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Adaptive Control of a Tilt – Roll Rotor Quadrotor UAV

Fatih Şenkul and Erdinç Altuğ

***Abstract*—In recent years quadrotor unmanned aerial vehicles are being used in various different studies. A regular quadrotor has fixed rotors. This inability to tilt its rotors lead to limited success in trajectory tracking due to controlling 6 DOF systems only with 4 input parameters. There are some studies on tilt rotor and tilt-roll rotor quadrotors that can compensate for versatile conditions. Some of these proposed quadrotors are able to hover and position hold at user defined desired angles unlike regular quadrotors. This study presents the design and control of a novel quadrotor system that can tilt its rotors independently so that it can adaptively update its rotor angles and speeds to compensate for more chaotic and realistic scenarios. After deriving the mathematical model, the designed control algorithms are explained by comparing with the latter studies' abilities. Proposed quadrotor with adaptive control is compared with regular and non-adaptive tilt-roll rotor type multicopters, in various simulations. The results show that the proposed design has clear advantages in certain situations, especially when environmental limitations and hardware inconsistencies and inefficiencies exist.**

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) have become very popular in the recent years in military, civilian sectors and in multiple scientific projects. They are very useful in vast numbers of missions including life threatening incidents such as nuclear plants leakages and natural disasters such as flood and conflagration, to name a few. Moreover, the more they become adaptable to the environmental conditions, the more they can handle some complicated tasks. Thus, extensive researches take place for the last decade about their aerodynamic, electronic and system control designs.

Vertical takeoff and landing (VTOL) capable UAVs are being more popular by the researchers, hobbyists and military. One of the most important reasons behind this fact is that they are quite practical to use without a need for an airfield base [1-4]. As being one of the types of VTOL unit, quadrotors have been used for many applications and research studies, as well. Regular quadrotors have to change their body angles in order to move towards the desired coordinates. However, in some certain applications where there is a lack of working area, it is not desired to change the body angle. What's more tilting body frame has some undesired effects such as poor stabilization, trajectory tracking and not able to hover at a desired frame angle. The stabilization and hovering skills have direct effects on the performance of onboard camera recordings and visual guided tasks.

Environment friendly and more adaptable systems are currently being researched. Tilt-able rotor design is one of the solutions to the need for adaptability. Quad Tilt Rotor (QTR) is one of the types of tilt-able geometry aircraft. QTR enables the transition from helicopter mode to aircraft mode by tilting the rotors at the same time along an axis perpendicular to the front direction of the vehicle (pitch angle) [17, 18]. Full-size aircraft prototypes similar to QTR are also developed [19-21].

There are a few studies on the tilt-able geometry quadrotors. Cetinsoy et al. [22] proposed design and construction of a quad tilt-wing UAV. Ryll et al. [23] proposed quadrotor UAV with tilting propellers that enable 4 propellers to actively rotate (tilt) about the axes connecting them to the quadrotor main body. Jeong et al. [24, 25] proposed tilting mechanisms on flying vehicles as well. Senkul et al. [26] proposed a tilt-roll rotor quadrotor whose rotor angles move in the same direction so that there is no extra need for tilting the body frame of the vehicle. Visualization of this study can be found in figure 1.

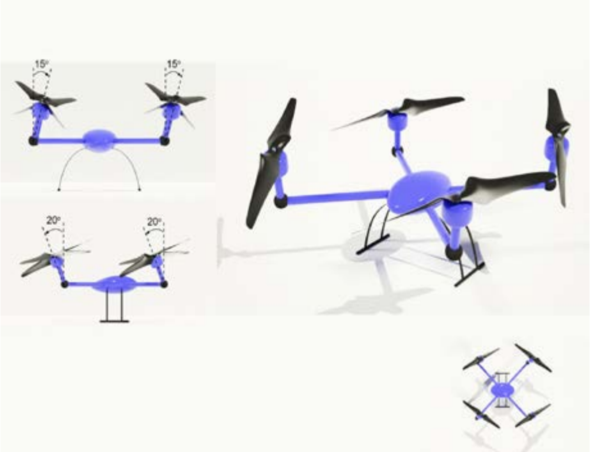

Fig. 1. Rotor movements and frame structure of a typical tilt-roll rotor quadrotor.

This study proposes adaptive improvements on the control algorithm designed in [26]. Unlike the study in [26], all the rotor angles can change independently from each other. This feature makes the proposed multicopter to compensate for any penalty gains occurring from actuator inefficiencies and/or outside effects such as windy conditions. Proposed quadrotor can enable tilting of each rotor independently along x and y axes such that the total number of inputs applied to the system are increased up to 12 instead of 4. Although these additional control inputs make the system mechanically more complex, it brings various advantages by converting the under-actuated system to an over-actuated one.

F. Şenkul is with the System Dynamics and Control Graduate Program, İstanbul Technical University, İstanbul, Turkey (e-mail: fatihsenkul@gmail.com).
E. Altuğ is with Department of Mechanical Engineering, İstanbul Technical University, İstanbul, Turkey (e-mail: altuger@itu.edu.tr).

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The paper is organized as follows: Section II describes the mathematical model of the proposed tiltable-rotor type quadrotor. The controllers are also presented in part B of Section II. The simulation model and simulation results supporting the objectives of the paper are presented in Section III. Concluding remarks and future work are presented in Section IV.

II. MODELING AND CONTROL

A. MODELING

The modeling of a tilt-roll quadrotor has been presented in [26]. It was assumed that there is no wind penalty on any axes of the quadrotor, all the motors' reaction time and inner structures are exactly the same without any transient delay, gyroscopic effects are assumed to be acceptably small and the required thrust vectors that are obtained from the control algorithm can be obtained from the motors without any limitations. However, in real life there will be cases in which in certain axes of the multirotor there may exist a continuous erroneous output. This erroneous behavior may exist by the following reasons: Insufficiencies in actuators, noisy output due to internal and external disturbances, the geometrical imperfections of the body frame with respect to the ideal system model, imbalanced propellers and their gyroscopic effects, windy conditions if the flight takes place in outdoor conditions. In this study all of these negative effects are modeled as one disturbance factor called "penalty gain factor". When modeling and adaptively correcting these conditions into more ideal space, it is assumed that the overall disturbance data is applied on certain axes of the rotors (only along x, y or z direction) and can be estimated in a tolerance of ±10 %.

Tilt – roll rotor quadrotor's mathematical model is similar to that of a regular quadrotor. In addition to the regular model, the axial force distributions of each of the rotors must be added to the model. Vehicle torque equilibrium in order to hold the body frame in the desired angle can only be achieved by calculating these force vectors namely F_{ix}, F_{iy} and F_{iz} where i corresponds to the rotor number i.e. $i = 1,2,3,4$ respectively.

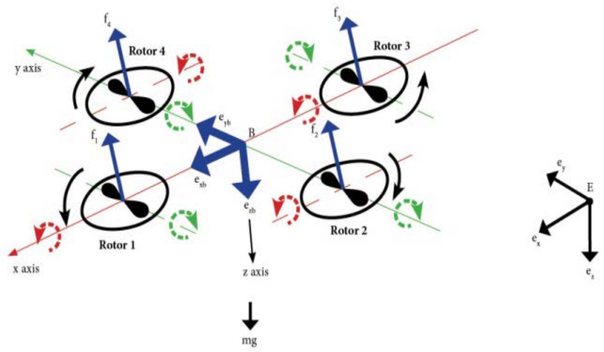

Fig. 2. Free body diagram of Tilt-Roll rotor quadrotor with North-East-Down (NED) geographical coordinate system representation.

The free body diagram of the tilt-roll rotor quadrotor is given as in figure 2 [26]. According to the assumed model N, E, D (North, East, Down) geographical coordinate system has been used in order to define the direction of the axes. Angles of rotations are named as pitch, roll and yaw with respect to the rotations about x, y and z axes respectively (Table 1 [26]). The earth's gravitational force mg is assumed to be constant and in downwards direction with respect to earth frame.

3D Rotation of the vehicle can be represented by a rotation matrix with Euler angles $(\varphi_i, \theta_i, \phi_i)$:

$$RPY(\varphi_i, \theta_i, \phi_i) = R(z, \varphi_i).R(y, \theta_i).R(x, \phi_i) \quad (1)$$

The force relation of the generic model of the tilt-roll rotor quadrotor is given below:

$$\vec{F_i} = \begin{bmatrix} F_{ix} \\ F_{iy} \\ F_{iz} \end{bmatrix} = -F_i \begin{bmatrix} \mathrm{Sin}(\theta_i).Cos(\phi_i) \\ -Sin(\phi_i) \\ \mathrm{Cos}(\theta_i).Cos(\phi_i) \end{bmatrix} \quad (2)$$

where F_{ix}, F_{iy} and F_{iz} forces are the components of the thrust force along the x, y, and z axes respectively as in (3).

$$F_i = \sqrt{F_{ix}^2 + F_{iy}^2 + F_{iz}^2}\ . \quad (3)$$

And the motor angle values are calculated as in (4, 5) in ideal conditions in which all the actuators of the system are exactly equivalent to each other and when there are no external disturbances that take effect on the vehicle.

$$\theta_i = atan\left(\frac{F_{ix}}{F_{iz}}\right) \quad (4)$$

$$\phi_i = asin\frac{F_{iy}}{\sqrt{F_{ix}^2+F_{iy}^2+F_{iz}^2}} \quad (5)$$

Tilt-roll rotor quadrotor design aims the user to define the set point of the body frame angle and move the vehicle to any 3D coordinates by keeping the same angle value. This can be achieved by introducing the following force equations to the model and the control system.

$$\textstyle\sum_{i=1}^{i=4} F_{i_x} = F_x,\ \sum_{i=1}^{i=4} F_{i_y} = F_y,\ \sum_{i=1}^{i=4} F_{i_z} = F_z \quad (6)$$

The rotation speeds of the rotors are described by Ω_i, the rotor thrust force is also equal to $F_i = b{\Omega_i}^2$, where parameter b is a constant namely the push factor (7).

$$\Omega_i = \sqrt{\frac{\sqrt{F_{ix}^2+F_{iy}^2+F_{iz}^2}}{b}} \quad (7)$$

Total moment, M_t is created using the following equation:

$$M_t = M_d + M_{gyro} + M_{th} \quad (8)$$

where M_d is the external disturbances, M_{gyro} is the gyroscopic effects of the propellers and M_{th} is the moment created by the rotation of the rotors. In this study we are interested with M_{th} along x, y and z axes and take $M_{gyro}\ and\ M_d$ as random total disturbances changing in time. Therefore we can assume that

$$M_{random} = M_d + M_{gyro} \quad (9)$$

Then M_t becomes;

$$M_t = M_{random} + M_{th} \tag{10}$$

Using the torque values in each arm of the quadrotor, the angular accelerations can be determined using (11) and by taking the integral of the terms in (11) p, q and r angular velocities can be calculated:

$$\dot{p} = \sum \frac{\tau_x}{I_{xx}},\ \dot{q} = \sum \frac{\tau_y}{I_{yy}},\ \dot{r} = \sum \frac{\tau_z}{I_{zz}} \tag{11}$$

In this study, it is assumed that M_{random} value is changing in time along one axis of an actuator. Suppose that this issue occurs with quadrotor`s one of the axes due to external (i.e. wind gusts) or internal (i.e. rotor, frame structure, propeller gains) disturbances. For ease of formulation, x vector is chosen as the effected axis (any of axes x, y or z can be chosen). Let's say the total disturbances effecting on x axis of motor 1 is called the force penalty factor, f_{pe}, which is assumed to be randomly changing between 0.1 to 1.9. In fact this function can be any polynomial that has the following relation: $1.9 > f_{pe}(t) > 0.1$ in any given time t. This penalty factor represents the total random disturbances acting on an actuator including gyroscopic effects of the rotors, external disturbances and electro-mechanical inefficiencies of the electrical motor in time. Therefore, it can have direct effect to change the force gains of F_{x_i} and F_{z_i}.

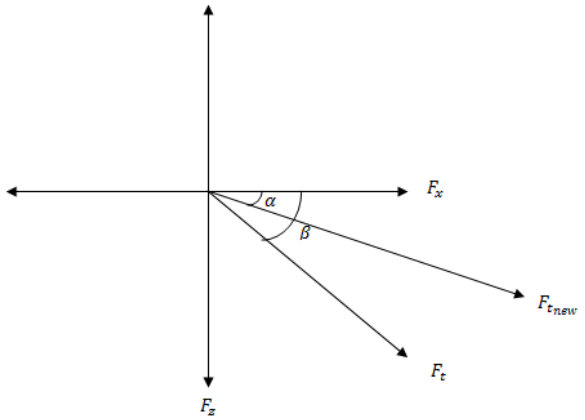

Fig. 3. Free body diagram of a motor that is adaptively corrected with new angle and force values.

For example, once the control algorithm determines required output speeds and angle values for the rotors which in normal conditions will produce a total desired thrust force of F_t. In this instance, f_{pe} is introduced to the system as a gain factor on F_t. Suppose that $f_{pe} = 0.75$ and is effective only on x axis. In this case force vector on x axis will be $0.75\ F_x$ instead of F_x. It is not possible to control and stabilize the quadrotor with inequalities between axial torque and force vectors. The modeling of the system is designed such that the same magnitude of F force will be produced at the defected axis without losing altitude and yaw control. Therefore, the resultant force F_{t_i} must be updated iteratively with adapted force vector of $F_{t_{new_i}}$. This can be achieved by changing the angle of the rotor while changing the speed of the rotor (i.e. changing the thrust force) so that the total force will be the same. In figure 3, the free body diagram of such system is given where β is the desired angle in ideal conditions that stands for the resultant force F_t and α is the updated angle for the updated force vector $F_{t_{new}}$. Finally the desired values of F_x and F_z must be close enough (in tolerance limits of 1 %) so that the equilibrium of the forces is maintained as before. We can say that (β-α) and change in the speeds of the rotors, Ω_i are proportional to each other, i.e. if (β-α) gets smaller and Ω_i is expected to change in smaller amounts and if (β-α)=0 this indicates that Ω_i will stay the same and vice versa for the case in which (β-α) gets bigger. Figure 3 represents one of the motor's force relation in 2D space including $F_x, F_z, F_t, F_{t_{new}}$ while adaptively controlling the halted direction.

B. CONTROL

The control of the tilt-roll rotor quadrotor differs from the regular quadrotor. The target is having a fully functional multi-rotor without moving the body frame but the motor axes. In this work, the control algorithm is designed such that all the motors can be able to tilt and/or roll independently from each other.

For performance and applicability purposes, cascaded PID control is chosen for control and simulation of the proposed aircraft. There exists total of 4 cascaded PID loops where each of motor angles are controlled with the inputs received from the vehicle's position, velocity, altitude and total force vectors (figure 4).

In this study the adaptive control of the aircraft is designed assuming that the aircraft will go towards to one direction at a time in 2D space. In the examples and formulation given in modeling and control chapters these axes are chosen to be X and Z. An adaptive control algorithm for tilt-roll rotor quadrotor is proposed. In order to stabilize the system in figure 4 the following expressions must be calculated:

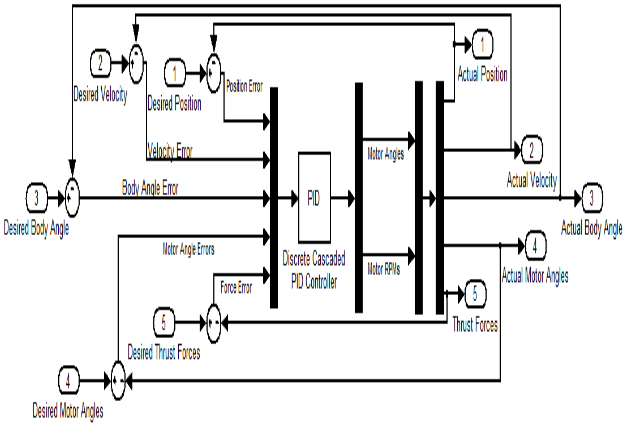

Fig. 4. Simplified cascaded block diagram of tilt-roll rotor quadrotor.

$$F_z = F_t * \sin(\beta) \tag{12}$$

$$F_{x_{gained}} = F_t * \cos(\beta) * f_{pe} \tag{13}$$

where $F_{x_{gained}}$ represents the final value of F_x if no adaptive stabilization is applied on this axis (ie less than desired x force, F_x if $f_{pe} < 1$ and more if vice versa). Thus, if $f_{pe} = 1$ then $F_{x_{gained}} = F_x$

Similarly;

$$F_x = F_t * \cos(\beta) \tag{14}$$

After adding the new angles and force vectors we get:

$$F_x = F_{t_{new}} * \cos(\alpha) * f_{pe} = F_t * \cos(\beta) \tag{15}$$

$$F_z = F_{t_{new}} * \sin(\alpha) = F_t * \sin(\beta) \tag{16}$$

By using the equations (7) and (8) new resultant force can be estimated as in the following:

$$F_{t_{new}} = F_t * \frac{\cos(\beta)}{\cos(\alpha) * f_{pe}} = F_t * \frac{\sin(\beta)}{\sin(\alpha)} \tag{17}$$

This is equal to the following equalities;

$$F_{t_{new}} * \cos(\alpha) * f_{pe} * \sin(\alpha) = F_t * \cos(\beta) * \sin(\alpha) = F_t * \sin(\beta) * \cos(\alpha) * f_{pe} \tag{18}$$

By using (10), the adapted angle, α is obtained as follows:

$$\alpha = \tan^{-1}\left(\frac{\sin(\beta) * f_{pe}}{\cos(\beta)}\right) \tag{19}$$

In figure 4 a simplified block diagram of the control algorithm of a tilt-roll rotor quadrotor is given. In adaptive version, the motor angles and speeds are controlled according to the above formulation with an extra feedback closed loop system.

III. SIMULATIONS

In order to analyze and compare the dynamic behavior of the proposed adaptive control algorithm, several simulations are held. In this section, the simulation results and the performance of the proposed control system will be presented. The cons and pros of the new and previously developed control systems will be defined so that they can be improved and applied to various systems in the future works.

A. *First Simulation*

The first simulation is done to compare 3 quadrotors that have control system designs that are different from each other. During the simulation, all quadrotors track the same trajectory on x and z axes. The first quadrotor, Quad1, is a regular quadrotor whose rotors are fixed and assumed to have no tilting or rolling motion. The second quadrotor, Quad2, is the tilt-roll rotor quadrotor that is proposed in [26]. Quad2 does not support adaptive control algorithm against halted components or outer penalty gains, such as wind. Quad2's body frame stays at almost zero degrees during the trajectory tracking and it is able to change 3D coordinates by tilting & rolling of its rotors. Quad2's all the rotor angles can change at the same time depending on each other. Quad3 has the tilt-able rotor geometry just as Quad2. However, it is equipped with the proposed adaptive control algorithm which enables the Quad3 to change its rotor speeds and angles independently from each other.

In the first simulation each of the three quads are given the same trajectory starting from the same location with the same heading position. However, it should be noted that penalty gain, f_{pe} is chosen to be 1 (no effect) during the first flight simulation. The resulting plots are given in figure 5 and 6.

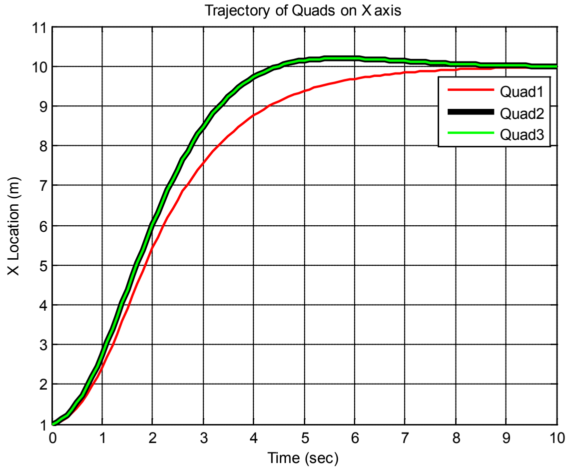

Fig. 5. First simulation results with a penalty gain of 1 on X axis.

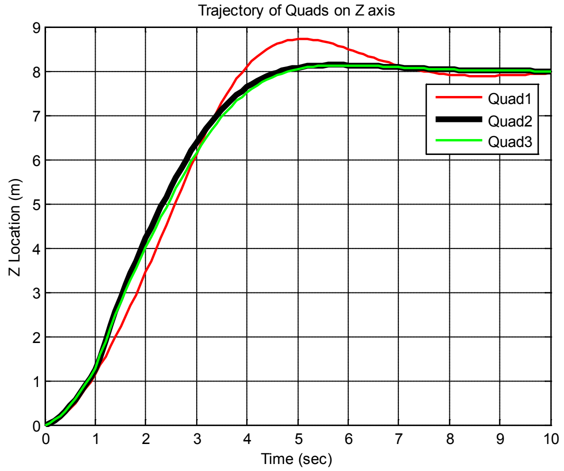

Fig. 6. First simulation results with a penalty gain of 1 on Z axis.

As seen from above figures, tilt-roll rotor quads, Quad2 and Quad3 has relatively better performance in terms of settling time, maximum overshoot with relatively less oscillations. By looking at these results it is clear that Quad2 and Quad3's performances are almost the same with each other. This phenomenon can be explained by comparing their rotor angles of both of the quadrotors during their flights. These rotor angles are measured to be very close to each other because it is assumed that no disturbances are taking place in this simulation. It has already been known [26] that tilt-roll quads are more likely to have better results in terms of settling time and max overshoot value with respect to regular quadrotors.

B. *Second Simulation*

The second simulation is done as we introduce a random penalty gain; f_{pe} that's changing from 0.1 to 1.9 as a function of time. Start and target points are chosen to be the same as before.

This simulation supposed to be done with 3 of the quads. However, Quad2 which does not have any compensation algorithm for large gain changes in penalty gain, go beyond the graph. That's why in figure 7 we only introduce Quad1 and Quad3. And further, simulation is done for Quad2 by giving a relatively lower and fixed penalty gain of 0.95. It is then compared with Quad3 which has the same random penalty gain factor on x axis in figure 8.

By looking at the plot in figure 7, it can be seen that Quad1 can barely compensate for the randomly changing penalty gain in the beginning of the simulation. But after the 5th second it begins to oscillate around z axis and can never reach the target point again. In the same graph Quad3 seems to track almost the same path as in the first simulation that's done in ideal conditions.

Even though the penalty gain margin is large, the proposed adaptive control algorithm can estimate the error and compensate for the force changes on x axis which directly affects the stabilization of altitude control in z axis. In figure 8, even if the penalty gain is static and only 0.95 for Quad2, it can clearly be seen that Quad2 is unable to reach the desired location although it has the tilt-able geometry just like Quad3.

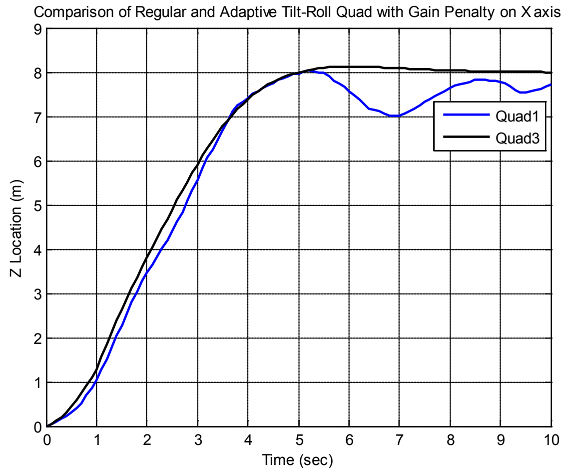

Fig. 7. Second simulation result: Penalty gain randomly changes between 0.1 and 1.9 on Z axis for both of the quads.

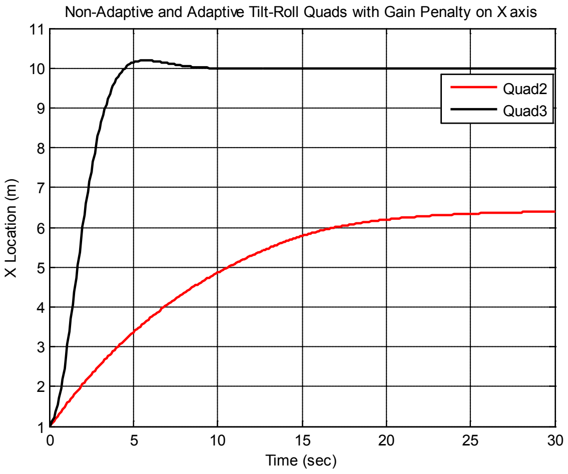

Fig. 8. Second simulation result: Penalty gain of non-adaptive tilt roll is fixed to 0.95. Penalty gain randomly changes between 0.1 and 1.9 for adaptively controlled quad.

C. *Third Simulation*

In the last simulation Quad3's performance characteristics are examined closely. In order to adapt itself to randomly changing penalty gains existing from inner and outer disturbances, Quad3 is able to change its' β, α angles and the force vectors F_t and $F_{t_{new}}$ as introduced in control section of this paper.

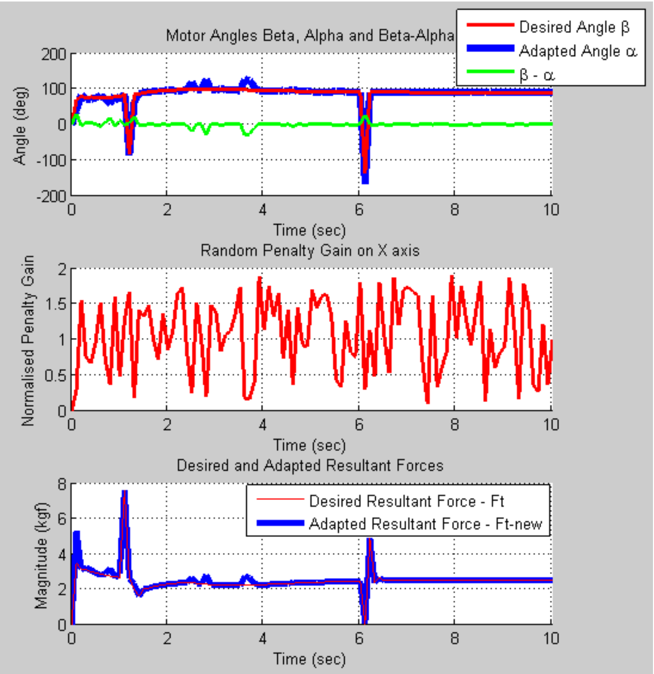

Fig. 9. Third simulation results: Penalty gain randomly changing from 0.1 to 1.9 on Z axis.

In figure 9 there are 3 subplots: First one represents the relation between desired angle, β and adapted angle, α and their differences, $(\beta - \alpha)$. The second subplot shows the introduced penalty gain to the system. And lastly the third subplot graphs the desired resultant force vector, $\mathrm{F_t}$ and the adapted resultant force vector, $\mathrm{F_{t_{new}}}$.

First of all, it is clear from the second subplot that penalty factor has a large variation as stated. It is changing between the values of 1.9 to 0.1 after t=0.

In order to understand the performance of the algorithm, subplot 1 and subplot 3 should be observed together. In the third subplot we see that both of the desired and adapted force vectors are almost matching with each other. In fact the more they get close to each other the better. Furthermore, by simultaneously comparing the subplots 1 and 3 of figure 9, it can be seen that the rapid movements of the vehicle in t=1.6, 3.8 and 6.1 are compensated by changing adapted angle, α with relatively higher amounts. In the meantime, the rotor speeds are updated as stated in the model and control sections. Still these rapid changes in angle values can further be taken under control by pulling the maximum and minimum values of the disturbance function given in subplot 2. This disturbance function used here is already at exaggerated rates which is usually a sign of a crashing multicopter. Moreover, it is always possible to assign some constrain values both for max angles and angle changing rates in the algorithm.

In the same graph, $F_{t_{new}}$'s noisy parts generally coincide with high sloped penalty gain changes (check for instance the behavior at 3.8 sec). But for these little differences in angle and force vectors, we know that Quad2 has already failed to reach its target point in simulation 2.

IV. CONCLUSIONS

The performance of quadrotors can be improved by enabling tilting-rolling the rotors around their axes. However, it is very likely to be introduced with fixed or changing erroneous axial forces. These unexpected disturbances can be due to imperfections of the inner structure of ESCs, electric motors, electronic components and propellers. What's more in out-door flights it is a must to compensate for changing wind forces during time. This study presented the design and control of a novel quadrotor system with tilt-roll rotor control that can compensate for penalty gains. Various simulations are developed on Matlab, in which the proposed control algorithm proves better performances with respect to regular quadrotors as well as better stability features with respect to another tilt-roll rotor capable quadrotor that does not have the proposed adaptive compensation algorithm.

The proposed vehicle can adaptively update its rotor angles and speeds to compensate for imperfect conditions. However, it is currently applicable only for 2D space solutions. In real life applications cross-functional trajectories will also be affected with some random distortions while the vehicle is moving along in 3D space. That's why the problem solution needs to be studied in a more complex rotation matrix. What's more an optimal control for each of the rotors' angle, force vector will be studied in order to assign the best stabilization factor as the total energy consumption is kept at minimum. It is currently an ongoing study which will be proposed in future works. We are currently studying both on development of the optimal control algorithm and building the proposed vehicle. Design verification plans are ready and will be accomplished once the fabrication of the tilt-roll rotor quadrotor is finished.

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