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Flight Control of a Multicopter with a Transformation Mechanism using Nonlinear Model Predictive Control

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Abstract: With the rapid aging of social infrastructure, the inspection and maintenance of bridges has become an urgent issue. As the number of bridges increases, the demand for new technologies such as multicopters is growing due to manpower shortages and reduced work efficiency. However, conventional multicopters struggle to maintain stable flight in confined spaces. To address this challenge, we are developing a multicopter capable of horizontal movement with minimal changes in attitude, equipped with multiple transformation mechanisms to adapt to infrastructure inspection tasks. In this paper, we present simulation results using nonlinear model predictive control (NMPC) and demonstrate that the proposed aircraft can maintain stable flight during transformation.

Keywords: Multicopter, Infrastructure inspection, Variable mechanism

1. INTRODUCTION

In recent years, the aging of infrastructure has increased the demand for more efficient bridge inspection methods [1]. Traditional inspections rely on visual assessments by workers, which involve safety risks associated with working at heights, heavy workloads, and high costs. To address these challenges, research has increasingly focused on automating inspection tasks using multicopters. However, conventional multicopters face difficulties in maintaining a stable attitude during horizontal movement, as they must tilt the entire body to generate lateral thrust [2]. This not only affects flight stability but also makes it difficult to conduct detailed inspections in close proximity to structures. To overcome these limitations, various specialized drones have been developed, including those that adhere to bridge surfaces for inspection, drones equipped with protective shells to avoid external collisions, and drones with manipulators for direct contact-based tasks [3-5].

This study proposes a hexacopter equipped with a telescopic rotating arm mechanism to enable more versatile infrastructure inspections. The arm's tilt function allows for horizontal movement with minimal changes in the drone's overall posture, while the telescopic feature enables close-range inspection of structures. Although methods using tilt mechanisms to enhance flight stability during horizontal movement have been previously proposed, conventional approaches tilt all rotors to generate horizontal thrust. This reduces the total available thrust and results in a lower payload capacity, making it difficult to mount multiple measurement devices [6]. Consequently, such limitations restrict their practical use in infrastructure inspection.

This paper presents the design of a multicopter with a transformation mechanism featuring telescopic and rotating arms, as shown in Fig. 1. To achieve stable flight with the proposed multicopter, nonlinear model predictive control (NMPC) is applied. The effectiveness of the proposed control method is evaluated through simulations.

Fig. 1 3D CAD model of proposed multicopter

2. MULTICOPTER CONCEPT

2.1. Design Guidelines

The proposed multicopter is based on a hexacopter configuration and incorporates a tilt and telescopic mechanism on two diagonally aligned arms. This allows for wide-area visual inspections while maintaining the multicopter's horizontal orientation.

2.2. Tilt Mechanism

By tilting the propellers from the horizontal to the vertical direction, thrust can be directed horizontally, enabling lateral movement without tilting the fuselage.

The tilt mechanism uses a Dynamixel MX-64AR servo motor to control the tilt angle of the propeller. Fig. 2 shows an image of the tilt mechanism. Connecting the two diagonal arms with a single pipe ensures perfect synchronization of the rotor and propeller tilt angle.Since a tilt mechanism is not required in both arms, the overall

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weight and size of the multicopter are reduced.

The incorporation of the above design improves tolerance to external disturbances, and in addition to horizontal movement without tilting the fuselage, it reduces fluctuations in the center of gravity and rotor thrust imbalance that are problems with conventional designs, enabling stable attitude control under disturbing environments.

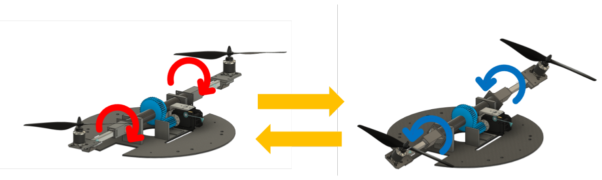

Fig. 2 Tilt mechanism operation diagram

2.3. Telescopic Mechanism

The telescopic arm tip allows the camera attached to the tip to move closer to the inspection area during visual inspections, thus expanding the inspection area in tight spaces and near structures. The telescopic mechanism uses a linear actuator that allows the arm tip to extend and retract up to 140mm as shown in Fig. 3. This makes it possible to inspect a large area without moving the machine, even when inspecting in close proximity to bridge structures.

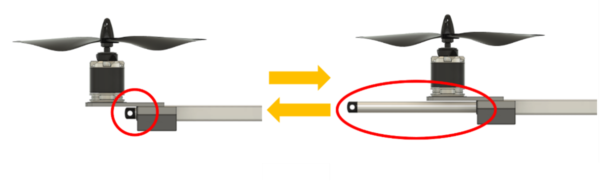

Fig. 3 Telescopic mechanism operation diagram

3. SYSTEM MODELING

This section describes the flight dynamics modeling of the proposed tilt rotor hexacopter. In this study, we do not consider the telescopic arm mechanism from the model to focus on the main flight dynamics. The proposed multicopter operates in two flight modes: Normal flight mode, in which it flies as a conventional hexacopter without using the tilt mechanism, and tilt flight mode, in which the two rotors are tilted to generate horizontal thrust and maintain a stable attitude. The modeling of each flight mode is described separately in the following subsections.

3.1. Normal flight mode

The hexacopter has six rotors, with rotors 3 and 6 equipped with tilt mechanisms. In the normal flight mode, the proposed hexacopter flies as a conventional multirotor without utilizing the tilt mechanisms. The state vector x consists of the position (X_r, Y_r, Z_r), the Euler angles (ϕ, θ, ψ), and their respective derivatives. The tilt angle α remains constant during this mode, i.e., $\alpha = 0$. The coordinate systems used in the modeling are shown in Fig. 4, where the world frame (X, Y, Z) is fixed to the ground and the body-fixed frame (X_r, Y_r, Z_r) is attached to the hexacopter. The orientation between these frames is defined by the ZYX Euler angles. The equations of motion for this mode follow standard multirotor modeling approaches and can be found in references [7-9].

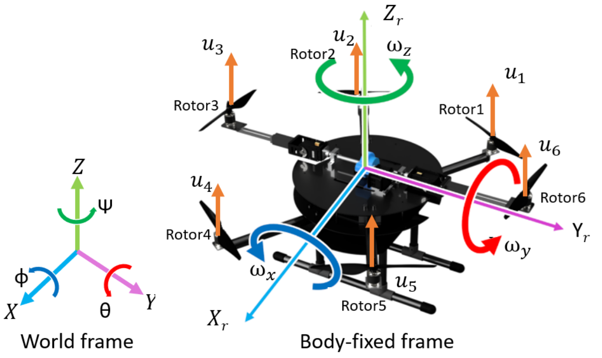

Fig. 4 Coordinate Systems

3.2. Tilt flight mode

In the tilt flight mode, rotors 3 and 6 are tilted by an angle α to generate horizontal thrust while maintaining a stable attitude. The tilt angle α is treated as a control input and varies over time.

The state vector $\boldsymbol{x}$ consists of the position (X_r, Y_r, Z_r), the Euler angles (ϕ, θ, ψ) representing the roll, pitch, and yaw angles, their respective derivatives, and the tilt angle α.

The orientation of the body is represented by the rotation matrix $\mathbf{R}$, constructed based on the ZYX Euler angles:

$$\begin{aligned}\mathbf{R} &= \mathbf{R_z}(\psi)\mathbf{R_y}(\theta)\mathbf{R_x}(\phi)\\ &= \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{pmatrix}\end{aligned} \quad (1)$$

where c and s denote $\cos(\cdot)$ and $\sin(\cdot)$, respectively.

The relationship between the angular velocity in the body frame $\boldsymbol{\omega}$ and the time derivatives of the Euler angles is given by:

$$\boldsymbol{\omega} = \mathbf{W}\dot{\eta} = \mathbf{W}\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix}, \quad (2)$$

where $\mathbf{W}$ is the transformation matrix defined as:

$$\mathbf{W} = \begin{pmatrix} 1 & 0 & -s_\theta \\ 0 & c_\phi & c_\theta s_\psi \\ 0 & -s_\phi & c_\theta c_\phi \end{pmatrix}. \quad (3)$$

An equivalent inertia matrix $\mathbf{J}_\eta$ is defined in terms of the Euler angle derivatives as:

$$\mathbf{J}_\eta = \mathbf{W^T I W}, \quad (4)$$

where $\mathbf{I}$ is the body-frame inertia matrix assumed to be diagonal:

$$\mathbf{I} = \begin{pmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{pmatrix}. \tag{5}$$

The Coriolis matrix $\mathbf{C}$ is defined by:

$$\mathbf{C}(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}}) = \frac{\mathbf{dJ}_\eta}{\mathbf{dt}} - \frac{\mathbf{1}}{\mathbf{2}} \frac{\partial \mathbf{J}_\eta}{\partial \boldsymbol{\eta}} \left(\dot{\boldsymbol{\eta}}^{\mathbf{T}} \dot{\boldsymbol{\eta}} \right), \tag{6}$$

where $\boldsymbol{\eta} = (\phi, \theta, \psi)^T$ is the orientation vector.

The rotor positions relative to the body-fixed frame are defined by the matrix $\mathbf{T}$ as:

$$\mathbf{T} = \begin{pmatrix} -\frac{\sqrt{3}}{2}l & -\frac{\sqrt{3}}{2}l & 0 & \frac{\sqrt{3}}{2}l & \frac{\sqrt{3}}{2}l & 0 \\ \frac{1}{2}l & -\frac{1}{2}l & -l & -\frac{1}{2}l & \frac{1}{2}l & l \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \tag{7}$$

where l is the distance from the center of mass to each rotor.

The thrust vectors generated by each rotor are expressed uniformly as:

$$\mathbf{T_i} = \begin{pmatrix} k u_i s_{\alpha i} \\ 0 \\ k u_i c_{\alpha i} \end{pmatrix}, \quad (\mathbf{i} = \mathbf{1}, \ldots, \mathbf{6}), \tag{8}$$

where α_i denotes the tilt angle of the i-th rotor. For rotors 1, 2, 4, and 5, $\alpha_i = 0$, and for rotors 3 and 6, $\alpha_i = \alpha$, and k is the thrust coefficient.

The total thrust vector $\mathbf{T}_{\text{body}}$ is obtained by:

$$\mathbf{T}_{\text{body}} = \sum_{\mathbf{i}=\mathbf{1}}^{\mathbf{6}} \mathbf{T_i}. \tag{9}$$

The torque vector $\boldsymbol{\tau}_\beta$ is calculated by:

$$\boldsymbol{\tau}_\beta = \sum_{i=1}^{6} r_i \times \mathbf{T_i} + \begin{pmatrix} 0 \\ 0 \\ \tau_\psi \end{pmatrix}, \tag{10}$$

where $\mathbf{r_i}$ are the rotor positions from the matrix $\mathbf{T}$, and τ_ψ is the yaw torque generated by the anti-torque effects of the rotors.

The translational and rotational dynamics of the hexacopter in the tilt flight mode are described by:

$$\begin{aligned} \dot{\boldsymbol{p}} &= \boldsymbol{v}, && (11) \\ \dot{\boldsymbol{v}} &= -g \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + \frac{1}{m} \mathbf{R} \boldsymbol{T}_{\text{body}}, && (12) \\ \dot{\boldsymbol{\omega}} &= \mathbf{J}_\eta{}^{\mathbf{-1}} (\boldsymbol{\tau}_\beta - \mathbf{C} \boldsymbol{\omega}), && (13) \\ \dot{\alpha} &= \frac{1}{\tau_\alpha} (\alpha_{\text{mv}} - \alpha), && (14) \end{aligned}$$

where α_{mv} is the control input for the tilt angle, and τ_α is the tilt actuation time constant.

4. CONTROL METHODS

This study employs NMPC to stabilize the position, attitude, and tilt angle of the proposed hexacopter in both normal and tilt flight modes. The controller is implemented using the Model Predictive Control Toolbox in MATLAB, based on a discrete-time nonlinear model derived from the continuous-time equations of motion and discretized using explicit Euler integration. Mode switching is performed according to the timing of the reference trajectory. The overall control structure is illustrated in Fig. 5.

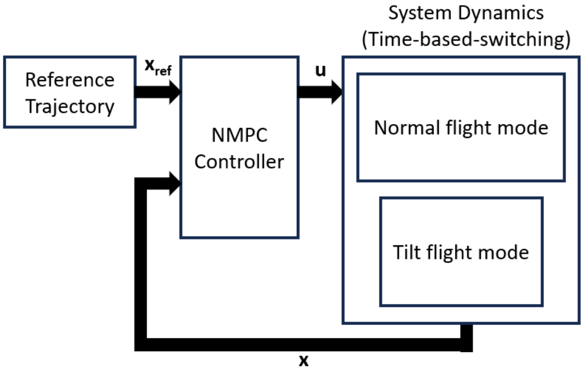

Fig. 5 Block Diagram

The state vector $\boldsymbol{x}$ and the control inputs vector $\boldsymbol{u}$ are defined as:

$$\begin{aligned} \boldsymbol{x} &= \begin{pmatrix} X_r & Y_r & Z_r & \phi & \theta & \psi & \\ \dot{X}_r & \dot{Y}_r & \dot{Z}_r & \dot{\phi} & \dot{\theta} & \dot{\psi} & \alpha \end{pmatrix}^T, && (15) \\ \boldsymbol{u} &= \begin{pmatrix} u_1 & u_2 & u_3 & u_4 & u_5 & u_6 & \alpha_{\text{mv}} \end{pmatrix}^T. && (16) \end{aligned}$$

The controller minimizes the following cost function:

$$J = \sum_{k=0}^{N_p} \Big(\|\boldsymbol{x}(k) - \boldsymbol{x}_{\text{ref}}(k)\|_Q^2 + \|\boldsymbol{u}(k) - \boldsymbol{u}_{\text{ref}}(k)\|_R^2 + \|\Delta \boldsymbol{u}(k)\|_S^2 \Big) \tag{17}$$

where N_p is the prediction horizon, Q and R are positive definite weighting matrices.

To improve computational efficiency, the Symbolic Math Toolbox in MATLAB is used to explicitly provide an analytic Jacobi matrix of the system dynamics with respect to states and inputs. This approach reduces the computational burden.

The optimization problem at each sampling step is solved using a sequential quadratic programming (SQP) method, which approximates the nonlinear problem by a series of quadratic subproblems.

5. SIMULATION RESULTS

5.1. Simulation Conditions

The simulation was conducted for 45 seconds with a controller updated at a sampling time of $T_s = 0.05$ s.

The prediction and control horizons were set to $N_p = 20$ and $N_c = 5$, respectively.

Mode switching was performed according to a fixed time schedule to evaluate performance in each flight mode. The flight sequence was designed as follows:

- 0–10 s: Vertical takeoff to a height of 5 m.
- 10–20 s: Horizontal movement in the y-direction (normal mode).
- 20–30 s: Horizontal movement in the x-direction (tilt mode).
- 30–35 s: Reset tilt angle to 0°.
- 35–45 s: Descent and landing.

The physical parameters used in the simulation are as follows: the mass of the hexarotor is 3.8 kg; the moments of inertia are 0.1076 kg·m² about the x-axis, 0.1338 kg·m² about the y-axis, and 0.2084 kg·m² about the z-axis; and the arm length is 0.4 m.

5.2. Simulation Results

The simulation results of the NMPC applied to the proposed multicopter are shown in Fig. 6. The flight was divided into five phases, and the control performance of each phase was evaluated.

From 0 to 10 seconds, the multicopter took off vertically in normal mode and climbed to an altitude of 5 m.

From 10 to 20 seconds, horizontal movement in the y direction was achieved by changing the pitch angle without using the tilt mechanism.

From 20 to 30 seconds, the multicopter switched to tilt mode, and the tilt angles of rotors 3 and 6 were changed while increasing their rotation speed to generate thrust in the x direction. This enabled the multicopter to move stably horizontally without major changes in attitude.

From 30 to 35 seconds, the tilt angle smooths back to 0 degrees and the multicopter returns to normal mode.

From 35 to 45 seconds, the multicopter performed a vertical descent and landed safely.

Overall, the proposed NMPC was confirmed to provide high tracking ability to the target trajectory and stable control input in both normal mode and tilt mode, and the tilt mechanism in particular enabled efficient horizontal movement with reduced attitude change.

5.3. Conclusion

In this paper, we propose a hexacopter equipped with a deformation mechanism that enables stable horizontal movement during infrastructure inspections. The NMPC was designed based on a nonlinear model and verified through simulation, demonstrating good tracking performance in both normal flight mode and tilt flight mode. As future work, although Euler angles are used in the simulation model, a quaternion-based controller will be implemented in Python using CasADi and tested on a Raspberry Pi 4B to evaluate its real-time feasibility in preparation for future flight experiments. Additionally, we plan to conduct flight tests using a prototype to further validate the proposed approach.

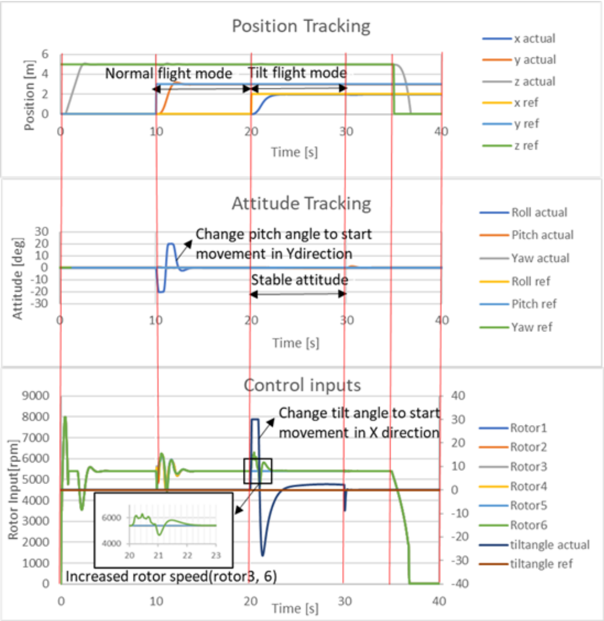

Fig. 6 Tracking performance and control inputs of the tilt-rotor hexacopter under NMPC

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