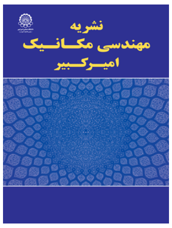

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(12) (2021) 813-816
DOI: 10.22060/mej.2019.15994.6245

# Cooperative Path Planning for Leader – Follower Formation of Multiple Quadrotors Based on the Minimum Energy Consumption for Load Transportation

H. Kiaee, H. Heidari*

Mechanical Engineering, Malayer University, Malayer, Iran.

**ABSTRACT:** Today, unmanned aerial vehicles are highly considered for both military and commercial fields due to low cost, high maneuverability, and good survival. One of the most important design challenges of multi-unmanned aerial vehicle systems is mission planning. In the broad class of unmanned aerial vehicles, Quadrotor is an important member. The capabilities of this vehicle in load transportation has attracted the attention of many research groups around the world. In this paper, path planning based on the minimum energy consumption is studied for load transportation. The purpose of the present study is to investigate the effect of proposed cost function in order to obtain optimal path for transporting loads based on reducing the energy consumption of quadrotors. The results indicate the 35.29% energy consumption of multi unmanned aerial vehicle compared to the energy consumption of an individual quadrotor. This also leads to an increase in load carrying capacity. On the other hand, the leader- follower formation is preserved until the end of the path based on the defined relationships. The simulation results illustrate the power and efficiency of the method to overcome the high nonlinearity nature of the problem such as path optimization of multi-rotor helicopters.

**Review History:**

Received: 13 Mar. 2019
Revised: 10 May. 2019
Accepted: 16 Jun. 2019
Available Online: 14 Jul. 2019

**Keywords:**

Path planning
Cooperative robots
Quadrotor
Optimal control
Load transportation

## 1- Introduction

Unmanned Aerial Vehicles (UAVs), which have high maneuverability, are widely used as platforms to work in various environments. When defining a mission, path planning is the crucial element of whole system. Generally, path planning targets at generating a real-time global path to the target, avoiding collisions with obstacles, and optimizing a given cost function under dynamic constraints [1].

Among the unmanned aerial vehicles, rotorcraft is more popular because of their high maneuverability and air hovering properties, as well as vertical ups and downsides. In the meantime, quadrotors are more important because of their simple structure. Because without the need for sophisticated mechanical joints, it is possible to make any desired movement through the rotor's changeover [2].

On the other hand, the planning of the optimal aerial robot path has been considered by many researchers among the two points. Hehn et al. [3] presented an algorithm suitable for designing a quadrotor robot path. Cetin and Yilmaz [4] proposed a parallel algorithm that simultaneously avoids obstacles in addition to the planning of the path. In this regard, various algorithms [5] including A*, genetics, particle swarm optimization and search methods have been proposed to find optimal path for different environmental conditions, but the proposed method in this paper is analytic and accurate. Formation control has been one of the most important issues in cooperative control for multi robot systems, which is defined as a coordination of a group of robots to get into and to maintain a formation with a certain shape.

In the leader-follower approach to controlling the flight path of the group, it is the responsibility of a member that is chosen as the leader and the other members follow the leader. A member may also be the leader of other members, while following. The formation of the movement is determined by the leader and its control is simple and has been widely implemented in the formation of a flight consisting of UAVs. This method was first developed by Dos et al. [6].

The main idea of this research is to define the cost function based on the voltage and current equations of the quadrotor motor, as well as to minimize the relative speed of the members and to stabilize and maintain the distance between the members, together with the leader's tracking. In this research, with the help of dynamic equations of quadrotor, dynamic equations of suspended load for load transportation, dynamic equations of cooperative quadrotor formation, and consideration of the optimal control problem for system path planning. At the beginning of this study, a path for a quadrotor is planned to optimize the energy system with suspended load. In the next step, the same conditions are considered for the three quadrotors, which, with the formation of leader follower, have carried suspended load.

## 2- Methodology

Cooperative quadrotor and load system are presented as a transient-rotary dynamic model. Initially, as shown in Fig. 1, the load is considered as the mass of a point suspended by a quadrotor of $n \geq 1$. The independent degrees of freedom of this system are the loading position $xL \in \mathbb{R}^3$, the suspended cable mode, $q_i \in S2$, and the quadrotor mode $R_i \in SO(3)$. By defining

*Corresponding author's email: hr.heidari@malayeru.ac.ir

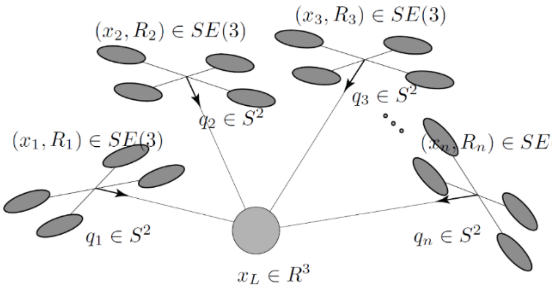

**Fig. 1. The rolling element bearings accelerated-life experiments test-rig**

the length of the i-th cable as $L_i$, according to the geometry of connecting the load to the quadrotor, the quadrotor position $xL \in \square^3$ is expressed.

The quadrotor motion equations with suspended load are expressed as follows:

$$\begin{aligned}
\ddot{\phi} &= \frac{I_{yy} - I_{zz}}{I_{xx}} \dot{\theta}\dot{\psi} - \frac{J_R}{I_{xx}} \dot{\theta} \Omega_R + \frac{l}{I_{xx}} u_2 \\
\ddot{\theta} &= \frac{I_{zz} - I_{xx}}{I_{yy}} \dot{\phi}\dot{\psi} + \frac{J_R}{I_{yy}} \dot{\phi} \Omega_R + \frac{l}{I_{yy}} u_3 \\
\ddot{\psi} &= \frac{I_{xx} - I_{yy}}{I_{zz}} \dot{\phi}\dot{\theta} + \frac{1}{I_{zz}} u_4 \\
\ddot{x} &= \frac{F_x}{n_Q m_Q} + (\sin\phi \sin\psi + \cos\phi \cos\psi \sin\theta) \frac{u_1}{m_Q} \\
\ddot{y} &= \frac{F_y}{n_Q m_Q} + (\cos\phi \sin\theta \sin\psi - \cos\psi \sin\phi) \frac{u_1}{m_Q} \\
\ddot{z} &= (\cos\theta \cos\phi) \frac{u_1}{m_Q} - g - \frac{m_L g}{n_Q m_Q}
\end{aligned} \tag{1}$$

where $m_Q$ is the quadrotor mass, g, gravity acceleration, $J_R = J_m + J_L$, the total engine moment of inertia, and $l$ is the distance between the center of quadrotor mass to the engine.

The $u_i$ coefficients are also [7]:

$$\begin{aligned}
u_1 &= \kappa_b (\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \\
u_2 &= \kappa_b (\omega_2^2 - \omega_4^2) \\
u_3 &= \kappa_b (\omega_3^2 - \omega_1^2) \\
u_4 &= \kappa_\tau (\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2) \\
\Omega_R &= \omega_1 - \omega_2 + \omega_3 - \omega_4
\end{aligned} \tag{2}$$

The optimal control problem is defined to minimize the energy of quadrotor control inputs. The cost function is defined by minimizing the relative speed of the members and fixing and maintaining distance to the leader, as well as tracking the leader, the arrangement of the follower leader. The proposed cost function is:

$$\begin{aligned}
J = \int_0^T & (\text{Quadrotor Energy}) dt \\
& + \sum_{i=1}^{3} \sum_{j \in Ni} (v_i - v_j) Q_{ij} (v_i - v_j)^T \\
& + \sum_{j \in Ni} (v_i - v_j) G (v_i - v_j)^T \\
& + \sum_{i=1}^{3} \sum_{j \in Ni} (p_i - p_j - d) Q_p (p_i - p_j - d)^T
\end{aligned} \tag{3}$$

The cost function parts are quadrotor energy consumption, speed control, leader tracking, and distance control, and $d$ represents the distance from the leader, $p_i$ represents the distance between the members, $v$ represents the optimal speed, $v_i$ represents the speed of the members

The energy consumption of quadrotors between the initial time $t_0$ and the end time $t_f$ is:

$$E = \int_{t_0}^{t_f} \sum_{j=1}^{4} e_j(t) i_j(t) dt \tag{4}$$

The four identical motors and given that $T_L(\omega(j)) = \kappa_\tau \omega_j^2$, the assumption $\omega_j(t_0) = \omega_j(t_f)$ and $j \in [1,2,3,4]$, Eq. (4) is rewritten as follows:

$$E = \int_{t_0}^{t_f} \left[ \sum_{j=1}^{4} \begin{pmatrix} c_1 + c_2 \omega_j(t) + c_3 \omega_j^2(t) + c_4 \omega_j^3(t) \\ + c_5 \omega_j^4(t) + c_6 \dot{\omega}_j^2(t) \end{pmatrix} \right] dt \tag{5}$$

The coefficients $c_1$, $c_2 \ldots c_6$, which depend on the parameters of the engines and the geometry of the propellers.

## 3- Numerical Simulation

The proposed approach is solved through the ACADO tool in MATLAB. For optimization methods, the following default options were considered in ACADO: As a result, a multiple detection of 20 nodes was used and integration with the Rang-Kutta method (rank 4.5) was performed.

In this section, the simulation conditions are applied to three quadrotors to carry the load under the leader's arrangement and maintain the arrangement in the direction. To carry group loads for quadrotors, the load is considered equal to $m_L = 1.5$ kg, which is three times the load weights determined individually for quadrotor. The purpose of this work is to investigate how much quadrotor the group consumes when consuming energy in comparison to individual conditions.

As can be seen, the average maximum energy consumption of a quadrotor in a cooperative mode is 15.31 kJ, which leads to a reduction of energy consumption of 29.29% compared to a quadrotor in a solitary state. Due to the fact that the weight of the load has increased up to three times, moving the quadrotors in a cooperative mode for a 1.5 kg load has led to a significant reduction in the energy consumption of the system. Indeed, the use of three robots has resulted in more quadrotor load balancing, and Pitch, Yaw, and Roll angles have been reduced to less than single Quadrotor, which has led to a reduction in their energy consumption. This suggests that by moving the group of quadrotors more loads than the capacity of a quadrotor can be displaced. The significance of this issue is evident when there is not enough time to transport the shipment for the shipment to be loaded, or that the volume of the shipment and the size of the vehicles are in such a way as to require a group shift.

The path of the formation of the follower leader has been created and maintained until the end of the movement is shown in Fig. 2.

In Fig. 3, the periods of the first quadrotor is shown in coordinate axes, respectively. This figure show that the continuous motion of quadrotor in individual mode, with the dependence of the quadrotors under the formation of the leader-follower, has largely been eliminated, and in most of the path, due to the load and oscillation, vibrations are observed and returned.

## 4- Conclusions

In this paper, the problem of designing the path of the

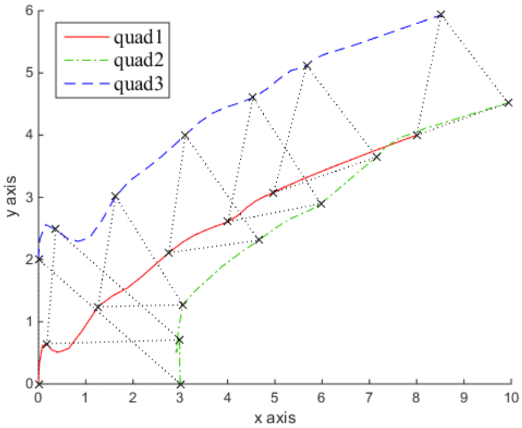

**Fig. 2. The comparison between the trend of SPMHDm and Vrms for all accelerated-life experiments**

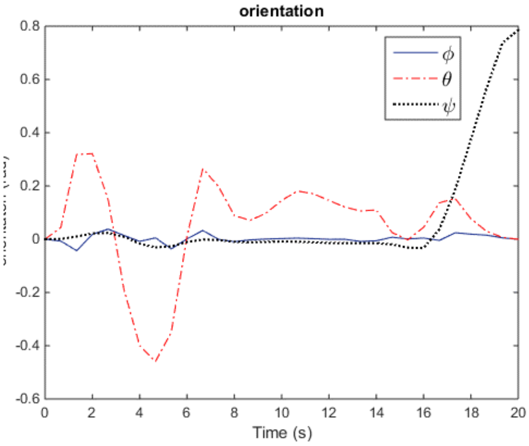

**Fig. 3. Compression between Envelope technique and SPM for early fault type detection**

cooperative quadrotors for the transfer of load is grouped. The proposed theory is illustrated using numerical experiments performed by Quadrotor DJI Phantom II. The results indicated a decrease of 35.29% of the average energy consumption of a quadrotor in a cooperative mode compared to a quadrotor individually, indicating an increased load capacity of quadrotors in group mode. This suggests the success of the proposed cost function and proves its accuracy. On the other hand, group arrangement was formed by attaching a follower to the leader through distance and angle preservation relationships.

## References

[1] L. Yang, J. Qi, J. Xiao, X. Yong, A literature review of UAV 3D path planning, in Proceeding of 11th World Congress on Intelligent Control and Automation, Shenyang, China: IEEE, (2014) 2376-2381.

[2] S. Ghazbi, Y. Aghli, M. Alimohammadi, and A. Akbari, Quadrotors unmanned aerial vehicles: a review, International Journal on Smart Sensing and Intelligent Systems, 9(1) (2016) 309-333.

[3] M. Hehn, R. Ritz and R. D'Andrea, Performance benchmarking of quadrotor systems using time-optimal control, Autonomous Robots, 33(1) (2012) 69-88.

[4] O. Cetin, G. Yilmaz, Real-time autonomous uav formation flight with collision and obstacle avoidance in unknown environment, Journal of Intelligent and Robotic Systems, 84(4) (2016) 415-433.

[5] L. Cai, J. Jia and J. Lei, Research on path optimization with PSO for unmanned vehicle, International Journal of Online and Biomedical Engineering, 11(8) (2015) 21-24.

[6] A.K. Das, R. Fierro, V. Kumar, J.P. Ostrowski, J. Spletzer, C.J. Taylor, A vision-based formation control framework, IEEE transactions on robotics and automation, 18(5) (2002) 813-825.

[7] K. Sreenath, N. Michael, V. Kumar, Trajectory generation and control of a quadrotor with a cable suspended load a differentially flat hybrid system, in Proceeding of International Conference on Robotics and Automation, Karlsruhe, Germany: IEEE, (2013) 4888-4895.