Autonomous flight of the rotorcraft-based UAV using RISE feedback and NN feedforward terms

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ABSTRACT

A position tracking control system is developed for a rotorcraft-based unmanned aerial vehicle (RUAV) using robust integral of the signum of the error (RISE) feedback and neural network (NN) feedforward terms. While the typical NN-based adaptive controller guarantees uniformly ultimately bounded stability, the proposed NN-based adaptive control system guarantees semi-global asymptotic tracking of the RUAV using the RISE feedback control. The developed control system consists of an inner-loop and outer-loop. The inner-loop control system determines the attitude of the RUAV based on an adaptive NN-based linear dynamic model inversion (LDI) method with the RISE feedback. The outer-loop control system generates the attitude reference corresponding to the given position, velocity, and heading references, and controls the altitude of the RUAV by the LDI method with the RISE feedback. The linear model for the LDI is obtained by a linearization of the nonlinear RUAV dynamics during hover flight. Asymptotic tracking of the attitude and altitude states is proven by a Lyapunov-based stability analysis, and a numerical simulation is performed on the nonlinear RUAV model to validate the effectiveness of the controller.

INTRODUCTION

A rotorcraft-based unmanned aerial vehicle (RUAV) is a versatile machine which can perform hover and vertical take-off and landing (VTOL) maneuvers. These characteristics have led to interests in the deployment of autonomous RUAV for military and civilian applications. Such applications involve low-speed tracking maneuvers in law-enforcement, reconnaissance, and operations where no runway is available for take-off and landing. While a fixed-wing aircraft is generally internally stable [1,2], the RUAV dynamics are naturally unstable without closed-loop control, which makes the control system design for the RUAV more challenging [3].

To improve the performance of the RUAV control system with a continuous control law, this study and the preliminary work in [5] propose the NN-based adaptive control system with robust integral of the signum of the error (RISE) feedback [6]. The RISE feedback control can compensate for disturbances or uncertainty while ensuring a semi-global asymptotic results with a continuous controller. When augmented with an adaptive feedforward term, the sufficient high

gain conditions of the RISE feedback are reduced, and the performance of the combined methods has been validated through simulation and experiment [6]. While the adaptive terms in [6] have been designed using a general adaptive control concept, a NN-based adaptive feedforward term is used in [7]. In this research, a linear dynamic model inversion (LDI) method is employed to reduce the design load of the control gain for the RISE feedback and adaptive feedforward term. The advantage of the LDI method is that, by utilizing a nominal model information, the need for heavier design efforts and large control gains for the RISE feedback can be avoided.
The proposed RUAV control system is divided into the outer-loop and inner-loop control systems. The outer-loop control system is composed of translational dynamics inversion and altitude control. In the translational dynamics inversion terms, roll and pitch commands $(\phi_{ref}, \theta_{ref})$ are generated corresponding to the given position $(x^S_{ref}, y^S_{ref}, z^S_{ref})$, velocity $(\dot{x}^S_{ref}, \dot{y}^S_{ref}, \dot{z}^S_{ref})$ and heading commands (ψ_{ref}), [8], where $(\cdot)_{ref}$ denotes the reference. To follow the given $z^S_{ref}, \phi_{ref}, \theta_{ref}$ and ψ_{ref}, altitude and inner-loop control systems are designed by the LDI method with the RISE feedback. The linear model for LDI is obtained by linearization of the nonlinear RUAV model at hover flight. The altitude and attitude tracking control systems are designed by differentiating z^S, ϕ, θ and ψ twice with respect to time. Therefore, their second time derivatives have to include the control inputs for designing the LDI. That is, the input gain matrix obtained in the linearization has to be invertible because the LDI method requires an inversion of the input gain matrix. However, while the control inputs X_{col} and X_{tail} directly affect the dynamics on the vertical velocity (w) and yaw rate (r), the dynamics on the pitch rate (q) and roll rate (p) are determined only by the flapping angles a_1, b_1 and other states. The longitudinal and lateral cyclic control inputs X_{lon} and X_{lat} directly decide the motion of a_1 and b_1 only [3]. To invert the input gain matrix, this study rearranges it such that the dynamics of q and p are directly influenced by X_{lon} and X_{lat}, and the dynamic effect on a_1 and b_1 is included in the uncertainty. Because this rearrangement increases the uncertainty that has to be removed by the RISE feedback, the NN-based adaptive feedforward term is added to the inner-loop control system to reduce the load of the RISE feedback. An adaptive rule for the NN approximator is designed to permit zero initial values by injecting more information (NN estimation terms) into the adaptive rule, without the need to design the initial values of the NN estimator [7].

DYNAMIC EQUATION FOR THE ALTITUDE CONTROL SYSTEM

This section describes the general nonlinear dynamic model of the RUAV and its linearization at hover flight. Then, to design the attitude and altitude control systems separately, the linearized system is divided into two subsystems: the first one for the attitude control and the other for the altitude control system.
Generally, the dynamics for the RUAV are given as

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \mathbf{u}(t)), \tag{1}$$

where $\mathbf{x}(= [u\, v\, w\, p\, q\, r\, \phi\ \theta\ \psi\, a_1\, b_1]^T)$ is a state vector and $\mathbf{u}(= [X_{col}\, X_{lon}\, X_{lat}\, X_{tail}]^T)$ is a control input vector [3]. The kinematics are represented as:

$$\dot{\mathbf{x}}_1 = \Phi(\mathbf{x}_1)\mathbf{x}_2, \tag{2}$$

$$[\dot{x}^S\, \dot{y}^S\, \dot{z}^S]^T = L^{B\to S}[u\, v\, w]^T \tag{3}$$

where $\mathbf{x}_1 = \left[\phi\ \theta\ \psi\right]^T$, $\mathbf{x}_2 = \left[p\, q\, r\right]^T$, and $\Phi(\mathbf{x}_1)$ and $L^{B\to S}$ are the direction cosine and trans-

formation matrices from the body coordinate B to the spatial coordinate S, respectively [1].
To derive our control law, the dynamic equations in (1) are linearized at hover flight condition:

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u} + d \tag{4}$$
$$\mathbf{y} = C\mathbf{x} \tag{5}$$

where A and B are the Jacobian matrices for a given flight condition [3], $\mathbf{y} = \left[u\ v\ w\ p\ q\ r\ \phi\ \theta\ \psi\right]^T$ is a measurable output, and C is the output matrix for extracting $\mathbf{y}$ from the state vector $\mathbf{x}$. The term d is considered as the uncertainty, which is composed of trim information and high order term derived by the linearization. It is defined as $d \triangleq -A\mathbf{x}_0 - B\mathbf{u}_0 + \Theta$, where the subscript zero denotes a trim value, and Θ is a high order term.
In this study, the attitude and altitude control systems are designed separately using (4) and (5). To facilitate this, the matrices A, B in (4) are divided into two parts: one for the attitude control and one for the altitude control. This is motivated by the fact that the attitude states $\mathbf{x}_1$ of the RUAV are mainly connected to the control input $\mathbf{u}_a$ which is composed of X_{lon}, X_{lat} and X_{tail}, while the altitude dynamics are dominated by the main-rotor collective stick X_{col} [3].

Dynamic equation for the attitude control system

The attitude states $\mathbf{x}_1$ are mainly dominated by the control input $\mathbf{u}_a$ [3]. To utilize this property in the attitude control system design, the attitude states are partitioned as

$$\mathbf{x}_1 \triangleq C_1\mathbf{x}, \quad \mathbf{x}_2 \triangleq C_2\mathbf{x} \tag{6}$$

where C_1, C_2 are output matrices for extracting $\mathbf{x}_1$ and $\mathbf{x}_2$ from the state vector $\mathbf{x}$, respectively. Differentiating (2) yields:

$$\begin{aligned}\ddot{\mathbf{x}}_1 &= \dot{\Phi}(\mathbf{x}_1)\mathbf{x}_2 + \Phi(\mathbf{x}_1)C_2\left(A\mathbf{x} + B_a\mathbf{u}_a + B_wX_{col} + d\right)\\ &= \dot{\Phi}(\mathbf{x}_1)\mathbf{x}_2 + \bar{A}_a\mathbf{y} + \Phi(\mathbf{x}_1)C_2B_wX_{col} + \bar{B}_a\left(\mathbf{u}_a - \mathbf{u}_{a_0}\right) + \delta_a\end{aligned} \tag{7}$$

where $\mathbf{u}_a \triangleq [X_{lon}, X_{lat}, X_{tail}]^T$, $\bar{A}_a \triangleq \Phi(\mathbf{x}_1)C_2AC^{\dagger}$, $\bar{B}_a \triangleq \Phi(\mathbf{x}_1)C_2B_a$, $\delta_a \triangleq \Phi(\mathbf{x}_1)C_2\left(d + B_a\mathbf{u}_{a_0}\right)$, the subscript a denotes attitude, $\mathbf{u}_{a_0}$ is trim control input at hover condition, B_a is a submatrix of the matrix B corresponding to the control input $\mathbf{u}_a$, B_w is a submatrix of the matrix B corresponding to the control input X_{col}, and $C^{\dagger}(\in \Re^{11\times 9})$ is the pseudo inverse of C which is composed of the identity matrix($\in \Re^{9\times 9}$) and zero matrix($\in \Re^{2\times 9}$). The term $\dot{\Phi}(\mathbf{x}_1)$ is computed using (2) and X_{col} is designed in the altitude control system. Therefore, all the elements in (7) are known except for the uncertainty δ_a.
The remaining concern is that $\bar{B}_a$ is a matrix of rank 1 because while the control input X_{tail} directly affects the dynamics on the yaw rate (r), the dynamics on the pitch rate (q) and roll rate (p) are not directly connected to the longitudinal and lateral cyclic sticks X_{lon} and X_{lat}. As shown in [3], X_{lon} and X_{lat} determine just the motion of the flapping angles a_1, b_1, and the dynamics on the pitch rate (q) and roll rate (p) are determined by a_1, b_1 and other states only. Since the inverse of $\bar{B}_a$ is required for the LDI, $\bar{B}_a$ is rearranged such that the control effectiveness for a_1 and b_1 dynamics with respect to X_{lon}, X_{lat} directly affects q and p. It is achieved by substituting the steady state flapping angles into q and p dynamics, which is obtained by setting the time derivative $\dot{a}_1, \dot{b}_1$ to zero in the flapping dynamics [3]. Then, it is possible to invert the matrix $\bar{B}_a$.

Dynamic equation for the altitude control system

While the longitudinal and lateral cyclic sticks affect just the motion of the flapping angles a_1 and b_1, the dynamics of the vertical velocity w is directly affected by the main rotor collective stick input X_{col} [3]. Thus, the LDI method can be directly applied to the design of the altitude control system, unlike the attitude control system.
To design the LDI-based altitude controller, the following differential equation is developed using (3) [1]:

$$\dot{z}^S = -u\sin\theta + v\sin\phi\cos\theta + w\cos\phi\cos\theta. \tag{8}$$

The time derivative of (8) can be written as

$$\ddot{z}^S = f_w + \dot{w}\cos\phi\cos\theta + \delta \tag{9}$$

where $\delta \triangleq -\dot{u}\sin\theta + \dot{v}\sin\phi\cos\theta$, $f_w \triangleq -u\dot{\theta}\cos\theta + v\dot{\phi}\cos\phi\cos\theta - v\dot{\theta}\sin\phi\sin\theta - w\dot{\phi}\sin\phi\cos\theta - w\dot{\theta}\cos\phi\sin\theta$.
Then, (9) is rearranged as

$$\begin{aligned}\ddot{z}^S &= f_w + C_w\Big(A\mathbf{x} + B_w X_{col} + B_a\mathbf{u}_a + d\Big)\cos\phi\cos\theta + \delta \\ &= f_w + \Big(\bar{A}_w\mathbf{y} + \bar{B}_w\big(X_{col} - X_{col_0}\big)\Big)\cos\phi\cos\theta + \delta_w\end{aligned} \tag{10}$$

where $\bar{A}_w \triangleq C_w A C^{\dagger}$, $\bar{B}_w \triangleq C_w B_w$, $\delta_w \triangleq C_w\Big(d + B_w X_{col_0}\Big)\cos\phi\cos\theta + \delta$, C_w is a output matrix for extracting w from $\mathbf{x}$, and X_{col_0} is trim control input at hover condition. Since $C_w B_a$ becomes a zero row vector [3], the effect with the control input $\mathbf{u}_a$ is removed. As pointed out previously, the control effectiveness $\bar{B}_w$ of X_{col} is a real constant value because X_{col} directly affects the dynamics on the vertical velocity w. Thus, the LDI method can be directly utilized for the altitude control system with $\bar{B}_w$. To design the attitude and altitude control systems with the RISE feedback, we need the following assumption on the uncertainties δ_a, δ_w in (7) and (10) :
Assumption 1 *The nonlinear uncertainties δ_a, δ_w are the functions of $\mathbf{x}_1, \dot{\mathbf{x}}_1$ and $z^S, \dot{z}^S$, respectively, i.e., $\delta_a \triangleq \delta_a(\mathbf{x}_1, \dot{\mathbf{x}}_1)$, $\delta_w \triangleq \delta_w(z^S, \dot{z}^S)$. Then, if $\mathbf{x}_1$, $\dot{\mathbf{x}}_1$, z^S and $\dot{z}^S \in \mathscr{L}_\infty$, δ_a and δ_w are bounded, and the first and second partial derivatives of δ_a (with respect to $\mathbf{x}_1$ and $\dot{\mathbf{x}}_1$) and δ_w (with respect to z^S and $\dot{z}^S$) exist and are bounded.*
In (7) and (10), δ_a is composed of $\mathbf{x}_1$, constant trim states and high order terms, while δ_w is mainly dominated by constant trim states and high order terms under small pitch and roll angles. This means that they are deviation from the specific trim point, and their magnitude is very small comparing to the known terms in (7) and (10). Therefore, δ_a and δ_w are dominated by Euler angle, their rates and vertical position, its velocity, respectively, because they are just small uncertainties generated in the motion of the rotational and vertical acceleration. Moreover, the fact that any planar translational motion of the RUAV is obtained through rolling or pitching the aircraft [3], and the control system of the RUAV can be properly designed by decoupling the vertical and translational motions [4] makes the above assumption reasonable.

LDI-BASED NN ADAPTIVE CONTROL FOR THE RUAV WITH RISE FEEDBACK

This section presents the LDI-based NN adaptive control for the RUAV with the RISE feedback. The objective of the proposed control system is to follow the given position $(x^S_{ref}, y^S_{ref}, z^S_{ref})$, ve-

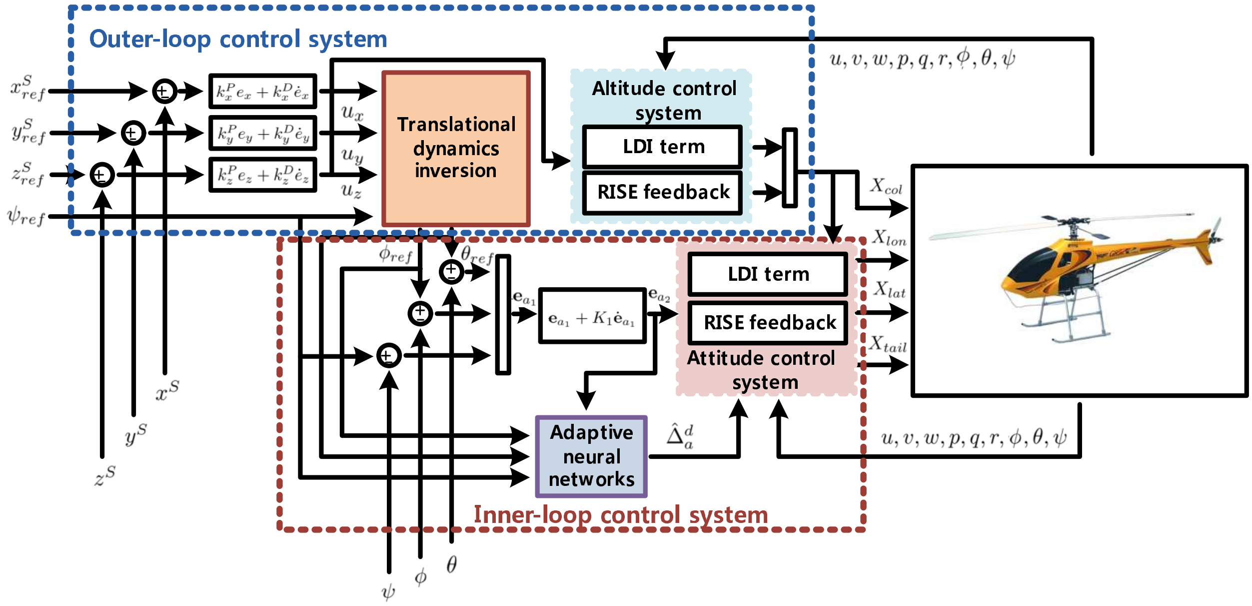

Figure 1. The overall structure of the LDI-based adaptive control system for the RUAV with the RISE feedback.

locity $(\dot{x}^S_{ref}, \dot{y}^S_{ref}, \dot{z}^S_{ref})$ and heading commands (ψ_{ref}). The control system is divided into outer-loop and inner-loop control systems. In the outer-loop control system, the reference attitudes ϕ_{ref} and θ_{ref} are generated corresponding to the given position, velocity and heading commands [8], and the altitude controller is designed using the LDI-based RISE feedback control. Then, the LDI-based NN adaptive control with the RISE feedback for the inner-loop system is designed to track ϕ_{ref}, θ_{ref}, and ψ_{ref}.

NUMERICAL SIMULATIONS

In this section, numerical simulation is performed using the nonlinear RUAV model to validate the performance of the proposed control system.
The objective of the numerical simulation is to perform an automatic landing maneuver, where the scenario is given in Fig. 2. At the first step, the heading of the RUAV is controlled from 0 deg to 45 deg, which is determined by the initial position $(0,0,40)$ and reference position $(20,20,40)$. In the second step, the RUAV flies from $(0,0,40)$ to $(20,20,20)$. Then, the RUAV vertically descends to 2 m and touches down. See the attached journal or conference paper.

CONCLUSIONS

An LDI-based NN adaptive controller is developed with the RISE feedback for autonomous flight of a RUAV. While the altitude controller in the outer-loop control system is designed by the LDI-based RISE feedback control, the inner-loop attitude control system requires the NN feedforward term to reduce the load of the RISE feedback for eliminating the uncertainty of the flapping angle dynamics. By utilizing the RISE feedback, semi-global asymptotic tracking of the NN-based adaptive control for the RUAV has been enabled with continuous control. Moreover, an adaptive rule for permitting zero initial values of the weight matrices of the NN estimator has been designed by adding the NN feedforward term. Finally, numerical simulation

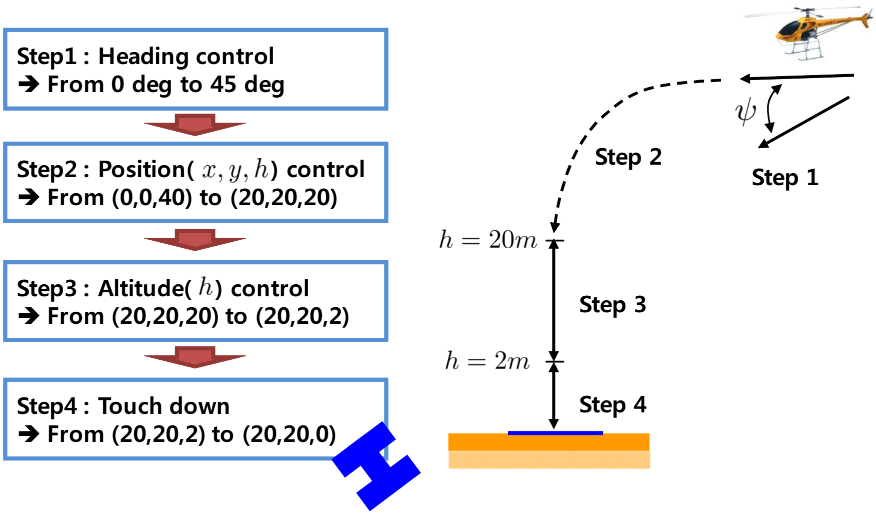

Figure 2. Automatic landing scenario.

for the automatic landing of the RUAV has been performed to validate the effectiveness of the proposed algorithm.

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