Linear Quadratic Integral Differential Game applied to the Real-time Control of a 3DoF Experimental setup of a Quadrotor

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*Abstract*—The accurate attitude control of a quadrotor is necessary, especially when facing disturbance. In this study, a linear quadratic with integral action based on the differential game theory is implemented on a quadrotor experimental setup. For this purpose, first, a continuous state-space model of the setup is derived using the linearization of nonlinear equations of motion, and its parameters are identified with the experimental results. Then, the attitude control commands of the quadrotor are derived based on two players; one finds the best attitude control command, and the other creates the disturbance by mini-maximizing a quadratic criterion, defined as the sum of outputs plus the weighted control effort and disturbance. The performance of the proposed structure is investigated in level flight and compared to the linear quadratic regulator controller. Results demonstrate that the proposed approach has an excellent performance in dissipating the disturbances.

Keywords—Linear Quadratic Differential Game, Quadrotor, Real-time, 3DoF Experimental setup, Optimal Control, Robust Control

# Introduction

A quadrotor is a type of helicopter with four rotors that plays a significant role in today’s society, including research, military, imaging, recreation, and agriculture. The performance of the quadrotor relies on the control system, including attitude, altitude, and position subsystems. In the attitude control of the quadrotor, it is vital to maintain the attitude outputs at the desired level using control commands such as the rotational speed of the rotors, when the disturbances occur suddenly. Therefore, much research is being conducted on the automatic control of the attitudes’ quadrotor in facing the disturbance.

In [1], a Proportional Integral Derivative (PID) controller is used to regulate the quadrotor attitude. However, the control objectives have not been effectively achieved with this con- trollers when the disturbance occurs. To solve this problem the model-based approaches [2] are utilized for controller design. These controllers work based on information from the quadrotor’s attitude model and disturbance to produce the best control command.

Various model-based controllers can be found within the literature, the most well-known of which are intelligent con- trol, the nonlinear control, robust control, and optimal control

to reduce the disturbance effect in the attitude control and provide a faster control algorithm in facing the modeling error. In the intelligent controller category, the artificial intelligence computing approaches like fuzzy logic [3], iterative learning [4], machine learning [5], reinforcement learning [6], and evolutionary computation [7] have been utilized to regulate the quadrotor’s attitude .

Moreover, nonlinear control methods such as Feedback Linearization (FBL) [8] and Sliding Mode Control (SMC) [9] have been applied to control the roll, pitch, and yaw angles of the quadrotor. In the optimal controller category, a Linear Quadratic Regulator (LQR) [10] and Linear Quadratic Gaussian (LQG) [11] have been implemented on the quadrotor based on the minimization of a quadratic criterion, including regulation performance and control effort to provide optimally controlled feedback gains.

Linear Quadratic Regulator Differential Game (LQR-DG) control approach [12], [14] is a class of optimal and robust controller methods that controls the outputs of a system based on its linear model and mini-maximization of a cost function. This approach has been utilized to stabilize and control various nonlinear and complex systems such as a ship controller [13]. Moreover, in the LQR-DG control method, the control commands are analytically generated based on a pursuit-evasion of two players, one tracks the best control command, and the other creates the disturbance. This is one of the distinctive features of the LQR-DG controller and an important difference from other optimal control methods.

In this study, an LQR controller method based on the differential game theory, with an integral action called Linear Quadratic Integral Regulator Differential Game (LQIR-DG) controller, is proposed to generate the most efficient control command for an experimental setup of the quadrotor when facing the disturbance. Since the LQIR-DG is affected by an accurate model of the system, first, the dynamic of the three- degree-of-freedom setup of the quadrotor is modeled. Then, the linear state-space form the quadrotor model is extracted using the linearization of the nonlinear equations of motion to utilize in the proposed control problem. Moreover, the model’s parameters are identified and verified against the experimental values. Next, the LQIR-DG technique is applied to the experimental setup of the quadrotor to reduce the effect of disturbance. The performance of the suggested controller is examined when the disturbance occurs. The results show the successful performance of the LQIR-DG scheme in reducing the disturbance.

In the remainder of this study, the problem is defined in section II. The dynamics model for the experimental setup of the quadrotor is derived in details, in section III. In section IV, The LQIR-DG architecture is denoted. Finally, in sections V and VI, Numerical results and conclusion are provided, respectively.

# PROBLEM STATEMENT

Here, a nonlinear dynamic is presented for the setup of the quadrotor, as illustrated in Fig.1. The quadrotor is free to rotate about its roll, pitch, and yaw axes. The Euler angles and angular velocities along three orthogonal axes are measured simultaneously using the Attitude and Heading Reference Systems (AHRS). These noisy measurements are utilizes in the LQIR-DG for control of the Euler angles. The block diagram of the controller structure is illustrated in Fig.2.

Ax

Ax

# MODELING OF THE QUADROTOR SETUP

Here, the model of the three-degree-of-freedom setup of the quadrotor is presented in details. For this purpose, first, the configuration of the quadrotor is denoted. Then, the nonlinear model of the attitude dynamics is derived to denote the state- space form. Finally, the nonlinear model is linearized to utilize in the control purposes.

## Configuration of the Quadrotor

Fig.3 denotes the quadrotor schematic. Each rotor has an angular velocity ,Ωi, rotating about the zB axis in the body coordinate system . Rotors 1 and 3 rotate counterclockwise, while rotors 2 and 4 rotate clockwise, to cancel yawing moment.

Ax

## Dynamic Model

The quadrotor kinetic model, derived using the Newton-Euler method, is stated as [15], [16]

\begin{align}

&\dot p = \dfrac{\mathrm{I}\_{\text{yy}} - \mathrm{I}\_{\text{zz}}}{\mathrm{I}\_{\text{xx}}} qr + q \dfrac{\mathrm{I}\_{\text{rotor}}}{\mathrm{I}\_{\text{xx}}}\Omega\_r + \dfrac{u\_{\text{roll}}}{\mathrm{I}\_{\text{xx}}} + \dfrac{d\_{\text{roll}}}{\mathrm{I}\_{\text{xx}}}

\\

&\dot q = \dfrac{\mathrm{I}\_{\text{zz}} - \mathrm{I}\_{\text{zz}}}{\mathrm{I}\_{\text{yy}}} rp + p \dfrac{\mathrm{I}\_{\text{rotor}}}{\mathrm{I}\_{\text{xx}}}\Omega\_r + \dfrac{u\_{\text{pitch}}}{\mathrm{I}\_{\text{yy}}} + \dfrac{d\_{\text{pitch}}}{\mathrm{I}\_{\text{yy}}}

\\

&\dot r = \dfrac{\mathrm{I}\_{\text{xx}} - \mathrm{I}\_{\text{yy}}}{\mathrm{I}\_{\text{zz}}} pq + \dfrac{u\_{\text{yaw}}}{\mathrm{I}\_{\text{zz}}} + \dfrac{d\_{\text{yaw}}}{\mathrm{I}\_{\text{zz}}}

\end{align}

where $(p, q, r)$ are the angular velocities. $d\_{\text{roll}}$, $d\_{\text{pitch}}$, and $d\_{\text{yaw}}$ are the disturbances, generated in $x\_B$, $y\_B$ and $z\_B$, respectively. Moreover, $\mathrm{I}\_{\text{xx}}$, $\mathrm{I}\_{\text{yy}}$, and $\mathrm{I}\_{\text{zz}}$ are the principal moment of inertia and $\mathrm{I}\_{\text{rotor}}$ is a rotor inertia about its axis.where $(p, q, r)$ are roll, pitch, and yaw angles. Moreover, Ωr , called the overall residual rotor angular velocity, is computed as

\begin{align}

\dot\phi &= p + (q\sin(\phi) + r\cos(\phi))\tan(\theta)\\

\dot \theta &= q\cos(\phi) - r\sin(\phi)\\

\dot\psi &= (q\sin(\phi) + r\cos(\phi))/{\cos(\theta)}\\

\end{align}

where $(\phi, \theta, \psi)$ are roll, pitch, and yaw angles.

Moreover, $\Omega\_r$, called the overall residual rotor angular velocity, is computed as

\begin{equation}

\Omega\_r = -\Omega\_1 + \Omega\_2 - \Omega\_3 + \Omega\_4

\end{equation}

## Control Commands

The control inputs $u\_{\text{roll}}$, $u\_{\text{pitch}}$, and $u\_{\text{yaw}}$ are roll, pitch, and yaw moments, obtained from the rotors, defined as

\begin{align}

&u\_{\text{roll}} = \mathrm{b\,d}\_{\text{cg}} (\Omega\_2^2 - \Omega\_4^2)\\

&u\_{\text{pitch}} = \mathrm{b\,d}\_{\text{cg}} (\Omega\_1^2 - \Omega\_3^2) \\

&u\_{\text{yaw}} = \mathrm{d} (\Omega\_1^2 - \Omega\_2^2 + \Omega\_3^2 - \Omega\_4^2)\\

\end{align}

Also, d and b are, respectively, drag and thrust coefficients. $\mathrm{d}\_{\text{cg}}$ is the distance of rotors from the gravity center . Hence, the angular velocity commands are obtained as

\begin{align}

\Omega\_{c, 1}^2 &= \Omega\_{\text{mean}}^2 + \dfrac{1}{2\mathrm{b\,d}\_{\text{cg}}}u\_{\text{pitch}} + \dfrac{1}{4d}u\_{\text{yaw}} \\

\Omega\_{c, 2}^2 &= \Omega\_{\text{mean}}^2 + \dfrac{1}{2\mathrm{b\,d}\_{\text{cg}}}u\_{\text{roll}} - \dfrac{1}{4d}u\_{\text{yaw}}\\

\Omega\_{c, 3}^2 &= \Omega\_{\text{mean}}^2 - \dfrac{1}{2\mathrm{b\,d}\_{\text{cg}}}u\_{\text{pitch}} + \dfrac{1}{4d}u\_{\text{yaw}} \\

\Omega\_{c, 4}^2 &= \Omega\_{\text{mean}}^2 - \dfrac{1}{2\mathrm{b\,d}\_{\text{cg}}}u\_{\text{roll}} - \dfrac{1}{4d}u\_{\text{yaw}}

\end{align}

where $\Omega\_{\text{mean}}$ is the nominal of the rotor angular velocities.

## State-Space Form

Here, the state-space model is presented for the control purposes. By defining $x\_1 = p$, $x\_2 = q$, $x\_3 = r$, $x\_4 = \phi$, $x\_5 = \theta$, and $x\_6 = \psi$; the model of in state-space form are denoted as

\begin{align}\label{eq:diffeq}

\dot x\_1 &= \dfrac{\mathrm{I}\_{\text{yy}} - \mathrm{I}\_{\text{zz}}}{\mathrm{I}\_{\text{xx}}} x\_2 x\_3 + x\_2 \dfrac{\mathrm{I}\_{\text{rotor}}}{\mathrm{I}\_{\text{xx}}}\Omega\_r + \dfrac{u\_{\text{roll}}}{\mathrm{I}\_{\text{xx}}} + \dfrac{d\_{\text{roll}}}{\mathrm{I}\_{\text{xx}}} \\

\dot x\_2 &= \dfrac{\mathrm{I}\_{\text{zz}} - \mathrm{I}\_{\text{zz}}}{\mathrm{I}\_{\text{yy}}} x\_1 x\_3 - x\_1 \dfrac{\mathrm{I}\_{\text{rotor}}}{\mathrm{I}\_{\text{xx}}}\Omega\_r + \dfrac{u\_{\text{pitch}}}{\mathrm{I}\_{\text{yy}}} + \dfrac{d\_{\text{pitch}}}{\mathrm{I}\_{\text{yy}}}\\

\dot x\_3 &= \dfrac{\mathrm{I}\_{\text{xx}} - \mathrm{I}\_{\text{yy}}}{\mathrm{I}\_{\text{zz}}} x\_1 x\_2 + \dfrac{u\_{\text{yaw}}}{\mathrm{I}\_{\text{zz}}} + \dfrac{d\_{\text{yaw}}}{\mathrm{I}\_{\text{zz}}}\\

\dot x\_4 &= x\_1 + (x\_2\sin(x\_4) + x\_3\cos(x\_4))\tan(x\_5)

\\

\dot x\_5 &= x\_2\cos(x\_4) - x\_3\sin(x\_4)\\

\dot x\_6 &= (x\_2\sin(x\_4) + x\_3\cos(x\_4))/\cos(x\_5) \label{eq:diffeq-end}

\end{align}

The measurement model is written as

\begin{split}

\boldsymbol{\mathrm{z}} &= \begin{bmatrix}

p\_m & q\_m & r\_m & \phi\_m & \theta\_m & \psi\_m

\end{bmatrix}^\mathrm{T}

\end{split}

## Linear Model

The continuous-time linear model is utilized to drive the control commands on the quadrotor. The linear state-space model is denoted as

\begin{equation}\label{eq:linear}

\boldsymbol{\dot{\mathrm{x}}}(t) = \boldsymbol{\mathrm{Ax}}(t) + \boldsymbol{\mathrm{Bu}}(t) + \boldsymbol{\mathrm{B\_{d}d}}(t)

\end{equation}

where $\boldsymbol{\mathrm{A}}$, $\boldsymbol{\mathrm{B}}$, and $\boldsymbol{\mathrm{B\_d}}$ are the system, input and disturbance matrices, respectively. Moreover, $\boldsymbol{\mathrm{d}}$ is the disturbance. The measurements equation is stated as

\begin{equation}

\boldsymbol{{\mathrm{z}}}(t) = \boldsymbol{\mathrm{x}}(t)

\end{equation}

According to Eqs.\eqref{eq:diffeq}-\eqref{eq:diffeq-end}, the linear dynamic model around the equilibrium points $(\boldsymbol{{\mathrm{x}}}\_e\!=\!0 \text{ and } \boldsymbol{{\mathrm{u}}}\_e\!=\!0)$ of the quadrotor setup is denoted as

\begin{equation}

\begin{split}

\boldsymbol{{\mathrm{\dot x}}} = \begin{bmatrix}

\boldsymbol{{\mathrm{\dot x\_{\text{roll}}}}}\\

\boldsymbol{{\mathrm{\dot x\_{\text{pitch}}}}}\\

\boldsymbol{{\mathrm{\dot x\_{\text{yaw}}}}}

\end{bmatrix} &= \begin{bmatrix}

\boldsymbol{{\mathrm{A\_{\text{roll}}}}} & \boldsymbol{0} & \boldsymbol{0}\\

\boldsymbol{0} & \boldsymbol{{\mathrm{A\_{\text{pitch}}}}} & \boldsymbol{0} \\

\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{{\mathrm{A\_{\text{yaw}}}}}

\end{bmatrix} \begin{bmatrix}

\boldsymbol{{\mathrm{x\_{\text{roll}}}}}\\

\boldsymbol{{\mathrm{x\_{\text{pitch}}}}}\\

\boldsymbol{{\mathrm{x\_{\text{yaw}}}}}

\end{bmatrix}

\\[1em]

& + \begin{bmatrix}

\boldsymbol{{\mathrm{B\_{\text{roll}}}}} & \boldsymbol{0} & \boldsymbol{0}\\

\boldsymbol{0} & \boldsymbol{{\mathrm{B\_{\text{pitch}}}}} & \boldsymbol{0} \\

\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{{\mathrm{B\_{\text{yaw}}}}}

\end{bmatrix}

\begin{bmatrix}

\boldsymbol{{\mathrm{u\_{\text{roll}}}}}\\

\boldsymbol{{\mathrm{u\_{\text{pitch}}}}}\\

\boldsymbol{{\mathrm{u\_{\text{yaw}}}}}

\end{bmatrix}\\[1em]

& + \begin{bmatrix}

\boldsymbol{{\mathrm{B\_{\text{roll}}}}} & \boldsymbol{0} & \boldsymbol{0}\\

\boldsymbol{0} & \boldsymbol{{\mathrm{B\_{\text{pitch}}}}} & \boldsymbol{0} \\

\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{{\mathrm{B\_{\text{yaw}}}}}

\end{bmatrix} \begin{bmatrix}

\boldsymbol{{\mathrm{d\_{\text{roll}}}}}\\

\boldsymbol{{\mathrm{d\_{\text{pitch}}}}}\\

\boldsymbol{{\mathrm{d\_{\text{yaw}}}}}

\end{bmatrix}

\end{split}

\end{equation}

where $\boldsymbol{\mathrm{x}}\_{\text{roll}} = \begin{bmatrix}

p & \phi

\end{bmatrix}^\mathrm{T}$, $\boldsymbol{\mathrm{x}}\_{\text{pitch}} = \begin{bmatrix}

q & \theta \end{bmatrix}^\mathrm{T}$, and $\boldsymbol{\mathrm{x}}\_{\text{yaw}} = \begin{bmatrix}

r & \psi

\end{bmatrix}^\mathrm{T}$.

Moreover, the state and input matrices are presented as

\begin{equation}

\begin{split}

\boldsymbol{\mathrm{A}}\_{\text{roll}} =\boldsymbol{\mathrm{A}}\_{\text{pitch}} = \boldsymbol{\mathrm{A}}\_{\text{yaw}} = \begin{bmatrix}

0 & 0\\

1 & 0

\end{bmatrix}

\end{split}

\end{equation}

\begin{equation}

\begin{split}

\boldsymbol{\mathrm{B}}\_{\text{roll}} = \begin{bmatrix}

\dfrac{1}{\mathrm{I}\_{\text{xx}}}

\\[1em]

0

\end{bmatrix};~ \boldsymbol{\mathrm{B}}\_{\text{pitch}} = \begin{bmatrix}

\dfrac{1}{\mathrm{I}\_{\text{yy}}}

\\[1em]

0

\end{bmatrix};~ \boldsymbol{\mathrm{B}}\_{\text{yaw}} = \begin{bmatrix}

\dfrac{1}{\mathrm{I}\_{\text{zz}}}

\\[1em]

0

\end{bmatrix}

\end{split}

\end{equation}

# Formulation of the Controller Design

In the LQIR-DG controller structure, an integral action is added to the LQR-DG controller to cancel the steady-state errors for reference tracking. For this purpose, first, the augmented state space of the linear quadrotor model is defined to utilize in the controller architecture. Then, the LQR-DG controller design procedure is presented to produce the best control commands for the experimental setup of the quadrotor.

## Augmented State Space Formulation

To add the integral action to the controller structure, the augmented states are defined as follows:

\begin{equation}\label{lqidg\_x}

\boldsymbol{\mathrm{x\_{a\_i}}} = \begin{bmatrix}

\boldsymbol{\mathrm{x\_i}} &

\displaystyle \int \boldsymbol{\mathrm{x\_i}}

\end{bmatrix}^\mathrm{T}

\end{equation}

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