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# Fuzzy Logic Force-Torque Feedback Controller For Multi-Drone Cooperative Transport With Offset CG

**Shraddha Barawkar** * **Manish Kumar** **

* *University of Cincinnati, Cincinnati, OH 45221 USA (e-mail: barawksd@mail.uc.edu).*
** *Department of Mechanical and Materials Engineering, University of Cincinnati, Cincinnati, OH 45221 USA (e-mail: manish.kumar@uc.edu)*

**Abstract:** A fuzzy logic (FL) force-torque feedback controller (FT-FC) is utilised to solve the problem of multi-drone cooperative transport with known offset center of gravity (CG). The control scheme is decentralised in the sense that no inter drone communication is required. The controller only needs measurements of contact forces and torques and minimum object information. Object reference model computes the desired forces and torques of the object required to reach the goal and compensate the effect of offset CG. This information is then utilised to calculate desired forces and torques at contact points of all drones. Based on these, the input of each drone is computed and sent to FL FT-FC and a proportional thrust controller to control each drone. One of the primary contributions of this paper is development and application of such schemes, previously used for ground robots, to drones. Second contribution consists of the development and application of FL based passive control to the proposed problem. Simulation results validate the effectiveness of the proposed controller.



*Keywords:* multi-drone system, cooperative transport, decentralized control, fuzzy logic, force-torque feedback control, offset CG.

## 1. INTRODUCTION

Cooperative transport (CT) of a common object using multiple drones has been a topic of interest since more than a decade. As compared to single drones, these systems provide perks such as fault tolerant capability, modularity, and increased payload capacity. However, these systems still present several technological problems which are needed to be addressed. These include control and coordination of all drones for effective transportation. In particular, control of such systems with offset center of gravity (CG) of the payload (or irregular payload) is specially challenging. "Offset CG" refers to a case when the CG does not coincide with the geometric center of object (Barawkar and Kumar (2019)). CG could be offset or dynamically changing in many practical applications including multi-drone flying car and package delivery system (Barawkar (2017)). CG can change due to movement of people inside the flying car or due to motion of the material inside the package. Hence there is a need address the control related challenges emerging from such issues.

Literature has demonstrated CT with ground/industrial robots as well as with drones (Wang and Schwager (2016); Lee et al. (2015)). Passive control, potential fields and caging are few control strategies for implementing decentralized manipulation (Culbertson and Schwager (2018)). Passive or force control is one prominent technique. Work of Barawkar (2017); Barawkar et al. (2017); Tagliabue et al. (2019) demonstrate force/torque based multi-drone CT for outdoor environments in presence of erroneous GPS. These utilise fuzzy logic (FL) and admittance controllers. In context to CT with offset CG, Culbertson and Schwager (2018) and Kawasaki et al. (2003) demonstrate decentralized adaptive schemes with object uncertainties using multiple ground/industrial robots. Kawasaki et al. (2003), additionally, provides control with robot parameter uncertainties. Thapa et al. (2020), on the other hand, shows decentralized adaptive force control for multi-drone CT systems, however, with uncertain mass of object. Aghdam et al. (2016) perform multi-drone CT with offset CG, however, with cabled connections. Work by Barawkar and Kumar (2019) solves the problem of control of multi-drone CT systems with offset CG. However, it uses a centralized PID controller and assumes complete inter-drone communication, which is not desirable.

This paper proposes a decentralized Fuzzy Logic (FL) based force-torque feedback control (FT-FC) for a multi-drone CT system with offset CG using rigid connections. Justification of choice of rigid connections is already discussed in Barawkar and Kumar (2019). FL provides unique benefits such as effective force-torque coordination, tolerance to sensor noise and inclusion of human logic and intuition in controller design (Barawkar (2017)). FL FT-FC does not require positional feedback of other drones. Positional feedback is generally obtained using GPS sensor which is prone to providing large relative errors if used to calculate positions of individual drones. FL FT-FC also allows decentralization. Moreover, in literature, most of such


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control strategies are implemented on ground/industrial robots. Application of existing schemes to multi-drone systems is challenging due to role of gravity and presence of nonlinear, coupled and unstable dynamics. In contrast to Kawasaki et al. (2006) that avoids use of force-torque sensor, since it is expensive and prone to damage, the proposed work allows implementation of such strategies using inexpensive noisy force-torque sensors made possible due to use of FL. It should be noted that offset CG creates residual forces and torques at contact points between drones and object. These forces and torques might mislead the drones if they follow passive/force-torque based control. The problem further gets complicated if rigid connections are utilised in which both drones and object share the same orientation.

This paper utilises a model from Kawasaki et al. (2003) to implement a decentralised FL FT-FC for multi-drone CT with known offset CG. The input for each drone is computed using desired motion of object. These inputs are then utilised by the proposed FL FT-FC and a proportional thrust controller to control each drone. FL FT-FC is based on principle of minimisation of contact forces and torques to achieve CT (Barawkar (2017)). It should be noted that this and previous works Culbertson and Schwager (2018); Kawasaki et al. (2003) are not completely decentralised since all drones still need certain global information about the object. Similar to Kawasaki et al. (2003), this work requires knowledge of object's actual position, actual velocity, desired position (goal), desired velocity (at goal) and desired acceleration (at goal) including both linear and angular components. This minimum information is required to be known by each drone.

The primary contribution of this work is in development of passive control (FL FT-FC) for the proposed control problem of multi-drone CT with offset CG. The proposed scheme of using force/torque information eliminates inter-drone communication and uses only minimal object information as global information. It may be noted that such decentralized force/torque based schemes for multi-drone CT have been developed for manipulators and mobile robots. Their application to drones is not a trivial extension due to highly complex, unstable, and nonlinear dynamics coupled with underactuation of quadrotor drones. Use of proposed FL FT-FC for solving this problem is first in literature. The structure of this paper is as follows. Sections 2 through 4 show Problem Formulation, Assumptions and Dynamics. Approach, Simulation results and Conclusion are shown in sections 5, 6 and 7.

## 2. PROBLEM FORMULATION

Consider a system of '$n$' drones cooperatively transporting a common object to a goal location. Refer to Fig. 1 showing the schematic diagram of the system with 5 drones. Given the offset CG $r_G$ (known) and a goal location $(x_g, y_g, z_g)^T$, the primary control objective is to compute the control action $\boldsymbol{u_i}$ of each drone in a decentralized fashion with minimum knowledge of the object and without inter-drone communication. In this way, this paper's problem formulation is different from our earlier paper (Barawkar and Kumar (2019)). The control action $\boldsymbol{u_i}$ of each $i^{th}$ drone consists of the desired roll angle $\phi_i^d$, pitch angle $\theta_i^d$, yaw angle $\psi_i^d$ and desired acceleration along vertical $Z_W$ axis

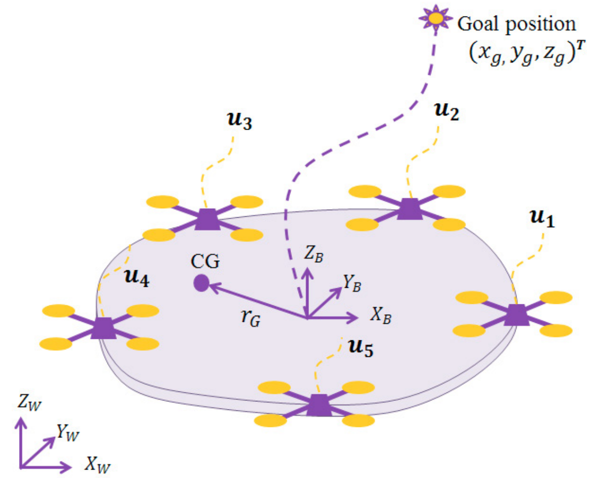


Fig. 1. Schematic diagram of the system.

$\ddot{r}_{i,z}^d$. Thus,

$$\boldsymbol{u_i} = (\phi_i^d, \theta_i^d, \psi_i^d, \ddot{r}_{i,z}^d) \tag{1}$$

The offset CG creates a moment $\tau_G$ at the payload's geometric center given by (Barawkar and Kumar (2019)),

$$\tau_G = r_G \times \begin{bmatrix} 0 & 0 & -m_o g \end{bmatrix}^T \tag{2}$$

where, $m_o$ is the mass of object and $r_G$ denotes a vector from the geometric center to the offset CG of object (in frame $B$). The control actions, $\boldsymbol{u_i}$s, of all drones are required to be computed such that, the moment $\tau_G$ gets compensated as well as the system reaches it's goal location $(x_g, y_g, z_g)^T$.

## 3. ASSUMPTIONS

We make the following assumptions without loss of generality. Payload is rigid. The offset CG $r_G$ is known. Each drone is required to know minimum object information-actual position and velocity of object $(r_o, \eta, \dot{r}_o, \omega)$ and desired object trajectories $(r_o^d, \dot{r}_o^d, \ddot{r}_o^d)$. The reference angular velocity of object is $\omega_{or} = 0$. The desired internal force in object $f_d^{int} = 0$ (for simplicity purposes). Contact forces and torques $F_i$s are measurable and required for control. Desired yaw angles for object and drones is assumed to be $\psi_o^d = \psi_i^d = 0$. Perfect rigid connections are assumed between drones and object. For $Z_W$ axis control, each drone is required to know the number of drones present in the system. It should be noted that proposed scheme requires only one GPS for measuring object's position and velocity which is communicated to all drones. Whereas drones utilise force-torque based feedback and do not require individual GPS.

## 4. DYNAMICS

Following the work of Kawasaki et al. (2003); Barawkar and Kumar (2019), we consider dynamics of '$n$' number of drones transporting an object with offset CG. Refer to Fig. 2 showing the free body diagram of object and a single drone. $W$, $B$ and $B_i$ are the world frame, body frame of object and body frame of $i^{th}$ drone. $X$, $Y$ and $Z$ are the respective coordinate axes with suffices $W$, $B$ and $B_i$ for different frames indicated above.

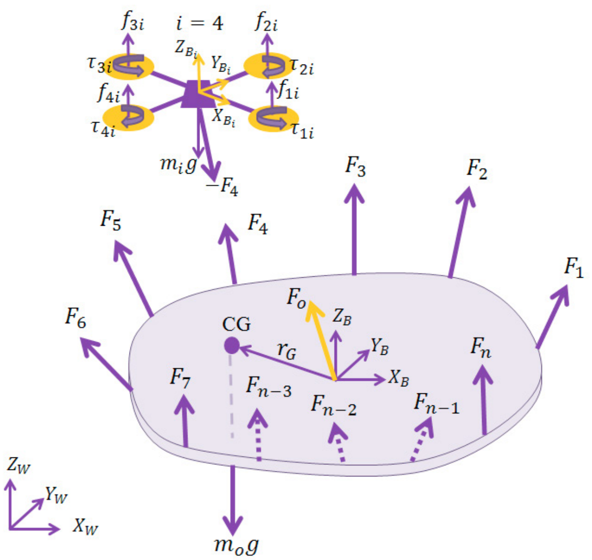


Fig. 2. Free body diagram of object and a single drone.

### 4.1 Object dynamics

Each drone exerts a contact interaction force $f_i \in R^3$ and a torque $\tau_i \in R^3$ at the point of contact with the object. Given application of forces and torques by $n$ such drones, the resultant force $f_o$ and torque $\tau_o$ on object is given by,

$$f_o = \sum_{i=1}^{n} f_i \qquad \tau_o = \sum_{i=1}^{n} (\tau_i + d_i \times f_i) \tag{3}$$

It should be noted that $\tau_o$ is evaluated about the offset CG and not about geometric center. $d_i \in R^3$ is the vector from offset CG of object to the point of contact between drone and object. $d_i$ is given by, $d_i = r_i - (r_o + Rr_G)$. $r_i \in R^3$ and $r_o \in R^3$ are the position of $i^{th}$ drone and the object (of geometric center) in world frame $W$. $R$ is the rotation matrix from body ($B$) to world frame ($W$) given by,

$$R = \begin{bmatrix} c\psi c\theta - s\phi s\psi s\theta & -c\phi s\psi & c\psi s\theta + s\phi s\psi c\theta \\ c\theta s\psi + c\psi s\phi s\theta & c\phi c\psi & s\psi s\theta - c\psi c\theta s\phi \\ -c\phi s\theta & s\phi & c\phi c\theta \end{bmatrix} \tag{4}$$

$\phi$, $\theta$ and $\psi$ are the roll, pitch and yaw angles, denoting the orientation of the system. $c(.)$ and $s(.)$ are the cosine and sine terms. Due to rigid connections, the rotation matrices of the object and drones are the same since they share the same orientation. Rewriting equation 3 as,

$$F_o = \sum_{i=1}^{n} \mathbb{W}_i F_i \tag{5}$$

where $F_o = \begin{bmatrix} f_o^T & \tau_o^T \end{bmatrix}^T$ is the external force and torque applied to the object by $n$ drones. $F_i = \begin{bmatrix} f_i^T & \tau_i^T \end{bmatrix}^T$ is the force and torque applied by $i^{th}$ drone to the object. $\mathbb{W}_i \in R^6$ denotes the grasp form matrix given by,

$$\mathbb{W}_i = \begin{bmatrix} I & 0 \\ \widehat{h} & I \end{bmatrix} \tag{6}$$

$I$ is the identity matrix. $\widehat{h}$ is defined by the relation $\widehat{h}a = h \times a$ for any vectors $h$ and $a$. Equation 5 can thus be written in a compact form as,

$$F_o = \mathbb{W}F \tag{7}$$

where $F = \begin{bmatrix} F_1^T & ... & F_n^T \end{bmatrix}^T$ and $\mathbb{W} = \begin{bmatrix} \mathbb{W}_1 & ... & \mathbb{W}_n \end{bmatrix}$. The rotational and linear dynamic equations of motion of object are given as,

$$m_o \ddot{r}_{CG} = f_o - \begin{bmatrix} 0 \\ 0 \\ m_o g \end{bmatrix} \qquad I_o \alpha = \tau_o - (\omega \times I_o \omega) \tag{8}$$

where $r_{CG}$ is position of offset CG of object with respect to $W$. $I_o$, $\alpha$, $\omega$ denote the moment of inertia, angular acceleration and angular velocity of object. Rigid body equation to compute acceleration is utilized to compute $\ddot{r}_{CG}$. It is expressed as follows,

$$\ddot{r}_{CG} = \ddot{r}_o + (\alpha \times (Rr_G)) + (\omega \times (\omega \times (Rr_G))) \tag{9}$$

After expanding the above equations, it can be observed that the dynamic model of object is linear in terms of the parameter vector viz. CG vector $r_G$. This can also be seen in works of Palunko and Fierro (2011); Kawasaki et al. (2003). In general, the dynamic equation of the object can be written as,

$$F_o = M_o(p_o)\ddot{p}_o + C_o(p_o, \dot{p}_o)\dot{p}_o + g_o(p_o) \tag{10}$$

where $p_o = \begin{bmatrix} r_o^T & \eta^T \end{bmatrix}^T$ is the position and orientation vector of object defined in world fame $W$. $M_o$, $C_o$ and $g_o$ are the symmetric positive definite inertia matrix, damping coefficient matrix and gravity force term respectively. The above equation forms a general class of nonlinear systems. Work of Kawasaki et al. (2003) uses them for industrial robot arms while this paper applies the same concept for multi-drone cooperative transport system with offset CG. Note that drone as well as object dynamics can be expressed in the form of above equation.

### 4.2 Drone dynamics

The linear and rotational equations of motion of each $i^{th}$ drone are,

$$f_i = R \begin{bmatrix} 0 \\ 0 \\ (f_{1i} + f_{2i} + f_{3i} + f_{4i}) \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ m_i g \end{bmatrix} - m_i \ddot{r}_i \tag{11}$$

$$\tau_i = \begin{bmatrix} L(f_{2i} - f_{4i}) \\ L(f_{3i} - f_{1i}) \\ \tau_{1i} - \tau_{2i} + \tau_{3i} - \tau_{4i} \end{bmatrix} - (\omega \times I_i \omega) - I_i \alpha \tag{12}$$

where $m_i$ is the mass of the $i^{th}$ drone. $f_{1i}$, $f_{2i}$, $f_{3i}$ and $f_{4i}$ are rotor thrust forces generated by the $i^{th}$ drone. Similarly $\tau_{1i}$, $\tau_{2i}$, $\tau_{3i}$ and $\tau_{4i}$ are the rotor torques generated by the $i^{th}$ drone. $L$ is the distance between the rotor center and drone center. $I_i$ is the mass moment of inertia of the $i^{th}$ drone. Similar to equation 9, the rigid body equation is then written as,

$$\ddot{r}_i = \ddot{r}_o + (\alpha \times (r_i - r_o)) + (\omega \times (\omega \times (r_i - r_o))) \tag{13}$$

This dynamic model was developed mainly to simulate the contact forces and torques ($F_i$s) acting at the point of contact between drones and object. It provides a realistic simulation framework for demonstrating cooperative transport of an object with irregular geometry and offset CG by $n$ drones.

## 5. APPROACH

As discussed in section of "Problem Formulation", the main goal is to compute the control inputs of all drones such that the object with offset CG reaches the goal location $r_o^d = (x_g, y_g, z_g)^T$. Offset CG creates an additional torque $\tau_G$ on object whose compensation is required by the drones. Thus the control problem is challenging. We assume that the CG is known. We follow Kawasaki et al. (2003) and perform the following steps to solve the problem. Briefly they are,

- First step consists of computing the desired forces and torques $F_o^d$ to be applied to the object to reach the goal $r_o^d$. This is done using a reference model. The reference model requires the desired trajectories of object $(r_o^d, \dot{r}_o^d, \ddot{r}_o^d)$ and object's position and velocity $(r_o, \eta, \dot{r}_o, \omega)$. The velocity error of object $s_o$ is also calculated using $F_o^d$.
- The desired forces and torques $F_i^d$ to be applied by each $i^{th}$ drone at contact point are then computed using $F_o^d$.
- The velocity error $s_i$ of each drone is calculated using $s_o$. Following this, the input $u_i$ of each drone is computed using $F_i^d$ and $s_i$.
- Lastly, the input $u_i$ of each drone is utilised by FL FT-FC to generate desired roll $\phi_i^d$ and pitch $\theta_i^d$ angles. The $Z$ axis part of input is utilised by a proportional controller to produce desired linear acceleration $\ddot{r}_{i,z}^d$ along $Z_W$ axis for thrust control.

Proofs of asymptotic stability are already provided by Kawasaki et al. (2003). For brevity purposes and since this paper does not focus on adaptive control requiring CG estimation, we have not indicated the proof here. Please note that due to similar dynamic form of equations, the stability analysis of the proposed work is similar to work of Kawasaki et al. (2003). Details of above steps are provided below.

### *5.1 Computation of desired force and torque $F_o^d$ at the object to reach the goal*

A controller similar to work of Mellinger et al. (2013) is chosen for the object. Let the reference acceleration $\ddot{r}_{or} = [\ddot{r}_{or}^x \ddot{r}_{or}^y \ddot{r}_{or}^z]^T$ of the object be defined as,

$$\ddot{r}_{or} = k_p e_o + k_d(\dot{r}_o^d - \dot{r}_o) \tag{14}$$

where, $e_o = r_o^d - r_o$ is the position error vector. $k_p$ and $k_d$ are the proportional and derivative gains. The desired orientation is then computed using $\ddot{r}_{or}$ as,

$$\phi_{or} = \frac{1}{g}(\ddot{r}_{or}^x sin\psi_o^d - \ddot{r}_{or}^y cos\psi_o^d) \tag{15}$$

$$\theta_{or} = \frac{1}{g}(\ddot{r}_{or}^x cos\psi_o^d + \ddot{r}_{or}^y sin\psi_o^d) \tag{16}$$

$$\psi_{or} = \psi_o^d \tag{17}$$

where, $\eta_{or} = \begin{bmatrix}\phi_{or} & \theta_{or} & \psi_{or}\end{bmatrix}^T$ forms the reference orientation of object. $\psi_o^d$ is the desired yaw angle of the object at goal location. It is assumed to be zero in this paper. $\eta_{or}$ is used to compute the reference angular acceleration $\alpha_{or}$ of the object as,

$$\alpha_{or} = I_o^{-1} k_{p,\eta}(\eta_{or} - \eta) + I_o^{-1} k_{d,\dot{\eta}}(\omega_{or} - \omega) \tag{18}$$

where, $\omega_{or}$ and $\eta$ are the reference angular velocity and actual orientation of the system. It should be noted that for simplicity purpose, to reduce tuning efforts, we assume $\omega_{or} = 0$ in this paper. The velocity error $s_o \epsilon R^6$ is,

$$s_o = \begin{bmatrix}\dot{r}_o \\ \omega\end{bmatrix} - \begin{bmatrix}\dot{r}_{or} \\ \omega_{or}\end{bmatrix} \tag{19}$$

This will be used to compute input $u_i$ of each drone. The desired forces and torques $F_o^d$ to be applied on object by $n$ drones is then defined by,

$$F_o^d = M_o(p_o)\ddot{p}_{or} + C_o(p_o, \dot{p}_o)\dot{p}_{or} + g_o(p_o) \tag{20}$$

Table 1. FL rules of FT-FC for pitch direction

| $u_{\tau_\theta}$ \ $u_{f_x}$ | **NL** | **NM** | **Z** | **PM** | **PL** |
|---|---|---|---|---|---|
| **NL** | NL | NM | NL | NM | Z |
| **NM** | NM | NM | NM | Z | PM |
| **Z** | NM | Z | Z | PM | PL |
| **PM** | Z | Z | PM | PM | PL |
| **PL** | Z | PM | PL | PL | PL |

### *5.2 Computation of desired forces and torques $F_i^d$ at contact point of each drone*

It is assumed that the forces and torques by $n$ drones, given by $F$, producing the required forces and torques at object $F_o$, exist. In this case the $F_i^d$s generating $F_o^d$ would satisfy equation 7. Thus, the desired forces and torques $F^d$ by $n$ drones at contact points can be computed based on equation 7 as,

$$F^d = \mathbb{W}^+ F_o^d \tag{21}$$

$\mathbb{W}^+$ denotes pseudo inverse of $\mathbb{W}$. It is given by,

$$\mathbb{W}^+ = \mathbb{W}^T(\mathbb{W}\mathbb{W}^T)^{-1} \tag{22}$$

### *5.3 Computation of input $u_i$ of each drone*

The velocity error of each $i^{th}$ drone can be written as: $s_i = \begin{bmatrix}\dot{r}_i^T & \omega^T\end{bmatrix}^T - \begin{bmatrix}\dot{r}_{ir}^T & \omega_{ir}^T\end{bmatrix}^T$ can be written as,

$$s_i = \mathbb{W}_i^T s_o - \Omega_i \Delta F_i - \Psi_i \eta_i \tag{23}$$

where, $\dot{r}_{ir}$ and $\omega_{ir}$ are reference velocities. $s_o$ is already computed earlier. $\Omega_i > 0$ and $\Psi_i > 0$ are positive symmetric gain matrices. $\Delta F_i = F_i^d - F_i$ is the difference between desired and actual contact forces and torques of $i^{th}$ drone. This is termed as contact force error. $\eta_i$ is the integral of this contact force error. The input $u_i$ which provides asymptotic stability is (Kawasaki et al. (2003)):

$$u_i = F_i^d - K_i s_i \tag{24}$$

where $K_i > 0$ is a feedback gain matrix. This input $u_i$ compensates $\tau_G$ as well as makes the system reach the goal $r_o^d$.

### *5.4 Implementation of FL FT-FC and proportional controller (for $Z_W$ axis)*

We propose FL FT-FC to control each drone. We use this controller from work of Barawkar (2017). The computed input $u_i \propto F_i^d$, thus we consider the proposed control strategy to be a force-torque feedback controller (FT-FC). FL FT-FC is utilised for roll and pitch axes. This controller is based on principle of minimisation of contact forces and torques to achieve cooperative transportation. This is indicated earlier. FL rules are accordingly designed using human logic and intuition. This is explained below.

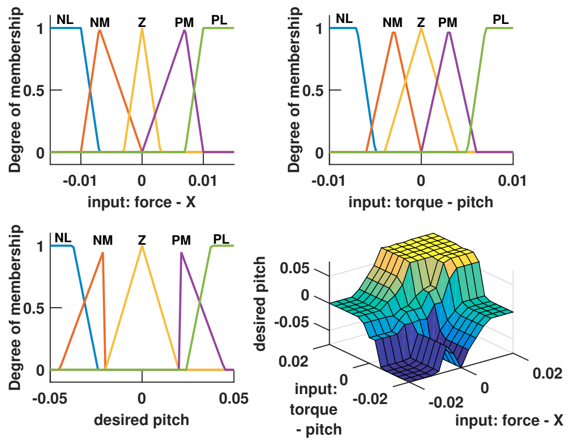


Fig. 3. Membership functions and control surface (bottom right) of FL FT-FC along pitch direction.

Firstly, note that $u_i \propto F_i^d$. This means that first three values of $u_i \epsilon R^6$ correspond to required force at contact point. Similarly other three components of $u_i$ correspond to required torque to be generated by each drone at contact point. Thus we can denote $u_i$ as,

$$u_i = \left[u_{f_x}\ u_{f_y}\ u_{f_z}\ u_{\tau_\phi}\ u_{\tau_\theta}\ u_{\tau_\psi}\right]_i^T \tag{25}$$

where subscripts $f_x$, $f_y$ and $f_z$ denote the corresponding force components of the input. Whereas, $\tau_\phi$, $\tau_\theta$ and $\tau_\psi$ denote the corresponding torque components of the input. Now, for underactuated quadrotor drones, $u_{f_x}$ and $u_{\tau_\theta}$ are responsible for producing motion along pitch or $X_W$ axis. Similarly, $u_{f_y}$ and $u_{\tau_\phi}$ produce motion along roll or $Y_W$ axis. The FL rules are then designed in the following manner.

The inputs to FL FT-FC for pitch axis are $u_{f_x}$ and $u_{\tau_\theta}$. The output of FL FT-FC for pitch axis is desired pitch angle $\theta_i^d$ for $i^{th}$ drone. Five membership functions are chosen for both inputs and outputs along roll and pitch axes. They are negative large (NL), negative medium (NM), Zero (Z), positive medium (PM) and positive large (PL). Now for example, let $u_{f_x}$ and $u_{\tau_\theta}$ be PL. Then according to principle of minimisation of contact forces and torques, for cooperative transport, the control action of the drone should be such that both $u_{f_x}$ and $u_{\tau_\theta}$ should be minimised. They can be reduced only when the drone produces a high pitching motion at contact point. Thus, if $u_{f_x}$ is PL and $u_{\tau_\theta}$ is PL then $\theta_i^d$ is PL. This represents the format of FL rules. Consider another rule. If $u_{f_x}$ is PL and $u_{\tau_\theta}$ is NM then $\theta_i^d$ is PM. This rule provides a compromise between $u_{f_x}$ and $u_{\tau_\theta}$ and also follows the principle indicated earlier. Similarly, FL rules for roll axis are also designed accordingly. Figure 3 shows membership functions and control surface of FL FT-FC along pitch direction. Table 1 shows the FL rules along pitch direction. For brevity purposes, figures of roll direction are not indicated. For vertical $Z_W$ axis, a proportional controller is implemented which uses $u_{f_z}$ to produce desired linear acceleration $\ddot{r}_{i,z}^d$ for each $i^{th}$ drone. Thus,

$$\ddot{r}_{i,z}^d = k_{pz}(u_{f_z} - \frac{m_o g}{n}) \tag{26}$$

where, $k_{pz}$ is the proportional gain. In this way, the $Z_W$ axis controller of each drone needs to know the number of drones '$n$' present in the system. All these controllers were tuned manually to provide optimum results. These values are then sent to the attitude controller of drone. See Barawkar and Kumar (2019).

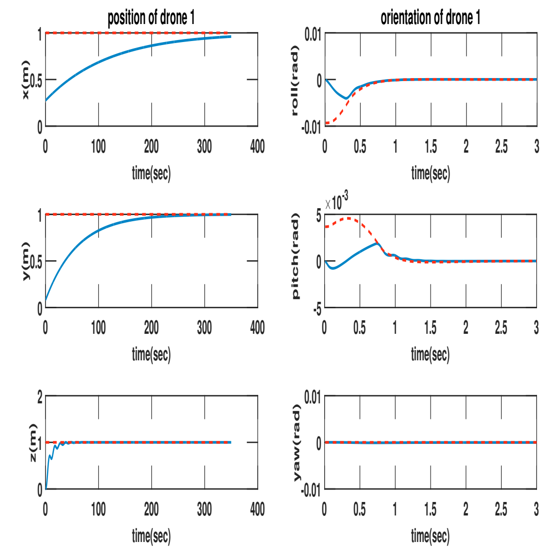


Fig. 4. Position and orientation of drone 1 (red dashed represents desired values and blue solid represents actual values).

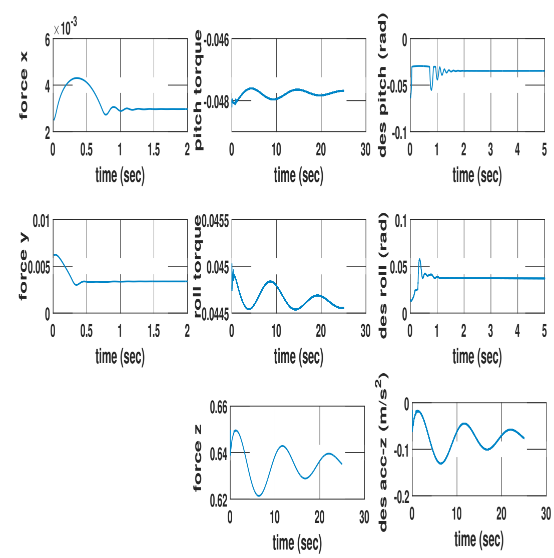


Fig. 5. Drone 1: Top two rows represent the fuzzy logic control inputs (left two columns) and the output (right column) for $X_W$ (top row) and $Y_W$ (middle row) directions. Bottom row represents the controller for $Z_W$ direction implemented by Eq. 26.

## 6. RESULTS

A 3-drone CT system with a planar triangular object was utilised for simulations. The lengths of the triangular object were chosen as $l_1 = 0.54m$, $l_2 = 0.41m$ and $l_3 = 0.35m$. The offset CG was known and kept at $r_G = (0.08m, 0.07m, 0m)^T$. Other simulation parameters were,

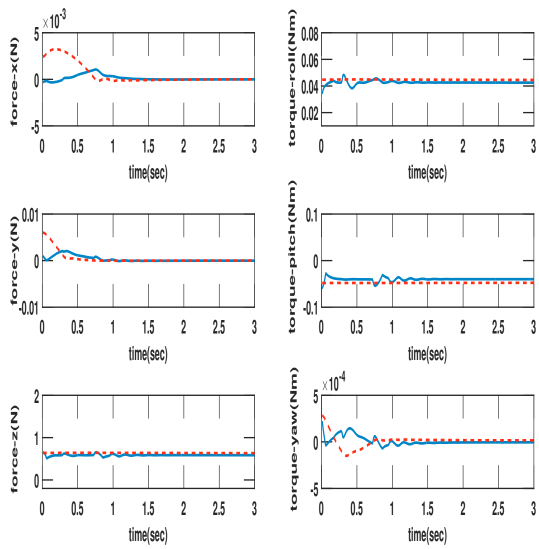


Fig. 6. Desired (red dashed) and actual contact (blue solid) forces and torques for drone 1

$m_i = 1kg$, $m_o = 0.2kg$, $L = 0.12m$, $k_p = \left[0.05\ 0.1\ 0.1\right]^T$,
$k_d = \left[6\ 6\ 0.9\right]^T$, $k_{p,\eta} = \left[0.1\ 0.1\ 0.01\right]^T$,
$k_{d,\dot{\eta}} = \left[0.001\ 0.001\ 0.001\right]^T$, $k_{pz} = 4$
$K_i = diag\left(0.1\ 0.1\ 0.1\ 0.004\ 0.008\ 0.001\right)$,
$\Omega_i = diag\left(0.1\ 0.1\ 0.1\ 0.01\ 0.01\ 0.01\right)$,
$\Psi_i = diag\left(0.01\ 0.01\ 0.01\ 0.01\ 0.01\ 0.01\right)$.
The goal location was taken as $r_o^d = (1m, 1m, 1m)^T$. Results are shown in Figures 4 to 6. It should be noted that for some results the time limits (X axis) have been kept short for improving clarity. Fig. 4 shows that the system effectively performs waypoint navigation. Fig. 5 shows the computed input $u_1$ for drone 1 with it's respective force and torque components. The corresponding outputs $\phi_1^d$, $\theta_1^d$ and $\ddot{r}_{1,z}^d$ (des acc-z in figure) are successfully computed by FL FT-FC and proportional thrust controller. These are shown in the same Fig. 5. Fig. 6 shows desired and actual contact forces and torques at $1^{st}$ drone. It can be seen that the actual forces and torques converge to the desired ones. It can also be seen that yaw maintains a desired value of zero in the entire simulation. These results validate the effectiveness of the proposed controller.

## 7. CONCLUSION

A FL FT-FC is implemented for a multi-drone CT system with known offset CG. All the drones act independently without communication. Each drone is required to know certain minimum object information. The object reference model computes desired forces and torques at object which are then used to find desired forces and torques at contact points with drones. Following this, each drone computes the input and sends it to FL FT-FC and thrust controller for it's control. Contributions of this work are two fold: i) development of decentralized force-torque based control scheme, that have earlier been used only on industrial/mobile robots, for multi-drone CT with offset CG; and ii) development of FL based scheme for implementing the contact force-torque control. Simulation results show that system performs effective waypoint navigation in presence of offset CG. Future work consists of relaxing the assumptions and performing experiments.

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