Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 55(10) (2024) 245-248
DOI: 10.22060/mej.2024.21904.7538

Reinforcement learning-based controller design for a proposed octorotor with tilt-arm angles

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ABSTRACT: The maneuverability of a quadrotor or octorotor UAV is limited in the standard configuration because the force vectors of the propellers are parallel and only have four active degrees of freedom. Therefore, they lack the controllability of six independent degrees of freedom. This study designs a novel configuration for an octorotor capable of hovering with roll or pitch angles in a specific position, contrary to UAVs with a standard configuration that can only hover in a horizontal position. In other words, in this octorotor, orientation tracking is also added to the octorotor's targets in addition to position tracking. The proposed model can be controlled by altering the velocity of the eight rotors and the tilt angle of the four arms. Such alterations in velocity and tilt angle are such that they can provide the aerial vehicle with the most optimum maneuverability. After deriving the proposed dynamic octorotor model, a controller is proposed using neural networks and reinforcement learning, capable of controlling the proposed octorotor with six independent degrees of freedom. Finally, trajectory tracking, octorotor position, and controller robustness to possible motor malfunctions are examined, and numerical simulation results are provided.

Review History:

Received: Nov. 02, 2022
Revised: Oct. 18, 2023
Accepted: Jan. 08, 2024
Available Online: Jan. 21, 2024

Keywords:

octorotor with tilt-arm angle
reinforcement learning
trajectory tracking
independent degrees of freedom
motor malfunctions

1- Introduction

most of the studies conducted on multirotors can be divided into two parts: (1) proposing a novel configuration for UAV's rotors and (2) designing a controller consistent with its expected performance. Below is a brief history of these studies.

Tadokoro et al. (2017) analyzed the maneuverability of UAVs concerning the tilt angles and configuration of a fully actuated hexa-rotor's propellers [1]. Zhu et al. (2020) proposed a new octocopter configuration based on preliminary aerodynamic considerations to rectify the drawbacks of conventional octocopters with monolayer and coaxial configurations. This study analyzed five different octorotor UAV models with three different configurations, including a conventional configuration, a coaxial configuration, and a new configuration, to achieve a precise aerodynamic analysis [2]. Quintana et al. (2018) presented a methodology for designing a hexa-rotor with disturbance rejection capability using tilted propellers. This method proposes using the robustness index as a measure of the ability to reject external disturbances and the energy index as a measure of the energy consumed by the hovering hexa-rotor[3]. Kase and Oya (2020) designed and implemented an adaptive trajectory tracking control scheme for hexacopters with wind disturbances [4]. Pi et al. (2020) proposed a quadrotor control algorithm using NNs with the model-free RL method. This study examines quadrotor training in two hovering and tracking modes of the proposed trajectory. Then, training is also implemented on a real-world quadrotor[5].

This study seeks to construct a novel rotor configuration for an octorotor and design a robust RL-based controller to create the capability of controlling the position and angle of the octorotor UAV separately.

2- Proposed octorotor configuration

This study considers the octorotor configuration (Fig. 1) in a way that its four rotors are positioned like a conventional octorotor, and the other four rotors are placed on four arms with tilt angles to achieve 6-DoF independently. All four angular arms are positioned so that one side is placed on the octorotor's CoM and has a tilt angle with the plane of the four fixed arms. Based on this configuration, the rotation axis of the four rotors positioned in the same plane is parallel, and the axis of the other four rotors is in different directions. The angles of the two facing arms are assumed to be the same to keep the CoM constant while tilting the angles. It is expected that by changing the rotor velocity and tilting the arm angles, it will be possible to create independent 6-DoF motion.

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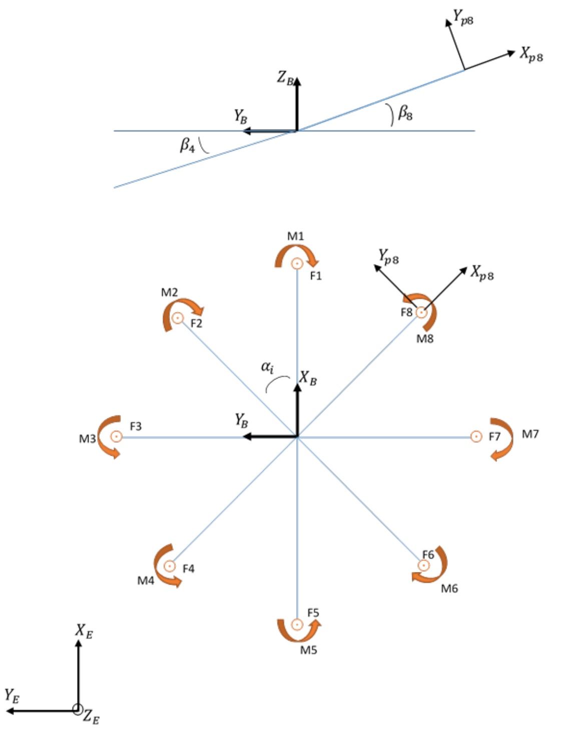


Fig. 1. Rotor configuration, thrust, and torque generated by octorotor rotors and reference frame display

3- The proposed controller configuration

This study aims to design an NN controller using the RL method to independently control the octorotor UAV in 6-DoF. Therefore, the NN training phase uses the following general equations as six independent dynamic equations to consider the training environment and six networks are trained separately to monitor them.

$$m\ddot{X} = \begin{bmatrix} F_x & F_y & F_z \end{bmatrix} \tag{1}$$

$$I\dot{\omega} + \omega \times I\omega = \begin{bmatrix} \tau_x & \tau_y & \tau_z \end{bmatrix} \tag{2}$$

In these equations, F_x , F_y and F_z denote the required force in the x, y, and z directions to achieve the desired position, and τ_x , τ_y and τ_z indicate the required torques around the x, y, and z axes to achieve the desired position.

One actor network and two critic networks are required for each degree of freedom to design and train the NNs using the TD3 algorithm. In network training, it is assumed that if an octorotor UAV is mounted on any position with any velocity, it is directed towards zero, i.e., positioned at the origin of coordinates, and remains to hover at that location. During training, the position within a radius of 2 meters and the position within a radius of 60 degrees are randomly selected. It is noteworthy that this learning will also create a robust controller in the octorotor UAV because external factors cause it to deviate from the target trajectory and the trained network returns to the target trajectory from any position with any velocity. The reward function in network training is also considered to achieve the objective with the least control effort and move towards the target. For instance, for training along the x direction, the reward function is defined as follows:

$$r = -\rho(x - x_d)^2 - (1-\rho)u^2 \tag{3}$$

where $x_d = 0$ represents the target position in the x direction, u denotes the control effort in the x direction, and ρ indicates the influence coefficient.

It is also worth noting that there is no need to retrain the network for a target position other than the origin of the coordinates. The octorotor UAV can be directed towards the desired targets only by making a variable change in the problem dynamics.

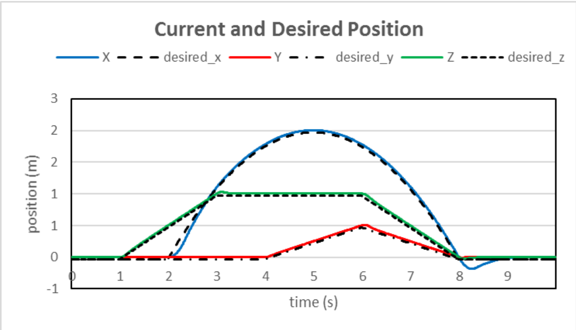
4- Results and Discussion

As mentioned earlier, in network training, it is assumed that if an octorotor UAV is mounted on any position with any velocity, it is directed towards zero, i.e., positioned at the origin of coordinates, and remains to hover at that location. Each network training episode is performed in four seconds, which includes 400 time steps. This study performed the full network training (for robustness in hovering mode) within less than 200-thousand-time steps for each degree of freedom. In contrast, other studies used RL for quadrotor control. For example, Hwangbo et al. (2017) [٦] needed about 2150 million time steps and Pi et al. (2020) [5] needed about 10 million time steps to achieve proper robustness in hovering mode. The proposed model and independent degrees of freedom have made it possible to reduce network dimensions compared to previous studies and significantly minimize training time, which is one of the advantages of the present study.

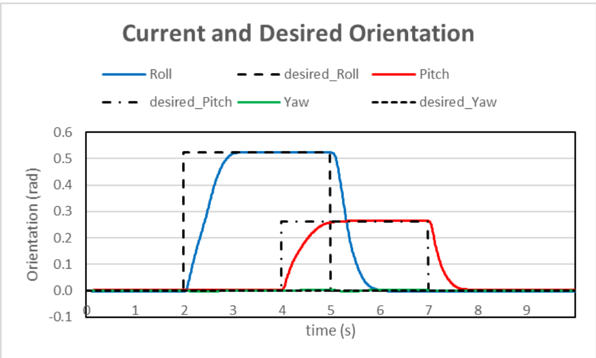
The graphs drawn in Fig. 2 represent the proposed octorotor capability in the independent control of 6-DoF in the trajectories and orientations defined in Table 3 within ten seconds, demonstrating the capabilities of the configuration and controller proposed for the octorotor. The maximum deviation in Fig. 2 (a) corresponds to the deviation of the octorotor UAV in the x-direction from the trajectory determined within eight seconds, which is due to a sudden change in the velocity. The drawn graph indicates the controller's capability to direct the UAV toward the predetermined target trajectory quickly.

5- Conclusions

This study proposed a novel configuration for an octorotor. The octorotor's four propellers were positioned like a conventional octorotor, and the other four propellers were mounted on four arms with a tilt angle. One of the capabilities



(a)



(b)

Fig. 2. (a) Trajectory tracking and (b) orientation graphs of the octorotor in independent 6-DoF

of this configuration is to add orientation tracking to UAV targets and position tracking. A controller based on NNs and RL was also designed for this UAV, which is robust to one or more motor malfunctions and the octorotor controllability in independent six independent degrees of freedom. Due to the independent degrees of freedom, the network dimensions considered for this controller were smaller than those of similar studies. The training time was significantly decreased without reducing the capabilities and precision of the designed controller.

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HOW TO CITE THIS ARTICLE

D. Sharifi, M. Irani Rahaghi, K. Torabi, H. Shahbazi, Reinforcement learning-based controller design for a proposed octorotor with tilt-arm angles, Amirkabir J. Mech Eng., 55(10) (2024) 245-248.

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