Controlling of an Under-Actuated Quadrotor UAV Equipped With a Manipulator

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This work was supported in part by the National Natural Science Foundation of China under Grant 91748106 and Grant 61573097, in part by the Key Laboratory of Integrated Automation of Process Industry under Grant PAL-N201704, in part by the Advanced Research Project of the 13th Five-Year Plan under Grant 31511040301 and Grant 30601120401, in part by the Fundamental Research Funds for the Central Universities under Grant 3208008401, in part by the Qing Lan Project and Six Major Top-talent Plan, and in part by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

ABSTRACT Unmanned aerial vehicles (UAV) equipped with a manipulator offer an additional flexibility and smart way to grasp the desired objects from inaccessible locations where the access of ground vehicles (GV) are not possible. In this research, we design an adaptive control based regulation, pole-placement and tracking (RST) control scheme for controlling the nonlinear behavior of an under-actuated quad rotor aerial vehicle. The overall performance of the system dealt by MIT rules. The aerial vehicle is equipped with a camera and a gripper that helps us to locate the wanted object from inaccessible location. The model of quad rotor UAV has six degrees of freedom (6-DOF) and the equipped gripper is about (2-DOF). For a successful flight operation UAV requires a reliable controller to stabilize the aerodynamic effects, disturbances that produced by the gripper. Due to aforementioned issue, design an adaptive RST controller, to control the dynamic behavior of the highly nonlinear complex system. Moreover, the effectiveness of the designed controller proven by applying computer-based simulation and it will verify experimentally. Lastly, it observes that the designed controller shows better robustness and good steady state performance to accomplish the given task.

INDEX TERMS Adaptive RST controller, UAV with gripper and dual control algorithm, EVBG.

I. INTRODUCTION

The use of unmanned aerial vehicles (UAVs) has become more popular in the last few years. They are capable of doing all the major stuff for example; surveillance, military applications, and professional video photography. Transporting cargo from one place to another and even transporting passengers. Due to its flying ability, it can easily cover large distance quickly with perfect maneuvering [1]–[4]. The advancement of this technology encourage to execute the grasping of an object using the electronic vision based gripping (EVBG) mechanism which is mounted on the base of UAV [5] and [6]. The additional capability of this technology to grasp the desired object by utilizing the “eye in hand” technology in which camera is equipped on the center of the clutch (gripper), that could increase the gasping efficiency [7] and [8].

Mobile manipulation, which is highly vigorous field of study, which mainly focus on unmanned vehicles that provide better stability during the clutching of object. In reference [9], [10], researchers implement the algorithm to grasp the wanted object by using a gripper with 1-DOF and 2-DOF. In past, many researchers implement the different methods due to valuable results rather than complex grasping techniques. Earlier, many researchers have implemented the idea of aerial gripping. For example, a group of European universities has been involved in one appropriate project called aerial robotics cooperation assembly system (ARCAS) [11]–[14]. Moreover, many researchers have presented mechanical design, modeling and construction of a quadrotor with a fixed mechanical gripper, having capability of gripping lightweight objects [11].

The modeling of UAV based on the Newton Euler classical approach in order to illustrate the dynamic and kinematic behavior of the aerial vehicle. The model contains large
equations because of the classical approach of helicopter theory that contain many non-linear sine and cosine functions. Some authors have already presented different control approaches to reduce the effects of non-linearities and to achieve the better stability. In [15], a simplified control theory proposed using an inverse kinematic algorithm for the motion, position and yaw angle control of the vehicle and it is equipped with a gripper. Earlier, different researchers that could only increase the complexity in the mathematical model already proposed another example of these types of systems with more number of actuators. By using more than four rotors rather than tri-rotor and quadrotor, UAVs it will directly affect the duration of flight timings. In this research, that is the main reason to use the quadrotor UAV, it may help to save the battery and increase the flight duration [16]–[18].

A multi-rotor multifunction aerial vehicle is constructed on a frame of a quad rotor along with dual multiple DOF manipulators to perform aerial manipulating operation [19]. However, a combined control algorithm designed to control the dynamic model of UAV along with its equipped gripper [20]. In reference [21], hybrid adaptive control scheme was developed to stabilize the dynamic behavior of a single DOF manipulator equipped on a quadrotor UAV. The hybrid adaptive controller is a combination of gain scheduling and Lyapunov based model reference adaptive control (MRAC). A novel adaptive back stepping and sliding mode controller (SMC) was designed for quadrotor aerial vehicle with a 2-DOF robotic arm [22]. In reference [23] dynamic model of hex-rotor UAV equipped with an integrated manipulator was formulated by using Newton-Euler’s approach. Previously, a camera was installed at the end effector of the manipulator also called “eye in hand camera” in which the camera position is totally depends on the movement of the manipulator because of its fixed structure [24]. On the other hand, we use gimbal camera, which is best suited for the mapping as well as detecting and grasping of object. In result to this, the camera angle varies with the motion of manipulator as well as the movement of aerial vehicle. Moreover, the performance of an under-actuated aerial vehicle equipped with a gripper verify by computer-based simulation as well as experimentally.

The state of the art work is recently, in [25], [26] a novel adaptive robust control based techniques designed for the trajectory tracking of cable driven robots by using time delay in the controller. Firstly, the system lumped dynamics are estimated by using time delay estimation and afterwards provide the model free configuration. Moreover, nonlinear-based innovative adaptive laws designed to enhance the control performance of the entire system. Secondly, the designed control architecture based on three constraints; time delay estimation, added system dynamics and adaptive laws. Furthermore, the chattering free and constant gains of the adaptive controller utilized to modify the performance under time varying instabilities. In reference [27], [28], a new robust control based control strategy designed for driving the cable driven gripper under disturbance and lumped uncertainty. To attain the precise and quick control in the dynamic performance of the robot, the authors proposed a switching component in the control hierarchy. In addition the designed method divided into three sub modules termed as time delay estimation, modified super twisting approach and fractional order nonsingular terminal sliding mode controller to retain the dynamic error in the system. The newly improved strategy verified by using computer based simulations and experimentally. Lastly, the authors achieve 20 percent improvement to apply the design algorithm for the refereed path.

The major contributions of this research are (i) to design a novel control scheme using classical RST controller combined with MRAC in cooperation the MIT rules (ii) to clutch the desired object by using rotocraft UAV which is equipped with a camera and griper to grab the object from inaccessible location; (iii) the quadrotor based UAV that is fully customized, with the developer kit, that is installed in it which is quite appropriate for the grasping task, it can carry the weight which is about 0.5 to 5 kg approximately; (iv) For gripper manipulation the parameters are manipulated by using Denavit-Hartenberg approach; (v) adaptive controller is capable to stabilize the overall dynamic and kinematic behavior of UAV, however the gains of adaptive controller is being fine tune by RST controller.

The rest of the manuscript structured as follows; Section II defines the modeling of quadrotor UAV and center of the mass, moment inertial distribution of complete system it followed by modeling of aerial manipulator in section III. Section IV, presents the combine’s dynamics of aerial vehicle with gripper Section V, discusses the dual control model and its structure. The simulation results discuss in section VI. Section VII, defines the overall complete hardware configuration of UAV whereas flight controller, wireless transmission controlling, purpose built propulsion system, global positioning system and guidance system is defined. In section VIII, the experimental results provided. Lastly, the whole article concluded in section IX.

II. MODELING OF QUADROTOR UAV AND CENTER OF MASS, MOMENT OF INERTIA DISTRIBUTION

The main objective of the mathematical model is to simulate, combine the dynamic and kinematic model of quadrotor and equipped gripper on it. Resulting the complexity in the mathematical model, the different aerodynamic effect (i.e. ground effects, flapping of blade, etc.) are considered to be neglected. The gripper dynamics are developed through the recursive Newton-Euler technique. It is feasible to separately model the translational and rotational movements of UAV via Newton-Euler based equations. The two different models couple together to develop a complete model of the proposed UAV along with a gripper [29].

Initially, the rotors that is proportional to the square of rotor speed $\delta_a$ produce the aerodynamic effects, i.e., the generated torque “$r$” and thrust “$T$”. The rotational speed is proportional to the applied voltage of the rotors is rewritten as $\delta_a U \ [V]$. When a gripper, grasp some payload / object it will
directly concern to the stability of UAV due to the grasp payload and that exists in a system. At that instant of time electronic speed controllers (ESC’s) to amplify, the controller governs the power of all motors, which may able to stabilize the whole flight scenario and the things. The fundamental dynamics of ESC model in the form of transfer function can be written as and that could be taken from [16] and [30].

\[ \delta_a = \frac{k_m}{1+tmf} f_q(U) \]  

(1)

Whereas \( k_m, t_m \) are the propulsion system, \( \delta_a \) is the rotational velocity and \( f_q(U) \) is the control inputs of the fixed body frame of UAV. The induced thrust by the actuators that is equivalent to the air passing through the unit time circle.

The complex non-linear functions i.e., thrust and the torque depends on vertical and horizontal speed, air density and wind, which are the aerodynamic conditions of the quadrotor UAV. The total thrust of the rotorcraft depends on the sum of all forces. The torque depends on the speed and thrust of each rotor.

\[ f_q(U) = \sum_{i=1}^{4} f(U)^i \]  

(2)

\[ T_i = C_{T_a} \delta_a \]  

(3)

where “\( T_i \)” defined as total thrust, \( C_{T_a} \) is denoted as the thrust of aerodynamic coefficient thrust and \( \delta_a \) is the angular velocity of the system. The fixed body frame forces denoted by \( f_B \).

\[ f_B = \begin{bmatrix} 0 \\ 0 \\ 4 \sum_{i=1}^{4} T_i \end{bmatrix} \]  

(4)

The UAV forces acting on the Earth’s co-ordinate system rewritten as:

\[ f_E = \begin{bmatrix} \sum_{i=1}^{4} T_i(cos \psi sin \theta cos \varphi + sin \psi sin \varphi) \\ \sum_{i=1}^{4} T_i(cos \psi sin \theta cos \varphi + sin \psi sin \varphi) \\ \sum_{i=1}^{4} T_i(cos \theta cos \varphi) \end{bmatrix} \]  

(5)

The relationship between the air resistance and the velocity of the quad-rotor can be:

\[ D_E = \begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} -0.5 |V_x| \cos \theta \cos \varphi - \sin \theta \sin \varphi \\ -0.5 |V_y| \sin \theta \cos \varphi - \sin \theta \cos \varphi \\ -0.5 |V_z| \sin \theta \cos \varphi - \sin \theta \cos \varphi \end{bmatrix} \]  

(6)

In equation (6) the drag coefficients and velocities are \( C_{dx}, C_{dy}, C_{dz} \); \( V_x, V_y, V_z \) and \( D_x, D_y, D_z \) along with Earth fixed frame respectively.

\[ \begin{bmatrix} m_\theta = l(T_2 - T_1) \\ m_\theta = l(T_1 - T_3) \\ m_\psi = d(\delta_1^2 + \delta_2^2 - \delta_3^2 - \delta_4^2) \end{bmatrix} \]  

(7)

where the length of each arm of the UAV denoted by “\( l \)”, “\( m_\psi \)” is the yaw moment, which produced by the difference of the velocity, and “\( d \)” is the coefficient of yaw moment. The quadrotor UAV is an under-actuated, multivariable and highly nonlinear in nature due to its complex aerodynamics. It has six degrees of freedom (6-DOF) along with four actuators and the number of actuators is less than the DOF, which is why categorized in under-actuated systems. The direction of the rotor 1, 3 and rotor 2, 4 are same and fixed parallel to each other, which shown in figure 1 [21]. It is obvious, that UAV equipped with a gripper, the center of mass of body \( C_{MB} \) will change as the link of gripper moves and their turning effect means torque becomes a non-linear function of the gripper link angles that rewritten as [31].

\[ T_q(U, q_A^i) = \sum_{i=1}^{4} \tau \ (U)^i + \Delta O_{CMB}^i (q_A^i) \times f(U)^i \]  

(8)

To control the altitude and attitude of quad rotor UAV, equation (1) to (7) utilize to control the dynamic behavior of UAV. By considering the generated torque and thrust force of the system which are entirely dependent on the velocities of its actuators. The sum of all torques does not depend on the developed thrust and velocities of each rotor. The two major components of torque generated by the drag of propeller and due to the movement of propeller from the \( C_{MB} \). The varying center of mass of body \( C_{MB} \) easily calculated by summing all the body part distances from the center of quad rotor structure [32] and [33].

\[ C_{MB}(q_A^i) = \frac{m_G \sum_{i=1}^{4} [C_i^A (q_A^i)] (q_A^i)}{m_q + 2m_G} \]  

(9)

The torque \( \tau_q(U, q_A^i) \) of the quadrotor thrust system is a nonlinear function and \( C_{MB}(q_A^i) \) is the centroid, due to change the position of gripper. The joint angle of the centroid shifts, the distance between each propeller and the centroid \( \Delta O_{CMB}^i (q_A^i) \), which may varies and written as [21],

\[ \Delta O_{CMB}^i (q_A^i) = [cos(\frac{\pi}{4} + (i - 1)\frac{\pi}{2}) \times sin(\frac{\pi}{4} + (i - 1)\frac{\pi}{2})] + C_{MB}(q_A^i) \]  

(10)
where \( i \) denotes each propeller which is due to the configuration, placed in a manner that each propeller closes an \( 45^\circ \) angle between its closest coordinate system axis. The total torque applied on the quadrotor UAV becomes [21]:

\[
T_q(U, q_A^I) = \sum_{i=1}^{4} \tau(U)^i + C_{MB}(q_A^I) \times f(U)^i
\]  

(11)

By considering the ideal structure of quadrotor, the resulting torque is zero out the first in the sum of all rotors,

\[
[\cos\left(\frac{\pi}{4} + (i-1)\frac{\pi}{2}\right) \sin\left(\frac{\pi}{4} + (i-1)\frac{\pi}{2}\right) \cdot f(U)^i]
\]  

(12)

The total moment of inertia changes but still it is controllable in two different steps; by changing the moment of inertia of each part of body from its own principle axis to the body origin coordinate system \( R_0^A \). Whereas \( R_0 \) is a \( 3 \times 3 \) transformation matrix of rotation part [21]. The following rotational matrix defines the relationship between the ground co-ordinate system and fixed body co-ordinate system as (13), shown at the bottom of this page. Consequently, the adjustment of coordinate system it is possible to apply the parallel axis theorem in order to make an appropriate expression for system moment inertia [34].

\[
I^A = m_l[(C^{A,l} - C^{A,l})I - C^{A,l} \otimes C^{A,l}]
\]  

(14)

where “C” is a vector distance from the body part center of mass to the center of structure, \( \otimes \) represent the outer product of the two vectors and \( I \) again denotes \( 3 \times 3 \) identity matrix. By combining it all together to get the equation for the moment of inertia variations with respect to gripper joint angle changes and taken from [32] and [34];

\[
I(q_A^I) = \sum_{i=1}^{2} \sum_{j=A,B} R_{0}^{A} q_{1}^{I} R_{0}^{T} + C_{MB}(C^{A,l} - C^{A,l} \otimes C^{A,l})
\]  

(15)

III. MATHEMATICAL MODEL OF GRIPPER

The proposed 2-DOF gripper equipped in a quadrotor UAV shown in figure 1. Table 1, shows the Newton-Euler based recursive method by using the constraints of Denavit-Hartenberg (DH) for advancing the kinematics of manipulator. The movement of gripper modeled by using chain rule that taken from [21]. The connection between the body frame of UAV and primary joint of the gripper statically fixed with a constant rotation. The DH constraints for the gripper is defined in table 1, where \( \theta, a \) and \( \alpha \) are the typical DH convention \( q_1^l \) and \( q_2^l \) are the combined variables of gripper arm, where \( i = [A] \). The DH constraints that could be used to link between arm and UAV and the dynamic equations of each link are consequent. However, the whole technique applied for the gripper specific link movement, where the first joint of arm is \( L_1 \) and second joint \( L_2 \). The specific links of the gripper are steady in weight, size and shape i.e. their kinematic constraint “a”, weight or mass “m” and inertia of tensor \( I_G \) which is identical. By considering the links of the gripper, it would balance with respect to the body frame of UAV and selected coordinate system [21] and [29]. The respective inertia of tensor express as:

\[
I_G = \begin{bmatrix}
I_{xx} & 0 & 0 \\
0 & I_{yy} & 0 \\
0 & 0 & I_{zz}
\end{bmatrix}
\]  

(16)

When the gripper starts moving, the inertia of tensor changed conferring to the linked angle changes. The matrix used for the transformation is essential for calculating the overall inertia and positively conceived by using DH constraints. By adjusting the configuration of gripper link is defined in table 1, it shows the vibrant transformation for each links are \( T_i \), whereas \( i \in \{1, 2\} \) due to 2-DOF [21].

The moment of inertia and the end effector (link or joint) with a constant angle, have their own transformation matrices for the link [21], [29] and [32];

\[
T_{i}^{E} = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(17)

By using recursive Newton-Euler method, neglecting friction forces, it can be drive the overall torque and forces that is created from all the joints and states that;

\[
\begin{bmatrix}
f_{A}(\partial \gamma A) \\ T_{A}(\partial \gamma A) \end{bmatrix} = D(q_A) + C(q_A, \dot{q}_A) + G(q_A)
\]  

(18)

where “D” is the general inertial tensor, \( C(\gamma, \dot{\gamma}) \) is the Coriolis and Centrifugal force matrix equation, \( G(\gamma) \) is the

| Link | \( \theta \) | \( a \) | \( \alpha \) |
|------|-------|------|------|
| 1    | \( q_A^l - \frac{\pi}{2} \) | 1.875 | \( \frac{\pi}{2} \) |
| 2    | \( q_A^2 \) | 1.875 | \( \frac{\pi}{2} \) |

### Table 1. Gripper parameters of UAV using Denavit-Hartenberg.
gravitational force and \( \partial \gamma_A = [\gamma_A, \dot{\gamma}_A] \), represents dual link, rotational velocity and acceleration [21] and [29].

### IV. QUADROTOR UAV WITH GRIPPER DYNAMICS

The mathematical model of overall system yields by joining the dynamic equations of the motion of an aerial vehicle with the attached gripper.

\[
\begin{bmatrix}
    f_q(U) \\
    T_q(U, q_A')
\end{bmatrix}
= \begin{bmatrix}
    f_A(\partial d_A) \\
    T_A(\partial q_A')
\end{bmatrix} = \begin{bmatrix}
    nI \\
    0
\end{bmatrix}
\begin{bmatrix}
    \dot{q} \\
    \dot{\omega}
\end{bmatrix}
+ \begin{bmatrix}
    0 \\
    0
\end{bmatrix}
\begin{bmatrix}
    \omega \\
    \times
\end{bmatrix}
\begin{bmatrix}
    I
\end{bmatrix}
\]  

(19)

The left-hand side equation consists of gripper dynamics and quadrotor propulsion system. The right-hand side equation is a vector form of rigid body. The concluded equation is in non-linear form where, \( m \) is the total mass of the body, \( I \) is a \( 3 \times 3 \) identity matrix, \( I(q_A') \) is a non-linear term. The total movement of inertia, \( \dot{v} \) and \( \dot{\omega} \) are the rotational velocities of complete system respectively. Formerly, many researchers work in this field and but they ignored the dynamics of gripper, they only focused the load of gripper attached with UAV and its stability concern matters. They used 1 DOF gripper to grasp the desired payload, instead of 2 DOF to attach 2 DOF gripper with the dynamics of UAV it’s little complex to solve the stability issues along with the payload. In this research, the main objective is too focused on gripper having 2 DOF along with the 6 DOF of quadrotor UAV. The dynamics of gripper introduced in the system dynamics that written in the left-hand side of equation (19) that focuses on the stability and may cause disturbance to the quadrotor control system. Moreover, the two fundamental effects that are analyzed directly, to the impact of quadrotor control are the change in the moment of inertia \( I \) and in total mass of body \( C_{MB} \). The overall mathematical model to form stability criteria for this UAV with gripper presented depending upon the result [21]. Table 2, defines the parameters of quadrotor UAV and its equipped gripper on it.

### V. DESIGNING OF CONTROLLER

To control the position, altitude and attitude of quadrotor UAV equipped with a gripper is achieved by classical control approach regulation, pole-placement and tracking RST controller conjunction with model reference adaptive control (MRAC) shown in figure 2. Mostly, in autonomous type of systems MRAC quite commonly used hereinafter-adaptive controller deals with the unwanted uncertainties of the system.

Now, the overall system illustration depending on time, \( U(t) \), \( U_c(t) \), \( Y(t) \) are the input of the system, control input of the system and output of the system. Where, \( R/S \), \( T/S \) are the RST controller and \( 1/S \) is the integrator. On one hand, the integrator in the feedback loop of the figure 2 increases the order of the system. On the other hand, it reduces the unwanted noises form the system, excludes steady state errors and improving the convergence rate of entire system. At the time when the aerial manipulator grasps the desired object the system inertia will change, due to this the entire air vehicle stability is affected. The integrator in the feedback loop of the controller helps to improve the rate of convergence by neglecting the unwanted noises and it reduces the steady state error in the system. The MRAC is responsible to deals with the uncertainties of the flight and ensure its better stability. Whereas, RST controller is capable for tuning the parameters of the system and overall stability concerned by MIT rule [36]. The complete system model including the rotorcraft and its motor dynamics taken from [30], and convert the continuous signal it in to discrete because RST controller works on it. The complete adaptive RST controller loop is shown figure 2, the overall dynamics of quadrotor and its equipped actuator belongs to the 4th order dynamic system. By initializing the sample time is about 0.2 seconds and now the continuous transfer function taken from [21] and convert in to discrete from as per the requirement of the applied control scheme which is rewritten as;

\[
H_{cl} = \frac{0.006516z^3 + 0.01996z^2 - 0.01505z - 0.005349}{z^4 - 3.56z^3 + 4.97z^2 - 3.205z + 0.8007}
\]  

(20)

Now from the transfer function, the degree of \( A_{ac} = 4 \), making 3rd order RST controller, hence gives \( \text{deg} A_c = 7 \), \( \text{deg} R = 3 \), \( \text{deg} S = 3 \), and \( \text{deg} T = 3 \). Then, RST polynomials written as,

\[
\begin{align*}
R(z^{-1}) &= 1 + r_1z^{-1} + r_2z^{-2} + r_3z^{-3} \\
S(z^{-1}) &= s_0 + s_1z^{-1} + s_2z^{-2} + s_3z^{-3} \\
T(z^{-1}) &= (t_0 + t_1z^{-1} + t_2z^{-2} + t_3z^{-3})a_0
\end{align*}
\]  

(21)

The general RST controller equation is;

\[
U(t) = \frac{T}{R} U_c(t) - \frac{S}{R} Y_{ac}(t)
\]  

(22)
where \( Y_{ac} \) given as

\[
Y_{ac} = \frac{BT}{AR + BS} U_c (t)
\]  

and

\[
AR + BS = A_c, \text{ where } A_c = A_0 A_{req}
\]  

Suppose \( A_0 = 1 \) then \( A_c = A_{req} \). Moreover, the desired output response written as,

\[
G_{req} = \frac{B_{req}}{A_{req}} = Y_{req}
\]

The system error is calculated via MRAC based scheme, such that,

\[
\begin{align*}
\{ e &= Y_{ac} - Y_{req} = Y(t) \\
\{ e &= \left( \frac{BT}{AR + BS} \right) U_c (t) - Y_{req}
\end{align*}
\]  

Now taking the partial derivative of RST polynomials, one by one, w.r.t error.

For polynomial of R;

\[
\begin{align*}
e &= \frac{BT}{A (1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}) + BS} U_c (t) - Y_{req} \\
de &= \left( \frac{BT}{A (1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}) + BS} \right) U_c (t) - Y_{req} \\
dr_1 &= \frac{BT}{A (1 + r_1 z^{-1} + r_2 z^{-2} + r_3 z^{-3}) + BS} Y_{ac} \\
dr_2 &= -A_{z^{-1}} Y_{ac} \\
dr_3 &= -A_{z^{-2}} Y_{ac}
\end{align*}
\]

For polynomial of S;

\[
\begin{align*}
e &= \left( \frac{BT}{AR + B(s_0 + s_1 z^{-1} + s_2 z^{-2} + s_3 z^{-3})} \right) U_c (t) - Y_{req} \\
de &= \left( \frac{BT}{AR + B(s_0 + s_1 z^{-1} + s_2 z^{-2} + s_3 z^{-3})} \right) U_c (t) - Y_{req} \\
ds_0 &= \frac{A_{req}}{Y_{ac}} \\
ds_1 &= -Bz^{-1} Y_{ac} \\
ds_2 &= -Bz^{-2} Y_{ac} \\
ds_3 &= -Bz^{-3} Y_{ac}
\end{align*}
\]

Finally, for polynomial T;

\[
\begin{align*}
e &= \frac{B(t_0 + t_1 z^{-1} + t_2 z^{-2} + t_3 z^{-3}) A_0}{AR + BS} U_c (t) - Y_{req} \\
de &= \left( \frac{B(t_0 + t_1 z^{-1} + t_2 z^{-2} + t_3 z^{-3}) A_0}{AR + BS} \right) U_c (t) - Y_{req} \\
dt_0 &= \frac{A_0}{T} Y_{ac} \\
dt_1 &= \frac{A_0 z^{-1}}{T} Y_{ac} \\
dt_2 &= \frac{A_0 z^{-2}}{T} Y_{ac} \\
dt_3 &= \frac{A_0 z^{-3}}{T} Y_{ac}
\end{align*}
\]

Now, for system stability, MIT rule cost function for yaw moment expressed as,

\[
\begin{align*}
\{ \hat{j} (\psi) &= \frac{1}{2} e^2 (\psi) \\
\frac{d\psi}{dt} &= -\xi e \frac{de}{d\psi}
\end{align*}
\]

\[ \therefore \text{The same cost function for Roll and Pitch moment as well.} \]

Finally, by putting RST polynomials in above equation gives

\[
\begin{align*}
dt_1 &= -\xi \frac{de}{dt_1} \Rightarrow dt_1 = \left( \frac{\xi A_{z^{-1}}}{A_{req}} \right) Y_{ac} \\
dt_2 &= -\xi \frac{de}{dt_2} \Rightarrow dt_2 = \left( \frac{\xi A_{z^{-2}}}{A_{req}} \right) Y_{ac} \\
dt_3 &= -\xi \frac{de}{dt_3} \Rightarrow dt_3 = \left( \frac{\xi A_{z^{-3}}}{A_{req}} \right) Y_{ac} \\
ds_0 &= -\xi \frac{de}{ds_0} \Rightarrow ds_0 = \left( \frac{\xi B}{A_{req}} \right) Y_{ac} \\
ds_1 &= -\xi \frac{de}{ds_1} \Rightarrow ds_1 = \left( \frac{\xi Bz^{-1}}{A_{req}} \right) Y_{ac} \\
ds_2 &= -\xi \frac{de}{ds_2} \Rightarrow ds_2 = \left( \frac{\xi Bz^{-2}}{A_{req}} \right) Y_{ac} \\
ds_3 &= -\xi \frac{de}{ds_3} \Rightarrow ds_3 = \left( \frac{\xi Bz^{-3}}{A_{req}} \right) Y_{ac}
\end{align*}
\]

Thus, the designed hybrid controller written as

\[
U(t) = \frac{T}{R} U_c - \frac{S}{R} (Y_{ac} - Y_{req})
\]
VI. SIMULATION RESULTS
In this part of the article to check the validity and effectiveness of the proposed controller, by simulating the model of UAV along with the gripper by clutching the targeted object on Simulink Matlab. The simulation results shown in figure 3 to 11 respectively.

Figure 3, shows the referred position of UAV along (x, y, z), the scenario initializing from the originated state (0, 0, 0) respectively at the time when the aerial gripper start movement and reach to the desired position where desired the object is placed in its local frame.

In figure 4 and 5, UAV position errors and velocities during the flight are presented in the highlight of control algorithm, during the flight there are certain fluctuations which are shown in (x, y, z) axis respectively, due to the change of altitude of UAV which is directly proportional the speed of UAV rotors. By increasing or decreasing the speed of rotors of the UAV, it will directly affect the altitude of UAV, whereas the outcome wanted forces in the inertial frame of moment, shown in figure 6 respectively.

The overall system torques and adaptive tuning parameters of Euler angles displayed in figure 7 and 8 respectively.

Lastly, the placement of robotic arm, errors of the manipulator and control torques of the manipulator shown in figure 9 to 11, it shows that the end effector of the gripper will converges to the preferred state asymptotically.

VII. HARDWARE CONFIGURATION OF COMPLETE SYSTEM
The system hardware configuration of our designed quadrotor UAV along with the gripper shown in figure 12 below.

The quadrotor type UAV is used for this experiment, our designed UAV is fully customized and developer type drone that is most suitable for engineering works, suited best for proposed work to carry payload from remote areas [37].
The selected UA V is equipped with servomotors based (2- DOF) gripper to rotate and grab the objects from the desired locations. The rotor craft consists of four arms (propellers) distributed at equidistance from the center of the mass. The gripper placed on the center bottom of UA V as shown in figure 12. The selected rotorcraft is equipped with easy-to-fly expertise and enhanced thru the modest programming via software development kit (SDK). The idea to deliver the object that is the reason to attach a gripper with UA V to carry and transport payload and return back to the originated position.

The selected UA V has a great ability to extend its services to carry any actuator or device that need to take in the sky for transportation. It can manipulate the information while finalizing the difficult tasks from a pigeon eye view using equipped zenmuse X3 HD gimbal based camera. Moreover, the rotorcraft is able to carry an additional battery to extend the flight time about 45 minutes with maximum payload of about 5 kg. This may result payload gripping ability within required flight interval. The duration of flight directly depends on the payload but it can adjusted. When UA V carrying payload, the controller is quite flexible to match the desired flight requirements, by modifying the arm angle. This rotorcraft has an ability to tilt their arms about 3 degrees and amplify the yaw torque for better stability. The major specifications of our designed quadrotor UAV are as follows;

**A. FLIGHT CONTROLLER**
The brain of the system (i.e. controller) of our designed UAV is Pixhawk PX4 flight controller, which is able to handle all flight operations. This flight controller is smart enough that it alone can control all the motors, power distribution system, buzzers, switches, radio transceiver, GPS, compass, servo motors all the telemetry systems and the robotic gripper. It has a 32-bit microprocessor 256KB RAM/2 MB flash equipped with a 16-bit gyroscopic sensor, barometer and 14-bit accelerometer/magnetometer. There are some advance features of Pixhawk PX4 flight controller such as, 14 PWM outputs with integrated backup system for in flight recovery and with the latest autopilot mode and GPS.

**B. WIRELESS TRANSMISSION AND CONTROLLING**
UA V controlled by wireless remote control (WRC) having frequency range is about 2.400 to 2.483 giga-hertz (GHz). For this purpose, an integrated Lightbridge type controller used because of flexible control and connection via cell phone device. Moreover, it is a perfect tool of modern era to control the system or device over cellular communication in the air or ground. The transmission distance is about 1.7 to 4.5 km’s having receiver sensitivity of $-101$dBm to $(+2)$ dBm. The operating range of temperatures are $-10$ to $50$ degree Celsius and it supports android / iPhone operating system (IOS) based cellular phone version. It has fully customized flying features using SDK of DJI app. The selected flight controller is capable for transmitting and receiving the data from the ground station with high definition (HD) cam view via X3 camera.

**C. PURPOSE BUILT PROPULSION SYSTEM**
An advanced form of DJI E800 electrical built in propulsion system that energize our aerial vehicle and remain it in flight. Four electronic speed controllers (ESC) that control the speed of powerful brushless DC motors can control the whole flight scenario. By increasing the payload and power, it ensures the flexibility to generate the system as per our desired requirement.

**D. GLOBAL POSITIONING SYSTEM (GPS) AND GUIDANCE**
It is equipped with an enhanced GPS tracking system, which can track the UAV in real time by supporting faster satellite communication. Along with this feature tracking and path, planning ability enhanced drastically. It is equipped with a guidance system having innovative optical sensing enriched with advanced core processors, integrated photosensitive cameras and ultrasonic sensors. The most innovative guidance enables high level of safety and stability for long-range flights. The guidance may also include one central core processor and five modern sensors are as follows;
a. Optical-odometer: Highly precise optical odometer, which is especially built-in for the developers/engineers that measures the speed of the guided area with a precision of centimeters. It contains the measurements of the UAV movement in the bounded/unbounded environment.

b. 3D Sensing: It gives complete assurance to the programmers/developers to build their own app and acquire data from the guidance, which could be able to sense the three-dimensional space. It computes its compact depth imagings in real-time with a precision of very few centimeters.

c. Obstacle Sensing: The proper guidance may help us to monitor the surrounding environment continuously and it may enable to detect the obstacles in real-world scenario. The developer UAV has an ability to dodge the smash even at very high velocity. Modern guidance systems are enriching its communication to the main flight controller automatically to avoid collision with obstacles. It monitored by the advance vision, ultrasonic sensors and with the help of other advanced sensors. Dodges or obstacles identified accurately at an extensive distance and optical sensors are able to identify objects like leaf of tree etc.

d. Multi Sensor Fusion: The information of all guidance sensors merged automatically. Guidance will automatically select the appropriate sensor to achieve the better positioning performance. It means that if there is any failure of data from one side, it will not disturb the whole flight scenario. Highly Precise Vision based Positioning System: Guidance will provide optical or visual position if there are no GPS signals present at remote areas, even when UAV is flying with very high velocity and altitude about 20 meters.

VIII. EXPERIMENTAL TEST BENCH

This part of the manuscript, presents experimental test bench by utilizing our designed quadrotor UAV with grasping capability to detect the targeted object via gimbal-based camera equipped in it. Keep in mind that the simulation and experimental scenario is different. The aerial gripper that weighs about 250 grams, which defined in table 2. It is equipped with PIXHAWK X4 flight controller for intelligently control the inputs, outputs and visual sensing by using camera. The altitude of the UAV control manually using remote control (RC). To control the attitude of the quad-rotor UAV the reference system estimation done by the equipped controller. Moreover, the position of the UAV sensed by a highly precise sensor via GPS. The complete experimental setup includes clutching of an object using gimbal based camera and a robotic gripper. Firstly, the UAV takes off from the ground station and keep in mind that to search the targeted object via camera.

Secondly, when the object seen it will decrease the altitude of UAV and the end effector is close enough to the targeted object. After that, the pilot can gives signal to the end effector of the gripper to grasp the targeted object after that the UAV goes back to the originated position and lands at there.

The whole scenario completed in 30 seconds from takeoff to landing with successfully clutching the targeted object. Firstly, the UAV takeoff and hover the flight for several seconds to check the stability of flight in the direction towards the desired object at 4-meter altitude lock. After that, the UAV heading towards the targeted object via camera based sensing in next 6 seconds. Moreover, when UAV reached at the desired position it will decrease the altitude to clutch the wanted object this done in 8 to 10 seconds. Lastly, the UAV will maintain its altitude, goes back to the originated position, and landed there with the desired payload.

The experimental results; are shown in figure 13, 14 and 15 respectively, whereas the gripper is able to grasp the object.
controller via vision based sensing. However, adaptive RST controller designed to settle the dynamic behavior of UAV along with the equipped gripper. At the time of grasping the desired object (movement of robotic arm) fluctuations occurred, which effect the stability of the flight. The designed controller is rapidly tuned the overall system, and provides better stability with less error margins. Furthermore, the designed controller validated experimentally as well as simulation results are also verified its validity and effectiveness.

X. FUTURE ENHANCEMENT

In this research, we choose a quadrotor UAV along with (2-DOF) gripper that grasp the desired object and deliver it to the originated state. We will enhance the clutching scenario by increasing the link of manipulator it will results quick grasping of the desired object. The model of the gripper, which attached on UAV, will be expandable with the help of Denavit-Hartenberg chain parameters for the manipulator. Lastly, the proposed controller algorithm is able to handle multiple links of the manipulator along with multiple DOF’s.

ACKNOWLEDGMENT

The authors thank the reviewers and editors for giving valuable comments, which are very helpful for improving this manuscript.

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IEEE Access VOLUME 8, 2020