Adaptive Control of Aerial Manipulation Vehicle

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***Abstract*—Adaptive Control of an Aerial Manipulation Vehicle is discussed here. The aerial manipulation vehicle consisting of a quadrotor and a robotic arm has a highly coupled dynamics. The nonlinear coupling introduces additional forces and moments on the quadrotor which prevents it from precisely hovering at a position and tracking of reference trajectory. A decentralized control of robotic arm and quadrotor is considered. The robotic arm is controlled by a PID approach with acceleration feedback, and the quadrotor is controlled by PD method in the inner loop and adaptive position control in the outer loop. The proposed method successfully handles the problem of hover stabilization and trajectory tracking.**

***Index Terms*- Aerial Vehicle, Robotic Arm, Adaptive control.**

I. INTRODUCTION

The Area of aerial manipulation has attracted enormous interest in the community of robotics in recent years. The reason behind this aspect is that the active tasking of UAV increases the employability of these vehicles. Interesting applications would be grasping, manipulation, transportation etc. These interesting applications have their own challenges and have been the subject of various research activities.

In [1] the load disturbance on a helicopter introduced by a gripped object was studied experimentally and stability bounds were determined. Here the manipulator was a simple gripper which holds the object between the skids of the helicopter. In [2] a ducted fan UAV interacting with the environment was modelled and controlled. In this case the interaction was modelled as a simple contact.

In [3] and [4] Cartesian Impedence control and redundancy had been studied using Euler-Lagrange formulation. In [5] and [6] a Newton-Euler approach had been used to model and control a quadrotor based manipulator. In [7] a Lyapunov based Model Reference Adaptive Control was used to stabilize a quadrotor with multi degree of freedom manipulator. But due to the complexity of the system only rigid body dynamics of the quadrotor were considered.

In [8] a vision based sensor was used to control a helicopter with manipulator experimentally using a simple gripper attached to the fuselage. In [9] indoor experiments were performed with a quadrotor equipped with a gripper and an IR camera was used to grip an object with LED placed on it.

In [10] Adaptive control was used to handle the problem of changes in the center of gravity due to load transportation and an optimal trajectory generation based on dynamic programming was developed for swing free manoeuvring. Here experiments were performed in an indoor environment with VICON system for precise information of position and orientation. In [11], [12] adaptive control was used with explicitly considering external disturbances in stability analysis. Here the problem due to shift in center of mass which is normally caused during manipulation of objects is handled. Here an adaptive position control was used in the outer loop and inner loop consist of PD roll-pitch control with center of mass estimation.

Compared to [11], [12], in the current research the problem of disturbance due to manipulator with payload is handled purely by adaptation of the outer position loop. Here a hypothesis is considered that a manipulator with payload will introduce external moments on the airframe which will finally prevent the quadrotor to reach or track a position reference. Hence an adaptive control in position loop should be sufficient to handle our problem as long as the inner attitude loop is stabilized properly.

Additional contributions of this article include the development of an Aerial Manipulation system where the complete non-linearity of the quadrotor is considered along with 2-link manipulator dynamics based on Recursive Newton Euler (RNE) formulation.

The paper is structured as follows. First the quadrotor dynamic is briefly described, then a Recursive Newton-Euler (RNE) method for a Floating base 2-link Manipulator is formulated. The dynamic model of the composite Aerial Manipulation Vehicle is presented. The control design of the quadrotor and the robotic arm is discussed and validated using simulations.

II. QUADROTOR DYNAMICS

Let $\mathbb{I} = \{\mathbb{I}_x, \mathbb{I}_y, \mathbb{I}_z\}$ be the inertial frame, $\xi = (x, y, z)$ be the origin of the body fixed frame $\mathbb{B} = \{\mathbb{B}_1, \mathbb{B}_2, \mathbb{B}_3,\}$. The rotation matrix R is defined by $R : \mathbb{B} \to \mathbb{I}$. Here v and Ω are linear and angular velocities in the body reference frame $\mathbb{A}$. The model used here is based on [13], [14]:

$$\begin{bmatrix} \mathbf{m} & 0 \\ 0 & \mathbf{I} \end{bmatrix} \begin{bmatrix} \dot{\mathrm{v}} \\ \dot{\Omega} \end{bmatrix} + \begin{bmatrix} 0 \\ \Omega \times \mathbf{I}\Omega \end{bmatrix} = \begin{bmatrix} \mathbf{G} + T \\ \mathbf{Q} + M \end{bmatrix} \qquad (1)$$

where we have $\mathbf{G} = \mathbf{m} g R^T e_3$ with $e_3 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$, $T = \sum_i t_i$, $\mathbf{Q} = \sum_i q_i$, $M = \sum_i m_i$ and for $i \in \{N, S, E, W\}$ we have rotor thrust $t_i = C_T \rho A r^2 \varpi_i^2 \mathbf{t}_{flap}$, torque $q_i = C_Q \rho A r^3 \varpi_i |\varpi_i| e_3$ and moment $m_i = t_i \times \mathbf{d}_i$.

The physical parameters the model depends on are mass $\mathbf{m}$, Inertia $\mathbf{I}$, gravity g, ρ the air density, r is the rotor radius with A the area of the rotor disc, $\mathbf{d}_i$ is the rotor distance from the quadrotor center of mass with $\mathbf{d}_N = \begin{pmatrix}0 & d & h\end{pmatrix}$, $\mathbf{d}_S = \begin{pmatrix}0 & -d & h\end{pmatrix}$, $\mathbf{d}_E = \begin{pmatrix}d & 0 & h\end{pmatrix}$, $\mathbf{d}_W = \begin{pmatrix}-d & 0 & h\end{pmatrix}$. Here d is the arm length of the quadrotor and h is the height of the rotors above the Center of Gravity. The term $\mathbf{t}_{flap}$ is a function of longitudinal and lateral flapping angles [13] and the constants C_T and C_Q are nondimensional thrust and torque coefficients respectively.

The quadrotor is controlled by the variation of forces and moments which can be obtained as a variation of rotor speeds $\begin{pmatrix}\varpi_1^2 & \varpi_2^2 & \varpi_3^2 & \varpi_4^2\end{pmatrix}^T = \mathbf{A}^{-1}\begin{pmatrix}T & \tau_x & \tau_y & \tau_z\end{pmatrix}^T$. Where $\mathbf{A}$ is a function of known parameters [15], [16], T is the total upward thrust as defined earlier and $M = (\tau_x, \tau_y, \tau_z)$ are the rolling, pitching and yawing torque applied to the body of the quadrotor.

III. Robotic Arm with a Floating Base

Here the dynamic equation of the robotic arm is discussed [17]. Formulation of dynamic equations of motions helps to understand the nonlinear behaviour of the system which is key to the efficient design of control laws. Different modeling methods exist in literature such as Newton-Euler, design based on Principle d'Alembert, Lagrange equations of motion, Kane's method , Gibbs-Appell equations of motions. But the Newton-Euler method is used here as it helps us to systematically integrate the robotic arm to the quadrotor model which was also based on Newton-Euler formulation.

A number of dedicated methods exists for floating base manipulators for example see [18]. One of the simplest way is to initialize the velocities and accelerations of the base link at a non-zero value. These velocities and accelerations are in turn transmitted from one link to another by forward recursion and would result in an additional resultant torque.

The manipulator to be considered is an open-chain mechanism consisting of N joints numbered from 1 to N connecting $N+1$ rigid links numbered from 0 to N. Link 0 is the base of the manipulator where as N carries the end-effector.

Here first the Kinematics [14] is discussed and then the Recursive Newton-Euler (RNE) Formulation is detailed.

A. Kinematics

A standard Denavit-Hartenberg convention is employed here. A joint i connects link $i-1$ to link i and hence the joint i moves link i. A link is defined by its length a_i and twist α_i. Similarly joints are defined through link offset d_i and joint angle θ_i. Here the coordinate frame $\{i\}$ is attached to the far end of the link i and the axis of joint i is aligned with the z_i-axis. In this convention the transformation from link coordinate frame $\{i-1\}$ to frame $\{i\}$ is defined by rotation and translation as [14]

$$^{i-1}A_i(\theta_i, d_i, a_i, \alpha_i) = T_{Rz}(\theta_i)T_z(d_i)T_x(a_i)T_{Rx}(\alpha_i) \quad (2)$$

which can be given as

$$^{i-1}A_i = \begin{pmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3)$$

where $c\theta, s\theta$ etc stands for $\cos\theta, \sin\theta$ respectively and similarly for other angles used in the above equation.

B. Newton-Euler Dynamic Equations of Motion

First the link specific parameters are defined. Here m_i is the mass of the link i, r_i is the location of the center of mass of link i with respect to origin of link i coordinates and I_i is the inertia matrix of the link i. A Recursive formulation consisting of Forward computation of velocities and accelerations of each link and Backward computation of forces and moments in each joints is discussed. The Recursive Newton-Euler formulation for fixed based was discussed in [19], [20] .This method is further detailed here but only the rotational joint will be considered since it is the one being used here.

1) Forward Recursion: Here the angular/linear velocities and accelerations of each link is calculated recursively in terms of its preceding link starting from the base to the end effector. The initial conditions for the base links are $v_0 = \mathrm{v},\ \dot{v}_0 = \dot{\mathrm{v}}$ and $\omega_0 = \Omega,\ \dot{\omega}_0 = \dot{\Omega}$ and are equal to that of the current velocity and accelerations of the quadrotor. With these initializations the following equations are calculated

$$\omega_i = \omega_{i-1} + z_{i-1}\dot{q}_i \quad (4)$$
$$\dot{\omega}_i = \dot{\omega}_{i-1} + z_{i-1}\ddot{q}_i + \omega_{i-1} \times z_{i-1}\dot{q}_1 \quad (5)$$

$$v_i = \omega_i \times p_i^* + v_{i-1} \quad (6)$$
$$\dot{v}_i = \dot{\omega}_i \times p_i^* + \omega_i \times (\omega_i \times p_i^*) + \dot{v}_{i-1} \quad (7)$$

$$\ddot{r}_i = \dot{\omega}_i \times r_i + \omega_i \times (\omega_i \times r_i) + \dot{v}_i \quad (8)$$
$$N_i = I_i\dot{\omega}_i + \omega_i \times (I_i \cdot \omega_i) \quad (9)$$
$$F_i = m_i\ddot{r}_i \quad (10)$$

where $p^* = \begin{bmatrix}d_i & a_i\sin\theta_i & a_i\cos\theta_i\end{bmatrix}^T$ and the above variables are defined here

- ω_i angular velocity of link i
- $\dot{\omega}_i$ angular acceleration of link i
- v_i linear velocity of origin of link i coordinates with respect to link $i-1$ coordinates
- $\dot{v}_i$ linear acceleration of origin of link i coordinates with respect to link $i-1$ coordinates
- $\ddot{r}_i$ linear acceleration of link i center of mass
- F_i total force exerted on link i
- N_i total moment exerted on link i
- q_i joint variable (θ_i) at joint i

2) Backward recursion: After the velocities and accelerations of the links are computed, the joint forces can be computed for each link starting from the end-effector to the base. The required equations are

$$n_i = n_{i+1} + N_i + (p_i^* + r_i) \times F_i + p_i^* \times f_{i+1} \tag{11}$$

$$f_i = F_i + f_{i+1} \tag{12}$$

$$\tau_i = z_{i-1} \cdot n_i \tag{13}$$

where the above variables are

n_i moment exerted on link i by link $i-1$
f_i forces exerted on link i by link $i-1$
τ_i torque exerted by actuator at joint i (rotational)

These equations are used to compute the joint torque by using velocities, accelerations, forces and moments in the local link coordinate.

3) Equation of Motion: The equation of motion of a manipulator can be written in a general form as [14], [19]

$$Q_m = M_m(q)\ddot{q} + C_m(q,\dot{q})\dot{q} + F_m(\dot{q}) + G_m(q) + J_m(q)^T w_e \tag{14}$$

where q, $\dot{q}$ and $\ddot{q}$ are respectively the joint coordinates, velocities and accelerations, M_m is the joint-space inertia matrix, C_m is the Coriolis and centripetal matrix, F_m is the friction force, G_m is the gravity loading and Q_m is the vector of actuator forces at the coordinate q. The last term gives the joint force due to wrench w_e applied at the end-effector and J_m is the manipulator Jacobian. Different methods exist to compute the above inverse dynamic equation (14) but the Method-1 of [20] will be used here. This method is based on the Recursive Newton Euler method discussed earlier.

IV. Quadrotor with Robotic Arm

The coupled equations of motion for the quadrotor with manipulator is

$$\begin{bmatrix} \mathbf{m} & 0 \\ 0 & \mathbf{I} \end{bmatrix} \begin{bmatrix} \dot{\mathrm{v}} \\ \dot{\Omega} \end{bmatrix} + \begin{bmatrix} 0 \\ \Omega \times \mathbf{I}\Omega \end{bmatrix} = \begin{bmatrix} \mathbf{G} + T \\ \mathbf{Q} + M \end{bmatrix} + \begin{bmatrix} f \\ n \end{bmatrix}. \tag{15}$$

where the vector $\begin{bmatrix} f & n \end{bmatrix}^T$ are forces and moments exerted by the manipulator on the quadrotor.

In order to analyse and study the complex dynamic behaviour of the Aerial Manipulation Vehicle (AMV), a benchmark problem was developed. The robotics simulation environment of [14] was used to implement the robotic arm and quadrotor model [13]. The quadrotor developed in [13] is a 4 Kg vehicle with a maximum payload of 1 Kg. Hence it was a suitable choice for the current problem considered here. A manipulator with three joints having two links was chosen here with lengths $a_1 = 0.25$ m,$a_2 = 0.35$ m and mass $m_1 = 0.1$ Kg,$m_2 = 0.12$ Kg with inertia matrix $I = ma^2/12 \ \mathrm{diag}(0,1,1)$. Here m and a are mass and length of each link independently.

V. Control of Quadrotor with Robotic Arm

The control of the composite system of Quadrotor and Manipulator or the Aerial Manipulation Vehicle can be subdivided into Independent control of Quadrotor and Manipulator. The two aspects will be discussed further here.

A. Control of Quadrotor

The basic control structure of the quadrotor can be seen in Figure-1 which is a hierarchical structure. The control of manipulator is also added to the structure.Starting with the quadrotor control a clear time scale separation is evident from the structure. First the inner-loop attitude control is discussed and then the outer-loop position control.

1) Baseline Attitude Control: The inner loop which has a fast dynamic uses a PD control for coupled pitch and roll dynamics. A simple controller could then be

$$U_{pr} = -K_p \left(\varepsilon_{pr} - K_d \dot{\Theta}_{pr} \right) \tag{16}$$

where we have $\varepsilon_{pr} = \Theta_{pr}^* - \Theta_{pr}$, with Θ_{pr}^* as the pitch and roll demand, U_{pr} gives us pitch (τ_y) and roll torque (τ_x). Similarly a PD control is also used for the yaw control loop

$$U_{yaw} = -K_p \left(\varepsilon_{yaw} - K_d \Omega_z \right) \tag{17}$$

where $\varepsilon_{yaw} = \psi^* - \psi$ is the yaw error with yaw demand ψ^*.

2) Adaptive Outer Loop Position control: The position control can be further divided into altitude control and horizontal position control. Adaptive control approach based on [11], [12] is used here and will be discussed briefly.

a) Adaptive altitude control: Let us define the altitude position error as $e_{z_1} = z_d - z$ and let $e_{z_2} = \delta_z \dot{e}_{z_1} + \lambda_z e_{z_1}$ with $\{\delta_z, \lambda_z\} > 0$. Also consider $e_{z_3} = \gamma_z - \hat{\gamma}_z$ as error function of system dynamic properties such as mass and moment of Inertia with $\hat{\gamma}_z$ being the estimate. Consider the Lyapunov function $V > 0$ given as

$$V(e_{z_2}, e_{z_3}) = \frac{m}{2} e_{z_2}^2 + \frac{1}{2} e_{z_3}^T k_{\gamma,z} e_{z_3}. \tag{18}$$

A simple choice that makes $\dot{V}(e_{z_2}, e_{z_3}) \leq 0$ can be

$$U_z := T = \frac{-1}{\cos\phi\cos\theta} (\hat{\gamma}_z + k_{p,z} e_{z_2}) \tag{19}$$

$$\dot{\hat{\gamma}}_z = k_{\gamma,z}^{-1} e_{z_2} \tag{20}$$

The output of the above control law U_z gives us the required thrust T to hover and manoeuvre the quadrotor carrying the manipulator. In the above control law γ_z includes the effect of uncertainties in the mass of the quadrotor and other payload attached to it. It also includes the external disturbances acting in the vertical axis.

b) Adaptive Horizontal position control: Let us define the error system for horizontal position control as $e_{xy_1} = \begin{bmatrix} x_d - x & y_d - y \end{bmatrix}$ and $e_{xy_2} = \delta_{xy} \dot{e}_{xy_1} + \lambda_{xy} e_{xy_1}$ with $\{\delta_{xy}, \lambda_{xy}\} > 0$. Let $e_{xy_3} = \gamma_{xy} - \hat{\gamma}_{xy}$. Now consider the Lyapunov function $V > 0$ defined as

$$V(e_{xy_2}, e_{xy_3}) = \frac{m}{2} e_{xy_2}^T e_{xy_2} + \frac{1}{2} e_{xy_3}^T k_{\gamma,xy} e_{xy_3}. \tag{21}$$

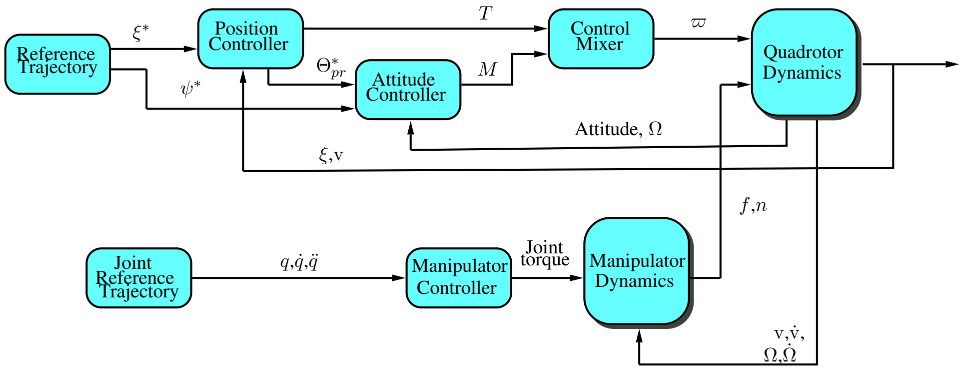

Fig. 1: [17] Control scheme of Quadrotor with manipulator. Here attitude controller is the inner loop and position controller is the outer loop in the quadrotor control. The manipulator is controlled separately using independent joint control.

TABLE I: Attitude control gains.

Attitude	K_p	K_d
Pitch/Roll	1500	0.1
yaw	1500	1

Let us choose

$$U_{xy} := \begin{bmatrix} -1 \\ 1 \end{bmatrix} \frac{1}{T} R_z(\hat{\gamma}_{xy} + k_{p,xy} e_{xy_2}) \tag{22}$$

$$\dot{\hat{\gamma}}_{xy} = k^{-1}_{\gamma,xy} e_{xy2} \tag{23}$$

which makes $\dot{V}(e_{xy_2}, e_{xy_3}) \leq 0$. The output of the control law U_{xy} gives us the desired pitch and roll demand. The details of the stability discussion of the above adaptive position control laws can be found in [11].

B. Control of Manipulator

For the manipulator control problem an independent joint control method was used preferable with PI-D-I configuration such as

$$U_m = \left(-K_p - \frac{K_{i1}}{s}\right) \tilde{q} - K_d \dot{q} - \frac{K_{i2}}{s} \ddot{q} \tag{24}$$

where $\tilde{q}$ is a joint angle error. Here the inner integral control is essential to deal with the problem of disturbances. Here an acceleration constraint $\ddot{q}_{min} < \ddot{q} < \ddot{q}_{max}$ is also necessary in order to keep the joint acceleration under safe limits.

VI. SIMULATIONS

Here we will discuss the application of the above defined controller through simulation on certain scenarios of control of the Aerial Manipulation Vehicle. While considering the usage of the aerial manipulation vehicle two important tasks are essential. These include manipulation of object with the robotic arm during hovering and then displacement of the quadrotor with the robotic arm in a fixed position. These two cases will be discussed here. The various controller gains are given in Tables- I-III

TABLE II: Adaptive Position control gains.

δ_z	1	λ_z	1	$k_{p,z}$	400
δ_{xy}	3	λ_{xy}	1	$k_{p,xy}$	$[100, 100]$
		$k_{\gamma,z}$	0.005		
		$k_{\gamma,xy}$	$[0.005, 0.005]$		

TABLE III: Manipulator control gains.

K_p	[50,50,50]	K_d	[2,2,2]
K_{i1}	[200,200,200]	K_{i2}	[10,10,10]

A. Object Manipulation using robotic arm with quadrotor in hover

Here the task is to manipulate an object by precisely controlling the position of the end effector while the quadrotor is hovering at a given position. A simple task of object manipulation is considered here. This task is performed under the assumption that the position of the object is precisely known. The objective is to hover the quadrotor at position $\{0, -1, -4\}$ and the manipulator joint should achieve final joint angle $\{0, -2.3, 1.5\}$ radians starting from initial joint angle $\{0, -2.3, 2.3\}$ radians. This scenario simulates reaching an object whose position is already known while the quadrotor is hovering. The manipulator control is handled using the independent joint control discussed above in Section-V-B and the hovering position control is based on Section-V-A.

The manipulator joint position error during hovering can be seen in Figure-2. The manipulation of the arm introduces drifts in the position and attitude as seen respectively in Figure-3 and Figure-4 which is compensated by adaptation of the gain. The evolution of the gain can be seen in Figure-5.

B. Quadrotor trajectory control with manipulator in a fixed position

Here the simulations are performed for trajectory tracking with manipulator position hold. The objective is that the aerial manipulation vehicle should move from initial position $\{0, -1, -4\}$ to $\{1, -2, -5\}$ with holding the manipulator at fixed position with joint angles $\{0, -2.3, 2.3\}$ radians. The respective results of the simulation can be seen here. The

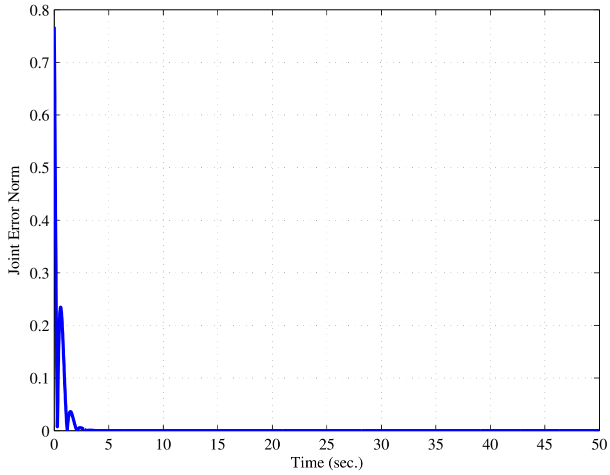

Fig. 2: Manipulator control in hovering: Joint position error norm.

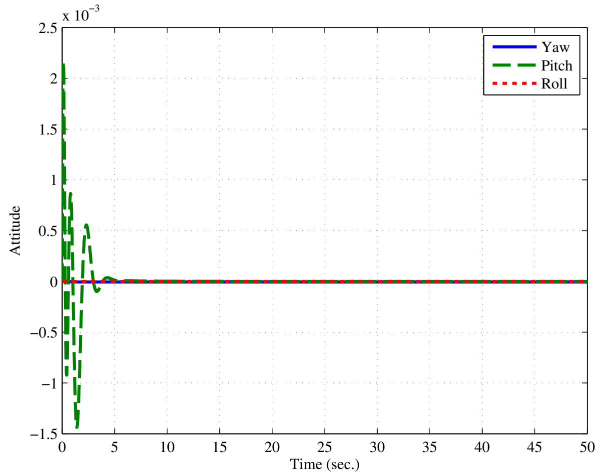

Fig. 4: Manipulator control in hovering: Quadrotor Attitude.

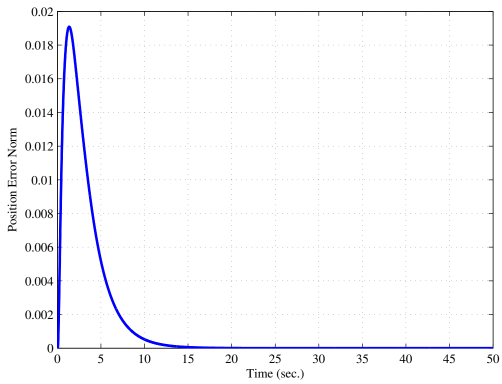

Fig. 3: Manipulator control in hovering: Quadrotor Position Error Norm.

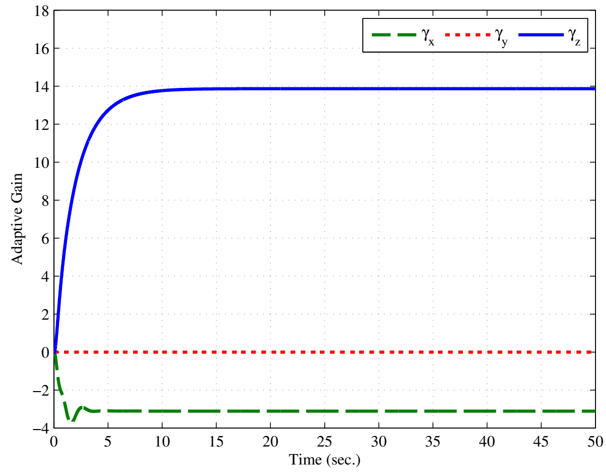

Fig. 5: Manipulator control in hovering: Evolution of Adaptive gain.

position error norm for the trajectory tracking control can be seen in Figure-6 with the attitude of the vehicle respectively in Figure-7. The evolution of the adaptive gains for the trajectory tracking problem can be seen in Figure-8. While the quadrotor is moving from its initial position to the final, the manipulator is controlled at a fixed position and the respective norm of the joint angle error can be seen in Figure-9.

VII. CONCLUSIONS

Adaptive control of an Aerial Manipulation vehicle is presented here. Simulations were performed to analyse the problem. The given adaptive control is able to stabilize the quadrotor from the disturbances caused due to resultant forces and moments acting on it by the manipulation of a robotic arm. Convergence of the trajectory tracking problem is also obtained while the manipulator is controlled at a fixed pose.

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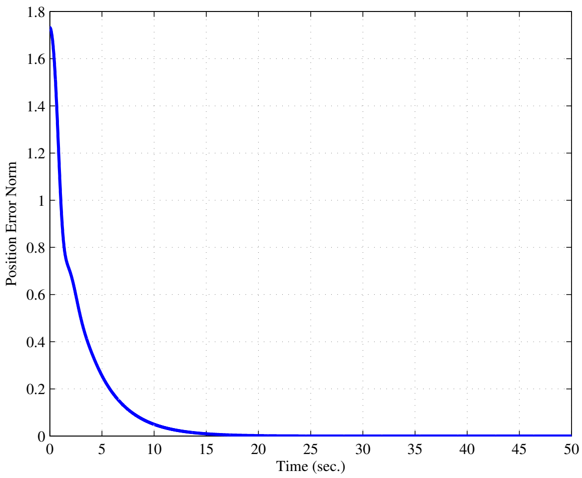

Fig. 6: Trajectory control: position error norm.

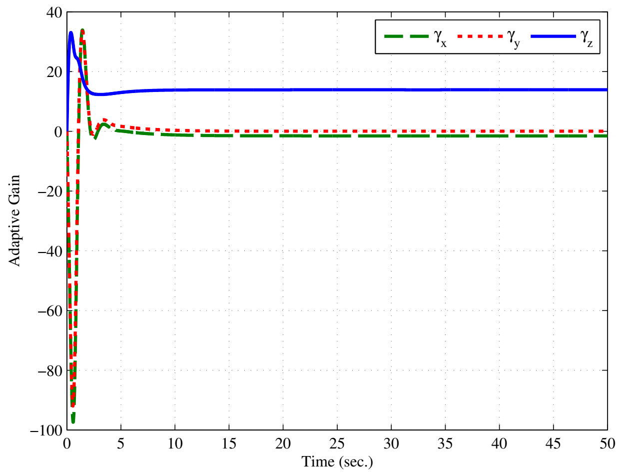

Fig. 8: Trajectory control:Evolution of the adaptive gains.

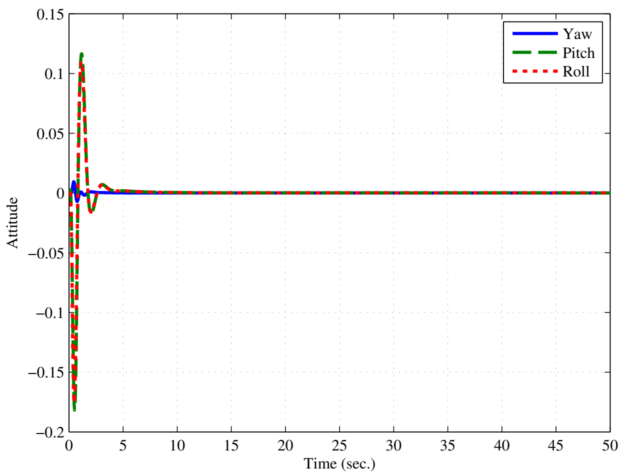

Fig. 7: Trajectory control:Attitude of the Quadrotor.

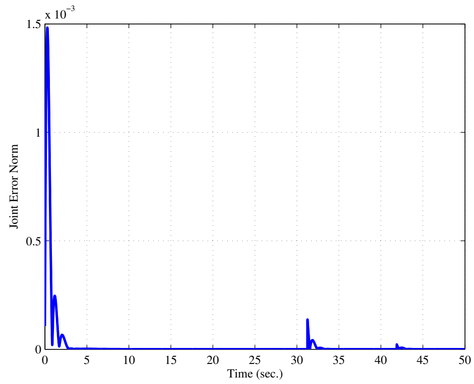

Fig. 9: Manipulator position hold: Joint position error norm.

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