the general dynamic inversion control law is defined as

$$M_{DI} = J\dot{\omega}_{des} + \omega \times J\omega \tag{3}$$

Since the kinematic inversion provides ω_{des} rather than $\dot{\omega}_{des}$, a first order reference system is needed.

$$\dot{\omega}_{rm} = K_{rm}\left(\omega_{des} - \omega_{rm}\right) \tag{4}$$

Where ω_{rm} is the angular rate of the reference model and the gain K_{rm} specifies the dynamics of the reference model. Moreover, since the existence of modelling error and uncertainties, it is necessary to correct the general dynamic inversion control law using proportional error feedback. So the M_{DI} can be redefined as follows

$$M_{DI} = J\left(\dot{\omega}_{rm} + K_P\left(\omega_{rm} - \omega\right)\right) + \omega \times J\omega \tag{5}$$

Where K_P is the proportional gain of angular rate error.

3. L₁ augmentation

According to [1] and [3], the L₁ augmentation consists of a state predictor, adaptation law and control law. In recent work, we take angular dynamics as the reference model of the state predictor, and apply the piecewise constant adaptation law which fits relatively low running speed of the small autopilot.

3.1. State predictor

$$\dot{\hat{\omega}} = -J^{-1}\left(\omega \times J\omega\right) + J^{-1}\left(M_{total} + \hat{\sigma}\right) + K_{SP}\left(\hat{\omega} - \omega\right) \tag{6}$$

Where $\hat{\omega}$ and $\hat{\sigma}$ are the estimation of angular rate and uncertainty, K_{SP} is Hurwitz matrix which introduces additive convergence poles. The state predictor produces the estimation of ω according to control moment and the estimation of uncertainty.

3.2. Adaptation law

The piecewise constant adaptation law is defined as follows

$$\hat{\sigma}(t) = JK_{SP}\left(I - \exp\left(K_{SP}T_S\right)\right)^{-1}\exp\left(K_{SP}T_S\right)\left(\hat{\omega} - \omega\right)\quad \forall t \in [iT_S,(i+1)T_S]\; i = 1,2\ldots \tag{7}$$

Where T_S refers to the sampling time of the control algorithm. This adaptation law is in discrete form, which implies that $\hat{\sigma}$ is only updated at each sampling instant.

3.3. Control law

The control law contains a low-pass filtered compensation of estimated uncertainty.

$$\begin{aligned} \tau(s) &= J(M_{AD} + \hat{\sigma}) \\ M_{AD} &= -K_C D(s)\tau(s) \\ M_{total} &= M_{DI} + M_{AD} \end{aligned} \tag{8}$$

Where the positive diagonal matrix K_C and the strictly proper transfer function $D(s)$ consist the following strictly proper transfer function

$$C(s) = \frac{K_C D(s)}{1 + K_C D(s)} \tag{9}$$

$C(s)$ should have unity DC gain and at least the relative degree of 1. We take an integrator as $D(s)$ in recent work for simplicity. Thus far, the L_1 augmented dynamic inversion control architecture is defined by (4)-(8), whose structure is shown in Fig.2. The performance bounds and stability of the proposed L_1 adaptive augmentation are theoretically determined in Chapter 3 of [4].

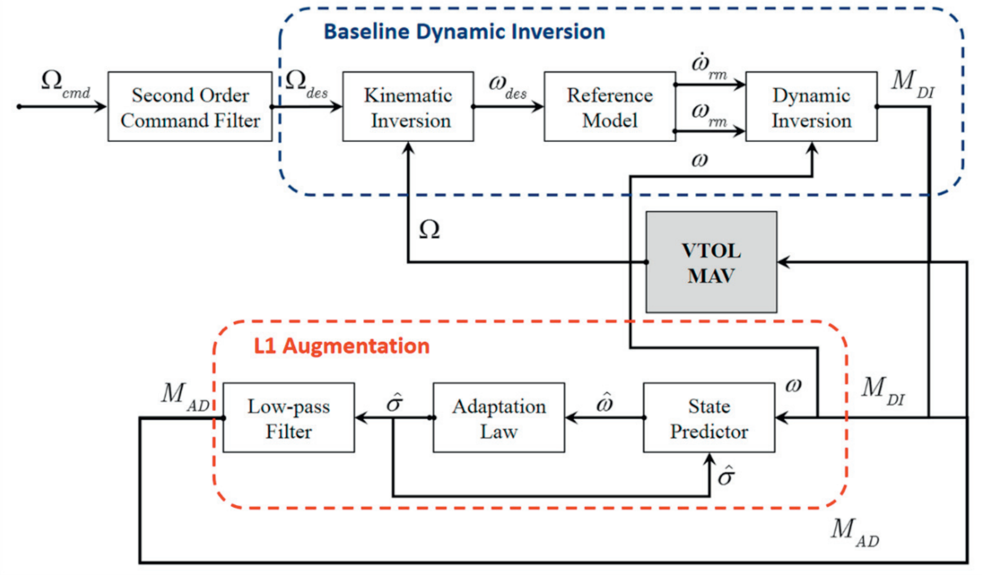

Fig. 2 L_1 augmented dynamic inversion control structure

4. Flight Validation

4.1. Implementation of the controller

The output of the proposed L_1 augmented dynamic inversion control architecture is control moment, so the control allocation method presented in [1] is applied to determine the control surfaces deflection from the control moment. The effectiveness of the control surfaces was determined using the vortex lattice method (VLM) while the aerodynamic moment was estimated by applying the method proposed in [5].

A customized autopilot is installed on the Novlit-3 MAV. It runs the control algorithm at 200Hz and flight data recorder at 100Hz. An explicit complementary filter (ECF), whose coefficients are adopted for fast response without GPS in a small disturbance hover, is applied for attitude estimation. As we concentrate on the hover attitude control in this paper rather than horizontal position and altitude control, the desired attitude angle is provided by the operator via R/C system, and the throttle setting is given by the control stick position directly. In order to ensure the smoothness of the desired attitude angle, a second order command filter is applied.

4.2. Flight test results

The pitch angle response of the Novlit-3 MAV is shown in Fig.3. The pitch angle θ follows the desired pitch angle θ_{des} with max deviation less than 1.5 degree, while the pitch angular rate q tracks the desired pitch angular rate q_{des} within 35ms time delay. Due to the introduction of the additive convergence pole in(7), the state predictor becomes less sensitive to angular rate measurement noise, so the estimation of the pitch angular rate q_{est} tightly follows q. This characteristic, together with the low-pass filter for the adaptive control output, ensures the robustness of the L_1 augmentation.

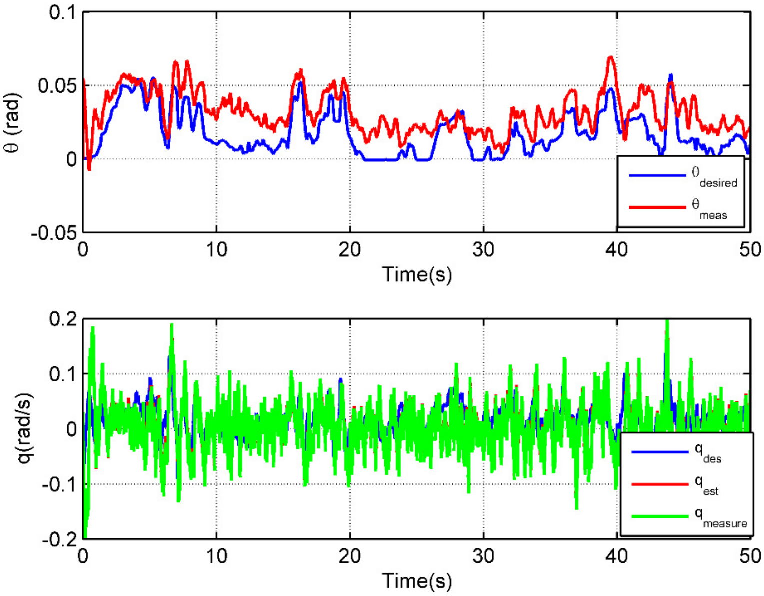

Fig. 3 Pitch angle response

5. Conclusion

This paper proposed a L_1 augmented dynamic inversion controller for hover attitude control of tail-sitter VTOL MAV. The controller is validated on a novel X shaped wing layout VTOL MAV named Novlit-3. The flight test results indicate the good tracking performance of attitude angle and angular rate. Since the adaptive control output is low-pass filtered, the close-loop system is free from aggressive control signal. The recent work confirms the fast adaptation and acceptable robustness of the L_1 adaptive augmentation.

In the future, implementation of the L_1 augmentation can be extended to some other baseline control architecture, including back-stepping and sliding mode. Moreover, because the output of the proposed architecture is the control moment, it is convenient to transplant the architecture onto helicopters, multirotors and other VTOL MAVs with less modification.

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