AIAA SciTech Forum
8–12 January 2018, Kissimmee, Florida
2018 AIAA Information Systems-AIAA Infotech @ Aerospace

10.2514/6.2018-0895

Cooperative Load Control and Transportation

Kuldeep K Dhiman,* Abhishek,† and Mangal Kothari‡

Department of Aerospace Engineering, Indian Institute of Technology Kanpur, Kanpur, UP, India - 208016

Suspended payload transportation by autonomous aerial vehicles like quadrotor is dangerous if load is not controlled properly because excessive load swinging of a cable suspended load can degrade the flight performance and stability of quadrotor. The transportation become more challenging when multiple vehicles are involved as this requires load distributions, swing control, and cooperative trajectory planning. This paper first derive a mathematical dynamics model of suspended quadrotor load systems using Newton-Euler method. Next, a cooperative control law is developed to control the motion of quadrotor and load. The proposed approach uses a combination of two PID controller for position control and transportation. The first PID controller control the motion of quadrotor whereas the second PID controller control the swing and simultaneously damp the oscillation of the load. The combination facilitates the waypoint transition and trajectory tracking of the load. The performance is demonstrated experimentally on a single and two quadrotors in 3D environment using the motion capture system.

Nomenclature

m_Q	=	Mass of the quadrotor, kg
m_L	=	Mass of the load, kg
I	=	Inertia matrix of the quadrotor with respect to the body fixed frame, kg/m^2
R	=	Rotation matrix of the quadrotor from body fixed frame to the inertial frame
Ω	=	Angular velocity of the quadrotor in the body fixed frame, rad/s
ω	=	Angular velocity of the suspended load in the inertial frame, rad/s
r_Q	=	Position vector of the quadrotor in the inertial frame, m
r_L	=	Position vector of the load in the inertial frame, m
v_Q	=	Velocity vector of the quadrotor in the inertial frame, m/s
v_L	=	Velocity vector of the load in the inertial frame, m/s
ρ	=	Position vector of the load with respect to the quadrotor, m
M	=	Moment vector for the quadrotor in the body fixed frame, Nm
L	=	Length of the suspension cable, m
T	=	Tension in the cable, N

I. Introduction

The last decade has witnessed tremendous surge in popularity of aerial robotics and its numerous applications that includes, but is not limited to, search and rescue operations, surveillance, terrain mapping, payload delivery, precision agriculture, sky crane etc. One of the key applications for autonomous aerial vehicles with hovering capability is to transport suspended or underslung payload by using one or more rotary wing Unmanned Aerial Vehicles (UAVs) like quadrotors and helicopters.[1]

Excessive swing of a cable suspended load can degrade the flight performance and stability of the quadrotor. To control the suspended payload oscillation, quadrotor must be controlled in such a way that load

*Graduate student, Department of Aerospace Engineering, Indian Institute of Technology, dhims@iitk.ac.in.
†Assistant Professor, Department of Aerospace Engineering, Indian Institute of Technology Kanpur, abhish@iitk.ac.in
‡Assistant Professor, Department of Aerospace Engineering, Indian Institute of Technology Kanpur, mangal@iitk.ac.in.

has permissible swing and the oscillations are damped promptly to prevent the possibility of payload swing to hinder the accomplishment of the given task. Further, if weight of the suspended load demands the deployment of multiple UAVs, then, the design of a controller and generation of trajectory becomes more challenging for the multiple vehicle system. While multiple vehicles carry a suspended load cooperatively, they should not collide during the flight and load distribution among the vehicles may have to be considered for trajectory generation for the vehicles.

Recently, intensive research on attitude stabilization and aggressive maneuvering of quadrotor[2–8] has been carried out and several control methods have been reported in literatures. Nonlinear dynamic inversion was used to develop outer loop control to help pilot in controlling helicopter slung load system.[9] Various other nonlinear controllers have been developed for to control suspended load.[10–12] Input shaping is another control method that has been employed to dampen the swing of suspended load.[13–15] A control law for the quadrotor carrying a suspended load was proposed based on the idea of nested saturation approach in.[16] A controller was also designed for lift maneuver with suspended load using hybrid system approach and simulation results were presented in.[17] Alothman et al.[18] implemented LQR and PD controllers and compared its performance for attitude and translation stabilization of suspended load. Tang and Kumar[19] used Mixed Integer Quadratic Program trajectory planning method to navigate a quadrotor with a cable-suspended payload through known obstacle-filled environments and experimentally validated their methodology. Bernard and Kondak[20] proposed use of force sensors in the cable to facilitate measurement of tension force along the cable to prevent cable slack.

While significant research has been carried out to study the dynamics and control of quadrotor with suspended load, relatively less literature is available related to cooperatively carrying of suspended payload using multiple vehicles. Lee et al.[21] simulated and studied the tracking control of multiple cooperating quadrotor UAVs with a suspended load assuming it to be a point mass and connected to quadrotors by rigid massless links. A geometric nonlinear controller for carrying a rigid body with multiple quadrotors was proposed by Goodarzi and Lee,[22] the coupling effects due to the dynamics of the rigid payload and flexible cables was also considered. Multiple quadrotors with suspended point load and rigid body load were shown to be differentially flat and this property was exploited to find dynamically feasible trajectories for the payload and quadrotors.[23] A control and collision avoidance strategy between two quadrotors when carrying a suspended payload is presented along with simulation results in.[24] Thus it can be noted that most of the research on cooperative control of suspended load has been studied largely using simulations and the challenges associated with real world implementation has not been fully understood.

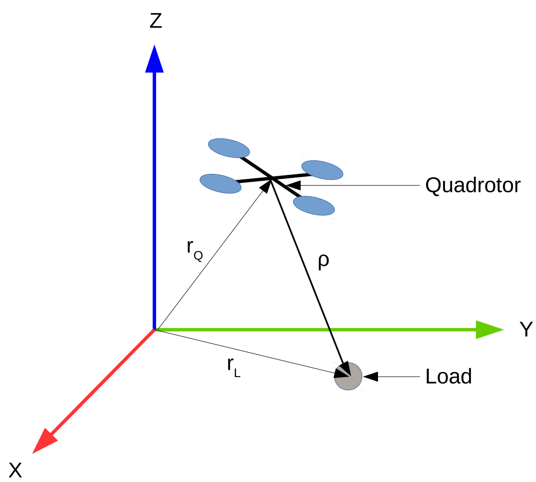
The goal of this paper is to design and experimentally validate a control law for control of the suspended load with one quadrotor and cooperatively with two quadrotors. Load should be controlled in such a way that it is stabilized quickly in the presence of disturbance and can be controlled to fly through specified waypoints and track circular trajectory with significantly reduced load swing and highly damped load oscillation. While in case of cooperative carrying of the suspended load, the trajectory for quadrotor is generated such that the load distribution between the two quadrotors remain equal as the two quadrotors used are identical. Controller is designed in two loops: inner loop and outer loop. The inner loop stabilizes the attitude dynamics and is designed as a PD controller like that proposed in.[25] The outer loop facilitate the waypoint transition and trajectory tracking and is a combination of two PID controllers. Each PID controller works independent to the other. One PID controller controls the force to move the quadrotor to a desired waypoint or trajectory and the other PID controller works to control the swing and simultaneously damp the oscillation of the load. The combination of these two outer loop controllers, control the quadrotor(s) to accomplish the allotted task and simultaneously control the load motion. Validation of control law is done experimentally with the help of Vicon motion capture system. The above presented approach for outer loop is simple and different from existing approaches available in literatures. A major drawback of traditionally used input shaping approaches is that it works toward controlling the oscillation due to pilot input only while in real world external sources like wind gust and other disturbances can also contribute toward undesired oscillations in suspended load. The proposed controller works against both internal as well as external sources of oscillation. Further, the performance of input shaping depends on how exactly the free oscillation frequency of suspended load is determined, which in turn depends on the cable length and the mass of load. For the case where the oscillation frequency differs from the actual frequency, it would result in residual oscillation. The performance of the present model free approach is not expected to change significantly with small changes of length of cable and mass of load.

The paper is organized as follows. Section II contains derivation of dynamics equation of motion of the suspended load quadrotor system. The development of the PD controller for inner loop and PID controller for outer loop is presented in Section III. A brief description of experimental setup and used system hardware is discussed in Section A. Finally experimental validation and results are discussed in Section IV and Section V concludes the paper.

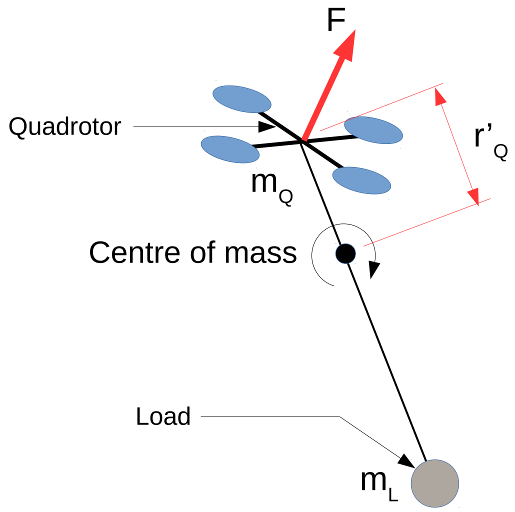
II. Flight Dynamic Modeling of Quadrotor with Suspended Load

The modeling of the quadrotor-slung load dynamics is widely available in literature. The Lagrangian method is widely used approach for deriving the equation of motion for the coupled quadrotor-load system.[2, 10, 12, 15, 21] The present work employs Newton-Euler method to derive the equation of motion for the quadrotor and the suspended load system. The following assumptions is made in derivation of the equation of motion: (i) The quadrotor and load are assumed to be rigid bodies; (ii) Point mass load is attached to the quadrotor centre of mass via a massless inextensible cable; (iii) Air drag on the quadrotor, load and cable is negligible; and (iv) Cable is assumed to be taut throughout the system operation. Figure 1 shows the quadrotor suspended load system in inertial X-Y-Z coordinate system. The position of load in the world frame can be written as

$$r_L = r_Q + \rho \tag{1}$$



(a) World Frame



(b) Relative Frame

Figure 1: Pictorial description of quadrotor suspended load system

The linear momentum balance equation of quadrotor with suspended load is

$$FRe_3 = m_Q\ddot{r}_Q + m_Q g e_3 + T \tag{2}$$

where e_3 is defined as $e_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$ and T is the tension in the cable due to the applied force on the load by the quadrotor and gravity which can be written as

$$T = m_L\ddot{r}_L + m_L g e_3 \tag{3}$$

Taking double derivative of Eq. (1) and combining with Eqs. (2) and (3) we get the final linear momentum balance equation

$$(m_Q + m_L)(\ddot{r}_L + g e_3) = FRe_3 + m_Q\ddot{\rho} \tag{4}$$

The time derivative of load position with respect to quadrotor, assuming cable is taut, can be written as

$$\dot{\rho} = \hat{\omega}\rho \tag{5}$$

where hat $(\hat{\cdot})$ is defined as $\hat{\omega}\rho = \omega \times \rho$. The angular momentum balance for suspended load system can be written as

$$r'_Q \times (RFe_3) + I'\dot{\omega} = 0 \tag{6}$$

where r'_Q is the position of centre of mass of the quadrotor and suspended load system with respect to quadrotor in the inertial frame as shown in Fig. 1(b). By definition of centre of mass, r'_Q is given as

$$r'_Q = \frac{m_L \rho}{m_Q + m_L} \tag{7}$$

The moment of inertia I' of the quadrotor suspended load system about its centre of mass is

$$I' = m_Q \left\| r'_Q \right\|^2 + m_L \left\| \rho - r'_Q \right\|^2 \tag{8}$$

Substituting the value of r'_Q and I' from Eqs. (7) and (8) into Eq. (6), followed by further simplification gives the following angular momentum balance equation for the suspended load

$$m_Q L^2 \dot{\omega} + \hat{\rho}(FRe_3) = 0 \tag{9}$$

The time derivative of rotation matrix R can be written as

$$\dot{R} = R\hat{\Omega} \tag{10}$$

Since, the load is suspended right at the centre of mass of the quadrotor, it does not have any effect on the angular momentum balance of the quadrotor. The angular momentum balance for the quadrotor is same as that for a rigid body, which is given as

$$M = \hat{\Omega}(I\Omega) + I\dot{\Omega} \tag{11}$$

where the external moment M on the quadrotor is due to the variation in thrust and torque of individual rotors. Taking the Eqs. (4), (5), (9), (10) and (11) together, the complete set of equations representing the coupled dynamics of the quadrotor with cable suspended load is given as

$$\left.\begin{aligned} \dot{r}_L &= v_L \\ (m_Q + m_L)(\ddot{r}_L + ge_3) &= FRe_3 + m_Q\ddot{\rho} \\ \dot{\rho} &= \hat{\omega}\rho \\ m_Q L^2 \dot{\omega} + \hat{\rho}(FRe_3) &= 0 \\ \dot{R} &= R\hat{\Omega} \\ M &= \hat{\Omega}(I\Omega) + I\dot{\Omega} \end{aligned}\right\} \tag{12}$$

The set of Eq. (12) is the same as that available in.[10,12,19] It should be noted from Eq. (12) that the quadrotor attitude dynamics (Eq. (11)) is decoupled from the load position (Eq. (4)) and load attitude dynamics (Eq. (9)).

III. Control Design

In this section, a cooperative control strategy is developed to control the motion of a quadrotor load system using linear control design techniques. A quadrotor suspended load system has four inputs and eight states to control. The inputs are thrust and three moments while the states are three position, three attitude of the quadrotor, and two relative position of load with respect to quadrotor in x-y plane. Thus this system is an under actuated system. The relative position of the load and quadrotor position can be controlled by the translation motions of the quadrotor. As known, quadrotor is an underactuated system and is controlled by exploiting differentially flatness with time scale separation principle. To solve the problem of cooperative load control and transportation, the following control objectives are defined: (i) Quadrotor should be able to hold a suspended load on a given position with no swing; (ii) Swing of the load should be damped immediately if perturbed; (iii) Transition between two load waypoints should happen with smaller load swing and fast damped load oscillation; and (iv) Load should track a given trajectory without undesired load oscillation.

To achieve the following control objectives, the design is divided into four parts. In the first part, the control design for position and attitude control of quadrotor is presented. In the second part, a strategy for position control of the load is presented. In the third part, a control algorithm is developed for quadrotor and load by combining the quadrotor and load control designs. In the fourth part, the trajectory generation of quadrotor(s) for given load trajectory is discussed.

A. Quadrotor Control

The quadrotor is an underactuated system and has been identified to be differentially flat, therefore it can be control by changing RPM of individual rotors. The general motion of the quadrotor is controlled by using a two loop structure: outer loop and inner loop. The outer loop is responsible for trajectory tracking, whereas, the inner loop provides attitude stabilization. For the outer loop, the inertial acceleration is computed as

$$\ddot{r}_Q^d = -K_{p_o} e_p - K_{i_o} \int_o^t e_p(t)dt - K_{d_o} \dot{e}_p + \ddot{r}_Q^{des} \tag{13}$$

where $K_{p_o}, K_{i_o}, K_{d_o}$ are positive definite gain matrices and $e_p = r_Q - r_Q^{des}$, where r_Q^{des} is the desired output of a quadrotor in the inertial frame. The required thrust and desired roll and pitch angles are computed from the desired position and heading as

$$\begin{aligned} T_d &= m_Q \sqrt{(\ddot{x}_Q^d)^2 + (\ddot{y}_Q^d)^2 + (g - \ddot{z}_Q^d)^2} \\ \phi_d &= \sin^{-1}(u_x \sin\psi_d - u_y \cos\psi_d) \\ \theta_d &= \sin^{-1}\left(\frac{u_x \cos\psi_d + u_y \sin\psi_d}{\cos\phi_d}\right) \end{aligned} \tag{14}$$

where $u_x = m_Q \ddot{x}_Q^d / T_d$ and $u_y = m_Q \ddot{y}_Q^d / T_d$. For attitude stabilization, the vehicle moments, $M = [l \;\; m \;\; n]^T$, are computed as

$$= I \left[-K_{p_i} e_E - K_{i_i} \int_o^t e_E(t)dt - K_{d_i} \dot{e}_E \right] \tag{15}$$

where $K_{p_i}, K_{i_i}, K_{d_i}$ are positive definite gain matrices and $e_E = [\phi - \phi_d \;\; \theta - \theta_d \;\; \psi - \psi_d]^T$, where superscript 'd' is used to denote the desired attitude.

B. Load Control

The relative position of the load with respect to quadrotor can be controlled by the translational motion of the quadrotor. The inertial acceleration required to generate the desired motion of the load in the inertial frame is computed as

$$\ddot{r}_L^d = -K_{p_L} e_L - K_{d_L} \dot{e}_L \tag{16}$$

where K_{p_L}, K_{d_L} are positive definite gain matrices and $e_L = \rho - \rho^{des}$, where $\rho = [\rho_x, \rho_y, \rho_z]^T$ and ρ^{des} is the desired position of the load with respect to the quadrotor. Once $\ddot{r}_L^d$ is computed, the desired thrust, roll, and pitch angles can be computed from Eq. (14) by replacing $[\ddot{x}, \ddot{y}, \ddot{z}]$ with $[\ddot{x}_L, \ddot{y}_L, \ddot{z}_L]$. For attitude stabilization, the vehicle moments is computed using Eq. (15).

C. Quadrotor and Load Control

For the given quadrotor and load positions, the inertial accelerations required is given in Eqs. (13) and (16). There are six equations and three inputs ($[T^{des}, \phi^{des}, \theta^{des}]^T$), it is not possible to satisfy all equations together. Therefore, the control is computed as follows:

$$\ddot{r}_{QL}^d = \ddot{r}_Q^d + \ddot{r}_L^d \tag{17}$$

Once $\ddot{r}_{QL}^d$ is computed, the desired thrust, roll, and pitch angles can be computed from Eq. (14) by replacing $[\ddot{x}_Q^d, \ddot{y}_Q^d, \ddot{z}_Q^d]$ with $[\ddot{x}_{QL}^d, \ddot{y}_{QL}^d, \ddot{z}_{QL}^d]$ and m_Q with $(m_Q + m_L)$. For attitude stabilization, the vehicle moments is computed using Eq. (15). A block diagram of control structure is shown in Fig. 2.

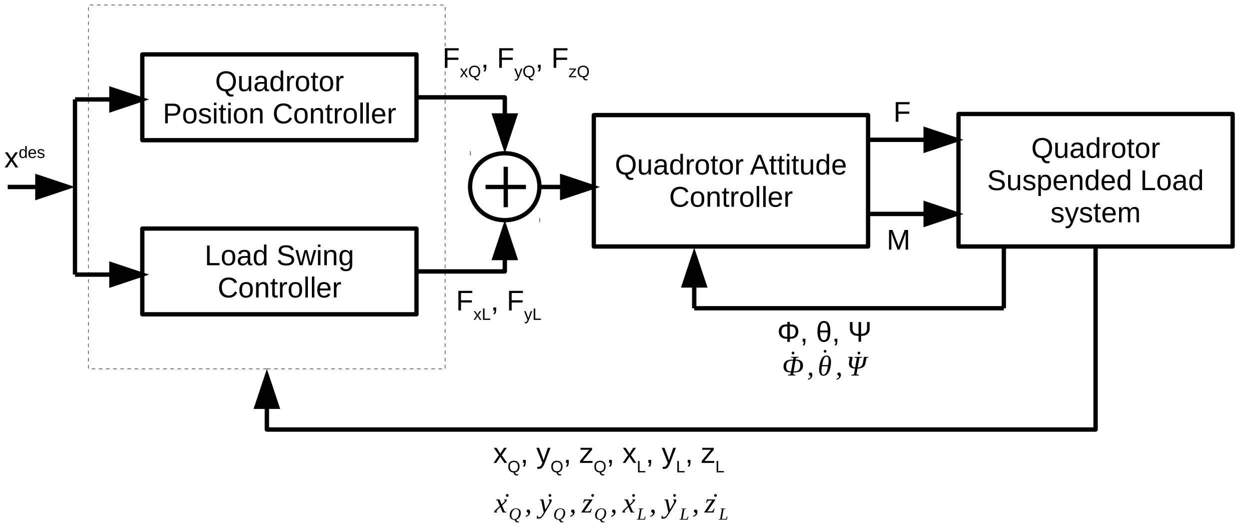
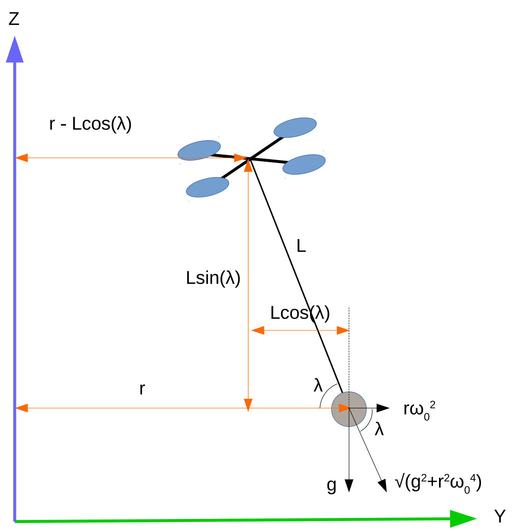


Figure 2: Control structure for quadrotor suspended load system

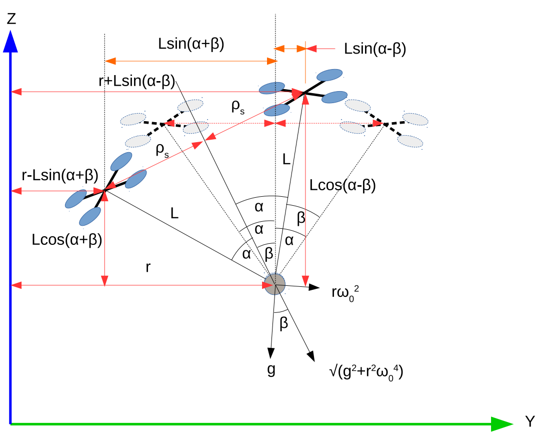
D. Cooperative Load Transportation

In order to follow a given load trajectory, not only the position of the load but also the position of quadrotor needs to be controlled. In this direction, the desired position of the quadrotor is determined for the given position of the load. Consider a case of a quadrotor with suspended load as shown in Fig. 3. For this case, it is required to follow a circular trajectory by suspended load in x-y plane with radius r and angular speed ω_0. It is assumed that the altitude of the load remain constant throughout trajectory tracking. The starting point is considered as $x = r, y = 0, z = h$. The load trajectory in inertial frame is given as follows.

$$\begin{bmatrix} x_L^{des} = rcos(\omega_0 t) \\ y_L^{des} = rsin(\omega_0 t) \\ z_L^{des} = h \end{bmatrix}, \begin{bmatrix} \dot{x}_L^{des} = -r\omega_0 sin(\omega_0 t) \\ \dot{y}_L^{des} = r\omega_0 cos(\omega_0 t) \\ \dot{z}_L^{des} = 0 \end{bmatrix}, \begin{bmatrix} \ddot{x}_L^{des} = -r\omega_0^2 cos(\omega_0 t) \\ \ddot{y}_L^{des} = -r\omega_0^2 sin(\omega_0 t) \\ \ddot{z}_L^{des} = 0 \end{bmatrix} \tag{18}$$



(a) A single quadrotor system



(b) A two quadrotor system

Figure 3: Trajectory generation geometries

From the geometric considerations (see Fig. 3), one can define $cos\gamma = \frac{r\omega_0^2}{\sqrt{r^2\omega_0^4+g^2}}$. Using the geometric relation, the desired trajectory of quadrotor required to satisfy the given desired trajectory of load is as follows

$$\begin{bmatrix} x_Q^{des} = (r - Lcos\gamma)cos(\omega_0 t) \\ y_Q^{des} = (r - Lcos\gamma)sin(\omega_0 t) \\ z_Q^{des} = z_L^{des} + Lsin\gamma \end{bmatrix}, \begin{bmatrix} \dot{x}_Q^{des} = -(r - Lcos\gamma)\omega_0 sin(\omega_0 t) \\ \dot{y}_Q^{des} = (r - Lcos\gamma)\omega_0 cos(\omega_0 t) \\ \dot{z}_Q^{des} = 0 \end{bmatrix}, \begin{bmatrix} \ddot{x}_Q^{des} = -(r - Lcos\gamma)\omega_0^2 cos(\omega_0 t) \\ \ddot{y}_Q^{des} = -(r - Lcos\gamma)\omega_0^2 sin(\omega_0 t) \\ \ddot{z}_Q^{des} = 0 \end{bmatrix} \tag{19}$$

The desired trajectory of load with reference to quadrotor trajectory in inertial frame is given as follows

$$\begin{bmatrix} \rho_x^{des} = Lcos\gamma cos(\omega_0 t) \\ \rho_y^{des} = Lcos\gamma sin(\omega_0 t) \end{bmatrix} \text{and} \begin{bmatrix} \dot{\rho}_x^{des} = -Lcos\gamma\omega_0 sin(\omega_0 t) \\ \dot{\rho}_y^{des} = Lcos\gamma\omega_0 cos(\omega_0 t) \end{bmatrix} \tag{20}$$

Consider a case of two quadrotors and a single load as shown in Fig. 3. The load is again asked to follow a circular trajectory with radius r and angular speed ω_0. The trajectory of the load is the same as given above for a single quadrotor case. The trajectory given to individual quadrotor should be such that the load distribution between the quadrotors remain equal when load maneuverer take place on its trajectory. Therefore, the first quadrotor Q1 encircles the given circle in the following manner.

$$\begin{bmatrix} x_{Q1}^{des} = r^+ cos(\omega_0 t) \\ y_{Q1}^{des} = r^+ sin(\omega_0 t) \\ z_{Q1}^{des} = z_L^{des} + Lcos(\alpha - \beta) \end{bmatrix}, \begin{bmatrix} \dot{x}_{Q1}^{des} = -r^+\omega_0 sin(\omega_0 t) \\ \dot{y}_{Q1}^{des} = r^+\omega_0 cos(\omega_0 t) \\ \dot{y}_{Q1}^{des} = 0 \end{bmatrix}, \begin{bmatrix} \ddot{x}_{Q1}^{des} = r^+\omega_0^2 cos(\omega_0 t) \\ \ddot{y}_{Q1}^{des} = -r^+\omega_0^2 sin(\omega_0 t) \\ \ddot{z}_{Q1}^{des} = 0 \end{bmatrix} \tag{21}$$

where $r^+ = r + Lsin(\alpha - \beta)$ $\alpha = tan^{-1}(\frac{\rho_y}{\sqrt{(L^2-\rho_y^2)}})$ and $\beta = tan^{-1}(\frac{r\omega_0^2}{g})$. The trajectory of second quadrotor Q2 is given as follows.

$$\begin{bmatrix} x_{Q2}^{des} = r^- cos(\omega_0 t) \\ y_{Q2}^{des} = r^- sin(\omega_0 t) \\ z_{Q2}^{des} = z_L^{des} + Lcos(\alpha + \beta) \end{bmatrix}, \begin{bmatrix} \dot{x}_{Q2}^{des} = -r^-\omega_0 sin(\omega_0 t) \\ \dot{y}_{Q2}^{des} = r^-\omega_0 cos(\omega_0 t) \\ \dot{z}_{Q2}^{des} = 0 \end{bmatrix}, \begin{bmatrix} \ddot{x}_{Q2}^{des} = -r^-\omega_0^2 cos(\omega_0 t) \\ \ddot{y}_{Q2}^{des} = -r^-\omega_0^2 sin(\omega_0 t) \\ \ddot{z}_{Q2}^{des} = 0 \end{bmatrix} \tag{22}$$

where $r^- = r - Lsin(\alpha + \beta)$ The trajectory of load with respect of quadrotors Q1 and Q2 is given as

$$\begin{bmatrix} \rho_{x1}^{des} = Lsin(\alpha - \beta)cos(\omega_0 t) \\ \rho_{y1}^{des} = Lsin(\alpha - \beta)sin(\omega_0 t) \\ \rho_{x2}^{des} = Lsin(\alpha + \beta)cos(\omega_0 t) \\ \rho_{y2}^{des} = Lsin(\alpha + \beta)sin(\omega_0 t) \end{bmatrix} \text{and} \begin{bmatrix} \dot{\rho}_{x1}^{des} = -Lsin(\alpha - \beta)\omega_0 sin(\omega_0 t) \\ \dot{\rho}_{y1}^{des} = Lsin(\alpha - \beta)\omega_0 cos(\omega_0 t) \\ \dot{\rho}_{x2}^{des} = -Lsin(\alpha + \beta)\omega_0 sin(\omega_0 t) \\ \dot{\rho}_{y2}^{des} = Lsin(\alpha + \beta)\omega_0 cos(\omega_0 t) \end{bmatrix} \tag{23}$$

IV. Experimental Results

This section contains the results from experiments conducted to validate the controller described earlier. Experimental results are presented for suspended load with one and two quadrotors for position hold, point to point translational motion in both load swing control mode and without swing control mode and trajectory tracking of the load with different angular speeds to validate the proposed controller.

A. Exprimental Setup

Figure 4 shows the schematic of the arrangement of motion capture system established in Micro Air Vehicle Lab at Aerospace Engineering Department, IIT Kanpur. The network of infrared cameras, Ethernet switch and host PC with NIC card (Network Interface Card) are the main hardware parts of motion capture system. Host PC is installed with motion capture software Vicon Tracker, provided by Vicon Motion Systems Ltd UK for accurate tracking of the states of the quadrotor and the suspended load.

Host PC provides the position and orientation of quadrotor and suspended load (both are fitted with marker) to the ground control station at the rate of 50 Hz. Ground control PC installed with ROS (Robot

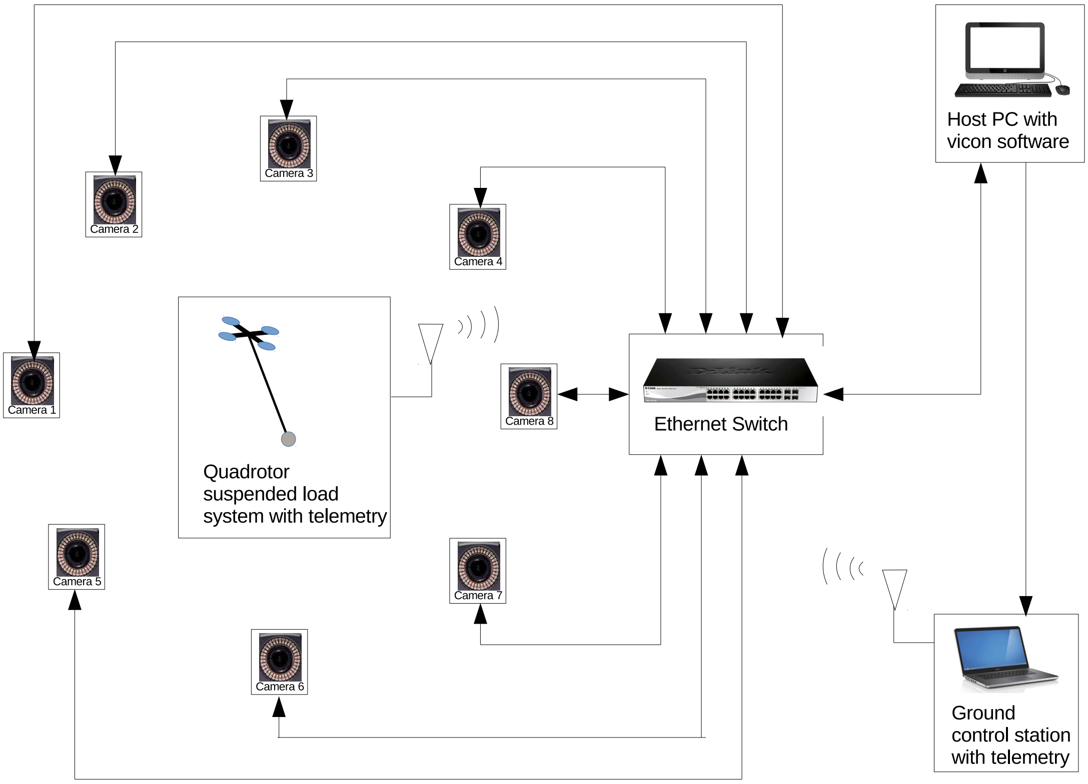


Figure 4: Schematic depicting the arrangement of motion capture system used for experimental validation of controller

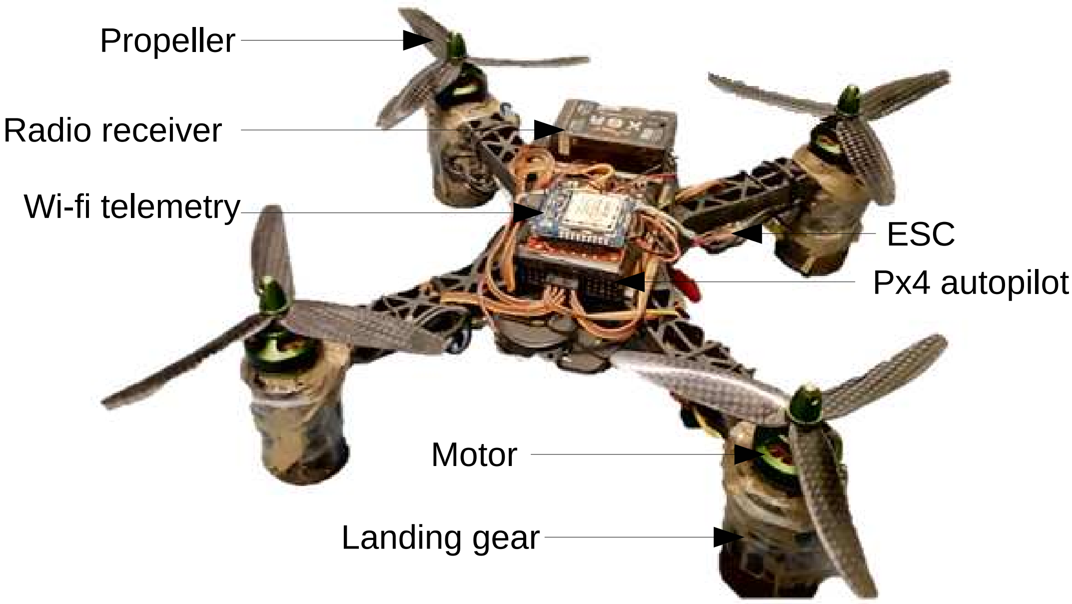
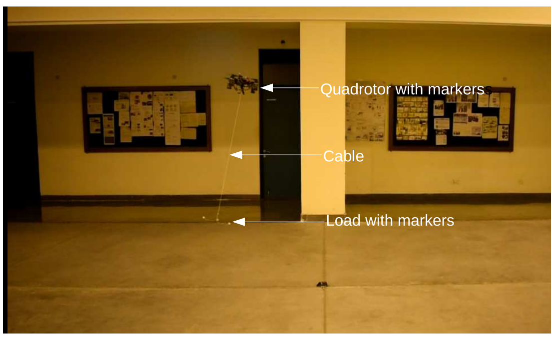
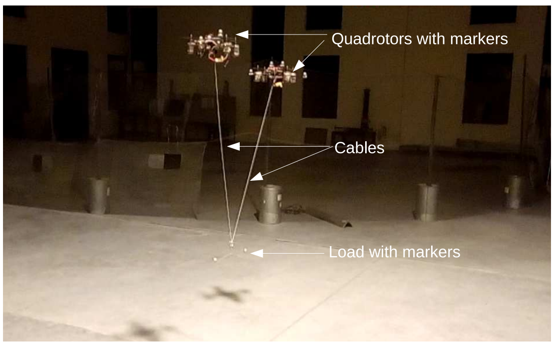


Figure 5: Quadrotor used in experiments



(a) A single quadrotor system



(b) A two quadrotor system

Figure 6: Transportation of suspended load with one and two quadrotors

Operating System) Indigo and is equipped with Wi-Fi module to communicate with quadrotor. Code of ground control station is written ussing C++ in ROS environment. MAVROS package of ROS is used to enable MAVLink as communication protocol between ground control station and quadrotor.

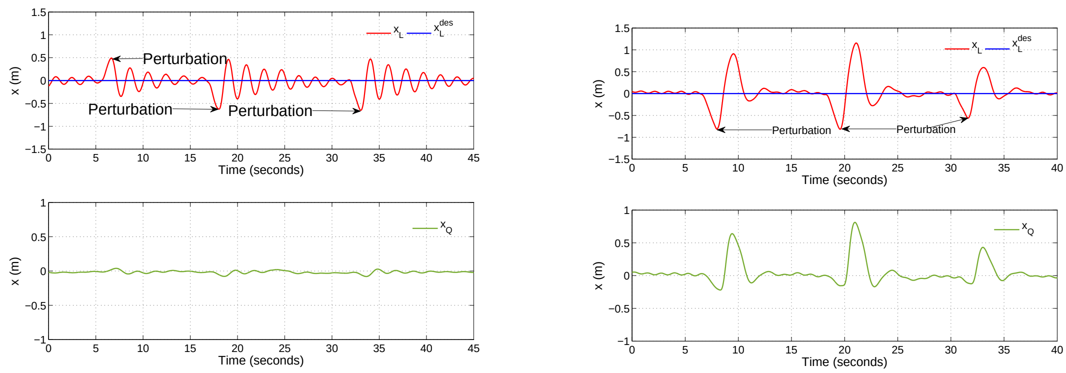
Ground control station which comes in outer loop of control structure, receives the position information of quadrotor and load from host PC and task command from the user and transmits attitude control command to the quadrotor.

For this experiment, an off-the-shelf small quadrotor frame was used which has a ready to fly mass of 500 gm. PixHawk autopilot board is used as autopilot which has inbuilt gyros, accelerometers and magnetometers. The inner loop runs on board at the rate of 200 Hz. Load mass of 22 gm is attached to the quadrotor via a 1.0 meter long inextensible string. The details of components used in conducting experiments is given in Table 1.

Table 1: Hardware

Component	Property	Weight(gm)
Frame	FPV250	140
Motor (CW/CCW)	Multistar Elite 2204-2300KV Multi-Rotor Motor 3-4S	30
Propeller (CW/CCW)	Carbon Fiber 3-blade Propeller 5x3	3.6
ESC	Afro ESC 12A	10
Px4 autopilot	PixHawk	36
Radio Rx	Fr SKY, X8R, 2.4 Ghz	19
Wi-Fi Telemetry	LairdTech RM024	11
Battery	LiPo, 3-cell, 1400 mAh	117
Others	Electrical wires, connectors, landing gear etc.	100

B. Demonstration of Controller Performance



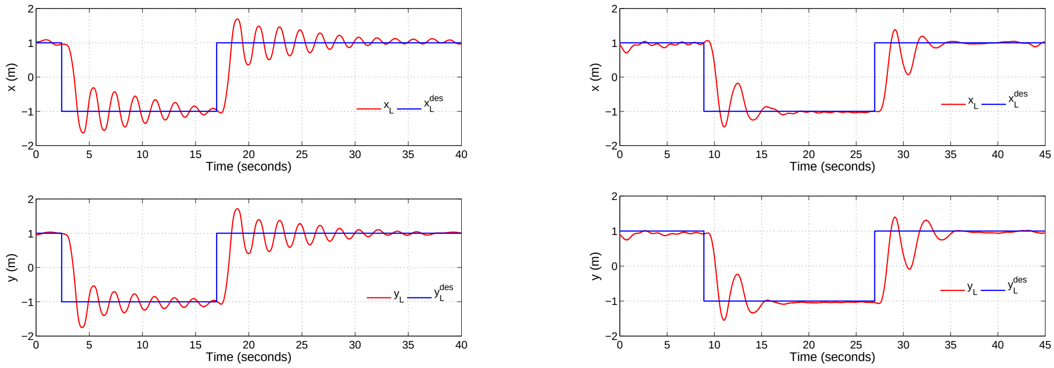
(a) Without swing control

(b) With swing control

Figure 7: Free and controlled swing of load with one quadrotor

Figure 7 shows the free swing and controlled swing of the suspended load for one quadrotor. In both the experiments load is perturbed manually three times using a wooden stick to impart swing to the load. The free swing of the suspended load, which takes more than 8 seconds to damp out, is shown in Fig. 7. It can be observed that the position of the quadrotor remains unchanged during this process. When the payload swing controller is turned on, the quadrotor moves to cancel out the swing of the load and the load comes to rest in 4-5 seconds as shown in Fig. 7.

After demonstrating the satisfactory performance of the quadrotor at canceling the oscillation of the suspended load, the quadrotor and the load is commanded to perform point to point flight. In this experiment,

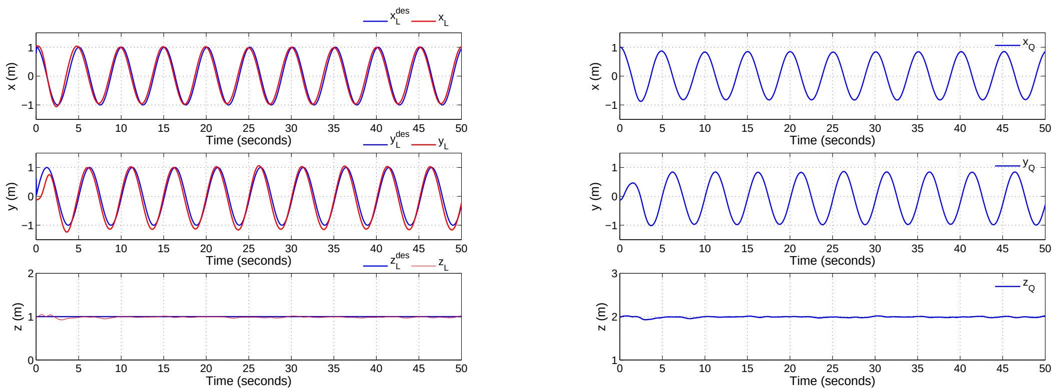


(a) Without swing control

(b) With swing control

Figure 8: Waypoint transition with and without controlling free swing

the quadrotor and the load system is commanded to move from position (1,1) m to (-1,-1) m, maintain position at that position and then move back to original position of (1,1) m. The time history of the motion of the suspended load with the swing controller "off" is shown in Fig. 8. It can be observed that the load undergoes significant oscillation during the entire flight and the oscillations take more than 10 seconds to subside. When the load swing controller is turned "on", the load oscillation is attenuated in a matter of 4-5 seconds as shown in Fig. 8. After testing the performance of the quadrotor for point to point translation, the system is commanded to trace a circle of 1 m radius with the load. The desired and measured trajectory of the load flown in a circle of 1 m radius at an angular velocity of 1.25 rad/sec is shown in Fig. 9. It is observed that the controller is able to achieve the desired objective satisfactorily. The corresponding trajectory of the quadrotor required for this flight is shown in Fig. 9.



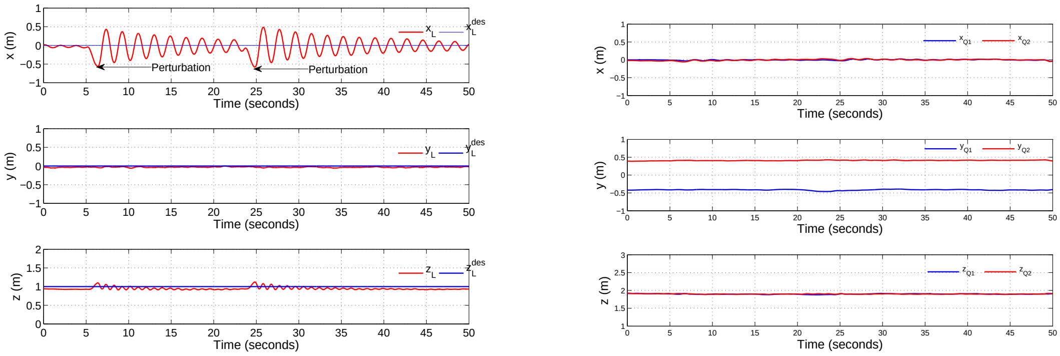
(a) Load position

(b) Quadrotor position

Figure 9: Positions of load and quadrotor

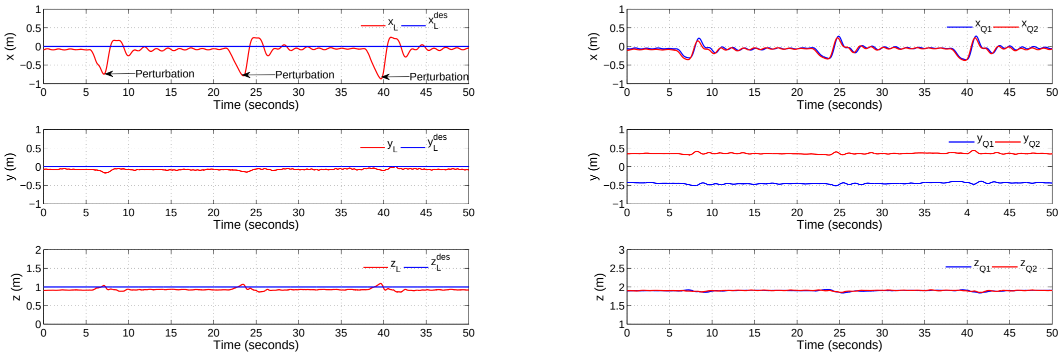
The load is next carried using two quadrotors cooperating for the task. The same set of experiments as that performed with single quadrotor with suspended load are repeated with the cooperating quadrotor system. Figure 10 shows the free oscillation of the load when the load swing controller is kept off. As expected, the load oscillation takes more than 10-15 seconds to die down (the only resistive force present here is air drag). The corresponding positions of the two quadrotors, which remains unchanged are shown in the figure. Once, the load swing controller is turned on, the load oscillation is canceled promptly in a matter of 4-5 second as shown in Fig. 11. The cooperative action of the two quadrotors for stabilization is symmetric as shown in the figure.

Next, the experiment of waypoint transition is conducted with and without swing load controller. Fig-



(a) Load position **(b)** Quadrotor position

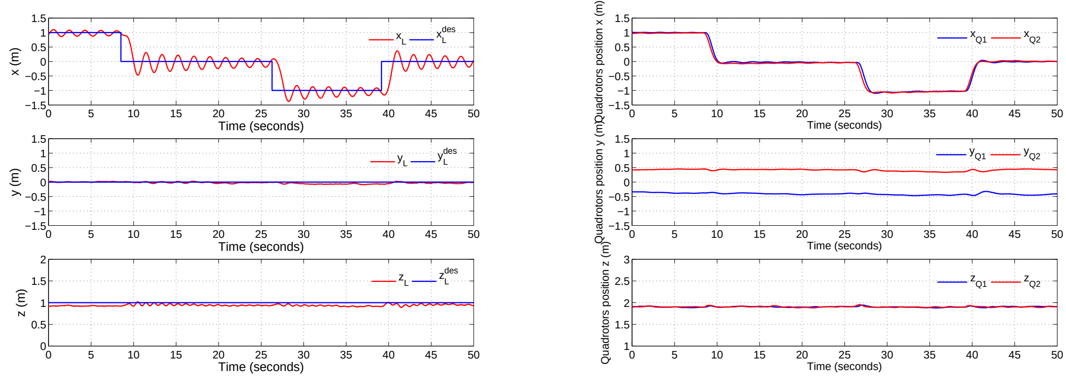
Figure 10: Free swing with two quadrotors



(a) Load position **(b)** Quadrotor position

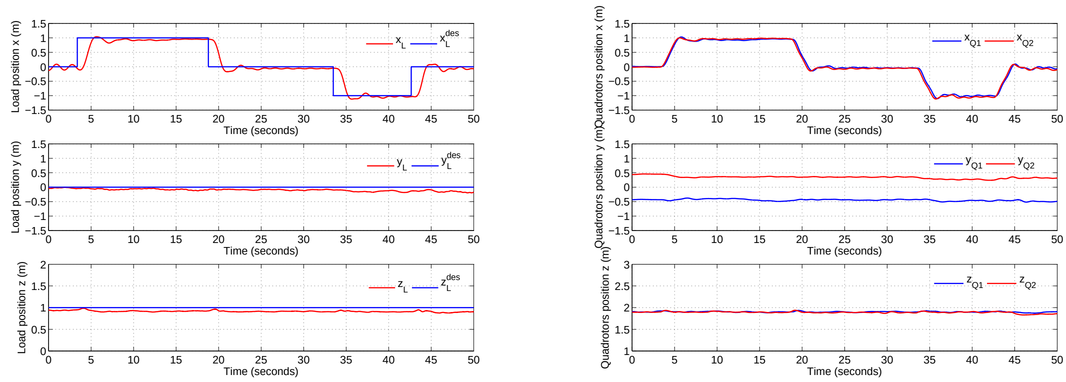
Figure 11: Cooperative swing control

ure 12 shows load and quadrotor positions without swing load controller. It can be seen from the figure that the load undergoes significant oscillation during the entire flight as observed in a single quadrotor system. The oscillations takes more than 15 seconds to subside. When the load controller is turned on, the load oscillation attenuates in a matter of 2-3 seconds as shown in Fig. 13. It can also seen from the figure that both quadrotors (x position) translates to cancel out swings.



(a) Load position **(b)** Quadrotor position

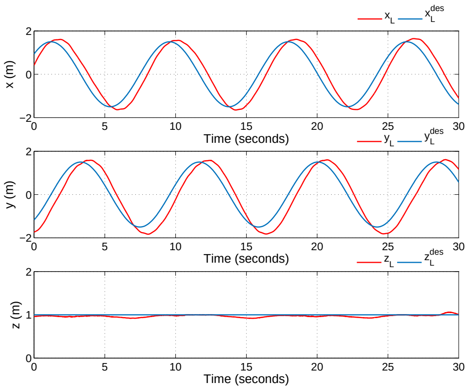
Figure 12: Waypoint transition with free swing



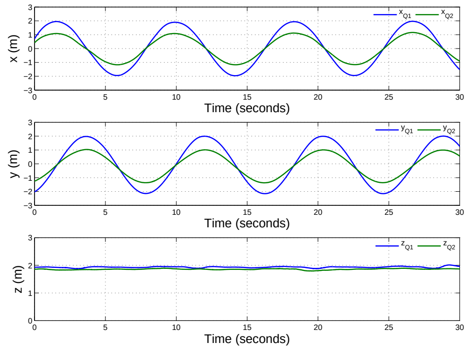
(a) Load position **(b)** Quadrotor position

Figure 13: Waypoint transition with control swing

In the final set of experiments, the load trajectory tracking performance is evaluated. Similar to the previous case, the performance is evaluated by commanding the load to trace a circle of 1 m radius. The desired and measured trajectory of the load flown in a circle of 1 m radius at an angular velocity of 0.75 rad/sec is shown in Fig. 14. It is observed that the controller is able to achieve the desired objective satisfactorily. The corresponding trajectory of the quadrotor required for this flight is also shown in the figure. It can be also seen from the figure that the cooperative action of the two quadrotors for trajectory tracking is symmetric as both quadrotors experience similar translation motion. Hence, the load is equally distributed. In this section, the performance of swing load controller is validated through experimental validation. It can be concluded that the proposed design is effecting in canceling out swing for cooperative load transportation.



(a) Load position



(b) Quadrotor position

Figure 14: Cooperative trajectory tracking of load

V. Conclusion

The problem of suspended payload transportation of quadrotor has been addressed in this paper using cooperative control. The cooperative control uses a combination of two PID controllers in the outer loop. The inner loop is designed using traditional PD approach. The first PID controller in the outer loop controls the motion of quadrotor whereas the second PID manages the swing and simultaneously damp the oscillation of the load. Thus, a combination facilitates point to point transition and trajectory tracking of the load. The approach is validated experimentally through three examples. The first examples has demonstrated that if load is perturbed, the controller quickly damps out load oscillations. The second example has demonstrated that the load can do waypoint transition without significant load oscillation. The third example has demonstrated cooperative trajectory tracking capabilities of the load. The performance of proposed designed is found to be satisfactorily from the real world experiment.

References

[1]Bernard, M., Kondak, K., Maza, I., and Ollero, A., "Autonomous transportation and deployment with aerial robots for search and rescue missions," *Journal of Field Robotics*, Vol. 28, No. 6, 2011, pp. 914–931.

[2]Lee, T., Leoky, M., and McClamroch, N. H., "Geometric tracking control of a quadrotor UAV on SE(3)," *49th IEEE Conference on Decision and Control (CDC)*, Dec 2010, pp. 5420–5425.

[3]Mellinger, D. and Kumar, V., "Minimum snap trajectory generation and control for quadrotors," *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, IEEE, 2011, pp. 2520–2525.

[4]Hehn, M. and D'Andrea, R., "Quadrocopter trajectory generation and control," *IFAC Proceedings Volumes*, Vol. 44, No. 1, 2011, pp. 1485–1491.

[5]Prabhakaran, B., Kothari, M., et al., "Nonlinear control design for quadrotors," *Computational Intelligence: Theories, Applications and Future Directions (WCI), 2015 IEEE Workshop on*, IEEE, 2015, pp. 1–6, DOI: 10.1109/WCI.2015.7495504.

[6]Gupta, N., Kothari, M., et al., "Flight dynamics and nonlinear control design for variable-pitch quadrotors," *American Control Conference (ACC), 2016*, IEEE, 2016, pp. 3150–3155, DOI: 10.1109/ACC.2016.7525402.

[7]Gupta, N., Kothari, M., et al., "Modeling and Control of Inverted Flight of a Variable-Pitch Quadrotor," *arXiv preprint arXiv:1709.06407*, 2017.

[8]Parwana, H., Patrikar, J., and Kothari, M., "A Novel Fully Quaternion based Nonlinear Attitude and Position Controller," *AIAA Guidance, Navigation and Control Conference and Exhibit*, 2018.

[9]Yomchinda, T., "Development of dynamic inversion based outer-loop anti-swing control law for a helicopter slung-load system," *2015 Asian Conference on Defence Technology (ACDT)*, April 2015, pp. 205–209.

[10]Sreenath, K., Lee, T., and Kumar, V., "Geometric control and differential flatness of a quadrotor UAV with a cable-suspended load," *Decision and Control (CDC), 2013 IEEE 52nd Annual Conference on*, IEEE, 2013, pp. 2269–2274.

[11]Klausen, K., Fossen, T. I., and Johansen, T. A., "Nonlinear control of a multirotor UAV with suspended load," *Unmanned Aircraft Systems (ICUAS), 2015 International Conference on*, IEEE, 2015, pp. 176–184.

[12]Sreenath, K., Michael, N., and Kumar, V., "Trajectory generation and control of a quadrotor with a cable-suspended load-a differentially-flat hybrid system," *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, IEEE, 2013, pp. 4888–4895.

[13] Bisgaard, M., la Cour-Harbo, A., and Bendtsen, J. D., "Adaptive control system for autonomous helicopter slung load operations," *Control Engineering Practice*, Vol. 18, No. 7, 2010, pp. 800–811.

[14] Potter, J., Singhose, W., and Costelloy, M., "Reducing swing of model helicopter sling load using input shaping," *2011 9th IEEE International Conference on Control and Automation (ICCA)*, Dec 2011, pp. 348–353.

[15] Sadr, S., Moosavian, S. A. A., and Zarafshan, P., "Dynamics modeling and control of a quadrotor with swing load," *Journal of Robotics*, Vol. 2014, 2014.

[16] Nicotra, M. M., Garone, E., Naldi, R., and Marconi, L., "Nested saturation control of an uav carrying a suspended load," *American Control Conference (ACC), 2014*, IEEE, 2014, pp. 3585–3590.

[17] Cruz, P. J., Oishi, M., and Fierro, R., "Lift of a cable-suspended load by a quadrotor: A hybrid system approach," *American Control Conference (ACC), 2015*, IEEE, 2015, pp. 1887–1892.

[18] Alothman, Y., Jasim, W., and Gu, D., "Quad-rotor lifting-transporting cable-suspended payloads control," *Automation and Computing (ICAC), 2015 21st International Conference on*, IEEE, 2015, pp. 1–6.

[19] Tang, S. and Kumar, V., "Mixed integer quadratic program trajectory generation for a quadrotor with a cable-suspended payload," *Robotics and Automation (ICRA), 2015 IEEE International Conference on*, IEEE, 2015, pp. 2216–2222.

[20] Bernard, M. and Kondak, K., "Generic slung load transportation system using small size helicopters," *2009 IEEE International Conference on Robotics and Automation*, May 2009, pp. 3258–3264.

[21] Lee, T., Sreenath, K., and Kumar, V., "Geometric control of cooperating multiple quadrotor UAVs with a suspended payload," *Decision and Control (CDC), 2013 IEEE 52nd Annual Conference on*, IEEE, 2013, pp. 5510–5515.

[22] Goodarzi, F. A. and Lee, T., "Dynamics and control of quadrotor UAVs transporting a rigid body connected via flexible cables," *2015 American Control Conference (ACC)*, July 2015, pp. 4677–4682.

[23] Sreenath, K. and Kumar, V., "Dynamics, control and planning for cooperative manipulation of payloads suspended by cables from multiple quadrotor robots," *rn*, Vol. 1, No. r2, 2013, pp. r3.

[24] Pizetta, I. H. B., Brandão, A. S., and Sarcinelli-Filho, M., "Cooperative quadrotors carrying a suspended load," *Unmanned Aircraft Systems (ICUAS), 2016 International Conference on*, IEEE, 2016, pp. 1049–1055.

[25] Bouabdallah, S. and Siegwart, R., "Full control of a quadrotor," *Intelligent robots and systems, 2007. IROS 2007. IEEE/RSJ international conference on*, Ieee, 2007, pp. 153–158.