Control of a Three Degree of Freedom Quadcopter Stand Using Linear Quadratic Integral Based on the Differential Game Theory

Hadi Nobahari
Department of Aerospace Engineering
Sharif University of Technology
Tehran, Iran
nobahari@sharif.edu

Ali BaniAsad
Department of Aerospace Engineering
Sharif University of Technology
Tehran, Iran
alibaniasad1999@yahoo.com

Abstract—In this paper, a quadcopter stand with three degrees of freedom was controlled using game theory-based control. The first player tracks a desired input, and the second player creates a disturbance in the tracking of the first player to cause an error in the tracking. The ???? move is chosen using the Nash equilibrium, which presupposes that the other player made the worst move. In addition to being resistant to input interruptions, this method may also be resilient to modeling system uncertainty. This method evaluated the performance through simulation in the Simulink environment and implementation on a three-degree-of-freedom stand.

Index Terms—Quadcopter, Differential Game, Game Theory, Nash Equilibrium, Three Degree of Freedom Stand, Model Base Design, Linear Quadratic Regulator

I. INTRODUCTION

Quadcopter is a type of helicopter with four rotors.

II. DIFFERENTIAL GAME

Differential games are a series of problems that arise while examining and simulating dynamic systems in game theory. Differential equations simulate how a state variable or set of state variables changes over time.

A. An introduction to the differential game

It is considered that two players are involved in this research. The space states of a continuous linear system are shown below.

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B_1}\mathbf{u_1}(t) + \mathbf{B_2}\mathbf{u_2}(t)$$
$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D_1}\mathbf{u_1}(t) + \mathbf{D_2}\mathbf{u_2}(t) \tag{1}$$

Where $\mathbf{x}$ is the vector of the state variables, $\dot{\mathbf{x}}$ is the time derivative of the state vector, $\mathbf{u_1}$ is the first player (controller) input vector, $\mathbf{u_2}$ is the second player (disturbance) input vector, $\mathbf{y}$ is the output vector, $\mathbf{A}$ is the state matrix, $\mathbf{B_1}$ is the first player input matrix, $\mathbf{B_2}$ is the second player input matrix, $\mathbf{C}$ is the output matrix, $\mathbf{D_1}$ is first player the output matrix and $\mathbf{D_2}$ is second player the output matrix. Equation (1) demonstrates how both participants have an impact on the system's dynamics. The second player may progress toward

the goal as a result of the first player's exertion, or vice versa. This paper considers the case that players do not cooperate in order to realize their goals. The situation where players do not work together (non-cooperative) to achieve their objectives is examined in the paper. In this case, every player knows at time $t \in [0, T]$ just the initial state $\mathbf{x_0}$ and the model structure. For the game (1,2), we will use the set of Nash equilibria. Formal Nash equilibrium is defined as follows. An admissible set of actions $(\boldsymbol{u_1}^*, \boldsymbol{u_2}^*)$ is a Nash equilibrium for the game (1,2); if for all admissible $(\boldsymbol{u_1}, \boldsymbol{u_2})$, the following inequalities hold:

$$J_1(\boldsymbol{u_1}^*, \boldsymbol{u_2}^*) \leq J_1(\boldsymbol{u_1}, \boldsymbol{u_2}^*) \ , \ J_2(\boldsymbol{u_1}^*, \boldsymbol{u_2}^*) \leq J_2(\boldsymbol{u_1}^*, \boldsymbol{u_2}) \tag{2}$$

B. LQDG controller

For the system described in equation (1), LQDG optimum control effort calculates from equation (3).

$$\mathbf{u_i}(t) = -\mathbf{R_{ii}}^{-1}\mathbf{B_i}^{\mathrm{T}}\mathbf{P_i}(t)\mathbf{x}(t) = -\mathbf{K_i}(t)\mathbf{x}(t), \quad i = 1,2 \tag{3}$$

In equation (3), $\mathbf{K_i}$ is the optimal feedback gain. Assuming that the other players will make their worst move, this gain is calculated to minimize the quadratic cost function equation (4) of player number i.

$$J_i(\mathbf{u_1}, \mathbf{u_2}) = \int_0^T \Big(\mathbf{x}^{\mathrm{T}}(t)\mathbf{Q_i}\mathbf{x}(t) + \mathbf{u_i}^{\mathrm{T}}(t)\mathbf{R_{ii}}\mathbf{u_i}(t) + $$
$$\mathbf{u_j}^{\mathrm{T}}(t)\mathbf{R_{ij}}\mathbf{u_j}(t) \Big) \mathrm{d}t \tag{4}$$

Here the matrices $\mathbf{Q_i}$ and $\mathbf{R_{ii}}$ are assumed to be symmetric and $\mathbf{R_{ii}}$ positive definite. $\mathbf{P_i}$ is found by solving the continuous time couple Riccati differential equation:

$$\dot{\mathbf{P_1}}(t) = -\mathbf{A}^{\mathrm{T}}\mathbf{P_1}(t) - \mathbf{P_1}(t)\mathbf{A} - \mathbf{Q_1} + \mathbf{P_1}(t)\mathbf{S_1}(t)\mathbf{P_1}(t) + $$
$$\mathbf{P_1}(t)\mathbf{S_2}(t)\mathbf{P_2}(t)$$
$$\dot{\mathbf{P_2}}(t) = -\mathbf{A}^{\mathrm{T}}\mathbf{P_2}(t) - \mathbf{P_2}(t)\mathbf{A} - \mathbf{Q_2} + \mathbf{P_2}(t)\mathbf{S_2}(t)\mathbf{P_2}(t) + $$
$$\mathbf{P_2}(t)\mathbf{S_1}(t)\mathbf{P_1}(t) \tag{5}$$

Using the shorthand notation $\boldsymbol{S_i} := \boldsymbol{B_i R_{ii}}^{-1}\boldsymbol{B_i}^{\mathrm{T}}$.

C. LQIDG controller

The absence of an integrator in the LQDG controller may result in steady-state errors due to disturbances or modeling errors. The LQIDG controller is based on the LQDG controller to eliminate this error.

The LQIDG controller adds the integral of the difference between the system output and the desired value to the state vector. Therefore, The augmented space states of a continuous linear system are shown below.

$$\mathbf{x_a} = \begin{bmatrix} \mathbf{x_d} - \mathbf{x} \\ \int (\mathbf{y_d} - \mathbf{y}) \end{bmatrix} \tag{6}$$

Where $\mathbf{x_a}$ is the vector of augmented state variables, $\mathbf{x_d}$ is the vector of the desired state variables, and $\mathbf{y_d}$ is the desired output vector. As a result, the state vector and the output vector are equal.

$$\mathbf{y} = \mathbf{x} \tag{7}$$

The following represents the system dynamics in the augmented state space.

$$\dot{\mathbf{x}}_a(t) = \mathbf{A_a}\mathbf{x_a}(t) + \mathbf{B_{a_1}}\mathbf{u_{a_1}}(t) + \mathbf{B_{a_2}}\mathbf{u_{a_2}}(t) \tag{8}$$

Where matrices $\mathbf{A_a}$ and $\mathbf{B_a}$ are defined as follows:

$$\mathbf{A_a} = \begin{bmatrix} \mathbf{A} & 0 \\ \mathbf{C} & 0 \end{bmatrix}, \quad \mathbf{B_a} = \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix} \tag{9}$$

By introducing a new space state for the system, the remaining design phases of the LQIDG controller are comparable to those of the LQDG controller. LQIDG optimum control effort calculates from equation (10).

$$\mathbf{u_i}(t) = -\mathbf{R_{ii}}^{-1}\mathbf{B_{a_i}}^{\mathrm{T}}\mathbf{P_{a_i}}(t)\mathbf{x_a}(t) = -\mathbf{K_{a_i}}(t)\mathbf{x_a}(t), \ i = 1,2 \tag{10}$$

In equation (10), $\mathbf{K_{a_i}}$ is the optimal feedback gain. Assuming that the other players will make their worst move, this gain is calculated to minimize the quadratic cost function, equation (11), of player number i.

$$J_i(\mathbf{u_1}, \mathbf{u_2}) = \int_0^T \left(\mathbf{x_a}^{\mathrm{T}}(t)\mathbf{Q_i}\mathbf{x_a}(t) + \mathbf{u_i}^{\mathrm{T}}(t)\mathbf{R_{ii}}\mathbf{u_i}(t) + \right.$$
$$\left. \mathbf{u_j}^{\mathrm{T}}(t)\mathbf{R_{ij}}\mathbf{u_j}(t) \right) \mathrm{d}t \tag{11}$$

$\dot{\mathbf{P}}_{a_i}$ is found by solving the continuous time couple Riccati differential equation:

$$\dot{\mathbf{P}}_{a_1}(t) = -\mathbf{A_a}^{\mathrm{T}}\mathbf{P_{a_1}}(t) - \mathbf{P_{a_1}}(t)\mathbf{A_a} - \mathbf{Q_1} +$$
$$\mathbf{P_{a_1}}(t)\mathbf{S_{a_1}}(t)\mathbf{P_{a_1}}(t) + \mathbf{P_{a_1}}(t)\mathbf{S_{a_2}}(t)\mathbf{P_{a_2}}(t)$$
$$\dot{\mathbf{P}}_{a_2}(t) = -\mathbf{A_a}^{\mathrm{T}}\mathbf{P_{a_2}}(t) - \mathbf{P_{a_2}}(t)\mathbf{A_a} - \mathbf{Q_2} +$$
$$\mathbf{P_{a_2}}(t)\mathbf{S_{a_2}}(t)\mathbf{P_{a_2}}(t) + \mathbf{P_{a_2}}(t)\mathbf{S_{a_1}}(t)\mathbf{P_{a_1}}(t) \tag{12}$$

Using the shorthand notation $S_{a_i} := B_{a_i}R_{ii}^{-1}B_{a_i}^{\mathrm{T}}$.

III. MATHEMATICAL MODELING

The dynamic model of the three degrees of freedom of the quadcopter stand can be described as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{13}$$

where $\mathbf{f}$ is described below.

$$\mathbf{f} = \begin{bmatrix} x_4 + x_5 \sin(x_1)\tan(x_2) + x_6\cos(x_1)\tan(x_2) \\ x_5\cos(x_1) - x_6\sin(x_1) \\ (x_5\sin(x_1) + x_6\cos(x_1))\sec(x_2) \\ A_1\cos(x_2)\sin(x_1) + A_2 x_5 x_6 + A_3 u_1 \\ B_1\sin(x_2) + B_2 x_4 x_6 + B_3 u_2 \\ C_1 x_4 x_5 + C_2 u_3 \end{bmatrix} \tag{14}$$

$$\mathbf{u} = \begin{bmatrix} u_1 & u_2 & u_3 \end{bmatrix}^{\mathrm{T}} \tag{15}$$

$$\delta\dot{\mathbf{x}} = \mathbf{A}\delta\mathbf{x} + \mathbf{B}\delta\mathbf{u} \tag{16}$$

$$\mathbf{x}^* = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} \tag{17}$$

$$\mathbf{u}^* = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} \tag{18}$$

$$\mathbf{A} = \left.\frac{\partial \mathbf{f}}{\partial \mathbf{x}}\right|_{\mathbf{x}^*} \tag{19}$$

$$\mathbf{B} = \left.\frac{\partial \mathbf{f}}{\partial \mathbf{u}}\right|_{\mathbf{u}^*} \tag{20}$$

$$\mathbf{A}_{\mathrm{roll}} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_4} \\ \frac{\partial f_4}{\partial x_1} & \frac{\partial f_4}{\partial x_4} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ A_1\cos(x_1) & 0 \end{bmatrix} \tag{21}$$

$$\mathbf{B}_{\mathrm{roll}} = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} \\ \frac{\partial f_4}{\partial u_1} \end{bmatrix} = \begin{bmatrix} 0 \\ A_3 \end{bmatrix} \tag{22}$$

$$\mathbf{A}_{\mathrm{pitch}} = \begin{bmatrix} \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_5} \\ \frac{\partial f_5}{\partial x_2} & \frac{\partial f_5}{\partial x_5} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ B_1\cos(x_1) & 0 \end{bmatrix} \tag{23}$$

$$\mathbf{B}_{\mathrm{pitch}} = \begin{bmatrix} \frac{\partial f_2}{\partial u_2} \\ \frac{\partial f_5}{\partial u_2} \end{bmatrix} = \begin{bmatrix} 0 \\ B_3 \end{bmatrix} \tag{24}$$

$$\mathbf{A}_{\mathrm{yaw}} = \begin{bmatrix} \frac{\partial f_3}{\partial x_3} & \frac{\partial f_3}{\partial x_6} \\ \frac{\partial f_6}{\partial x_3} & \frac{\partial f_6}{\partial x_6} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \tag{25}$$

$$\mathbf{B}_{\mathrm{yaw}} = \begin{bmatrix} \frac{\partial f_3}{\partial u_3} \\ \frac{\partial f_6}{\partial u_3} \end{bmatrix} = \begin{bmatrix} 0 \\ C_2 \end{bmatrix} \tag{26}$$

IV. SIMULATION

used Simulink

A. LQR

LQR weighting matrices are optimized using the TCACS optimization method in the simulation. ITSE is considered for the TCACS input cost function. Here are the weighting matrices for the optimized output.

$$\mathbf{Q}_{\text{LQR}} = \begin{bmatrix} 0.5215 & 0 \\ 0 & 0.0745 \end{bmatrix}, \quad R_{\text{LQR}} = 0.0001 \quad (27)$$

B. LQDG

The weighting matrices used in the LQDG portion are chosen like that of the LOR.

$$\mathbf{Q}_{\text{LQDG}} = \begin{bmatrix} 100 & 0 \\ 0 & 0.078 \end{bmatrix}, \quad R_{1_{\text{LQDG}}} = 1, \quad R_{2_{\text{LQDG}}} = 99.96 \quad (28)$$

$$\dot{\mathbf{P}}_1 = \begin{bmatrix} 286.0470 & 39.1188 \\ 39.1188 & 8.8510 \end{bmatrix} \quad (29)$$

$$\mathbf{K}_1 = \begin{bmatrix} 39.1188 & 8.8510 \end{bmatrix} \quad (30)$$

C. LQIDG

LQIDG weighting matrices are chosen like the method used in the LQR and LQDG sections.

Roll:

$$\mathbf{Q}_{\text{LQIDG}} = \begin{bmatrix} 0.1707 & 0 & 0 & 0 \\ 0 & 0.12 & 0 & 0 \\ 0 & 0 & 837.8606 & 0 \\ 0 & 0 & 0 & 756.1341 \end{bmatrix} \quad (31)$$

$$R_{1_{\text{LQIDG}}} = 1, \quad R_{2_{\text{LQIDG}}} = 7.7422$$

$$\dot{\mathbf{P}}_{a_1} = \begin{bmatrix} 10924.84 & 39.83 & 1014.34 & -10629.93 \\ 39.83 & 8.40 & 27.22 & 11.70 \\ 1014.34 & 27.22 & 1047.80 & -756.13 \\ -10658.93 & 11.70 & -756.13 & 10658.93 \end{bmatrix} \quad (32)$$

$$\mathbf{K}_{a_1} = \begin{bmatrix} 28.1410 & 8.4017 & 27.2223 & 11.6894 \end{bmatrix} \quad (33)$$

Roll-Pitch:

$$\mathbf{Q}_{\text{LQIDG}_{\text{roll}}} = \begin{bmatrix} 585.9 & 0 & 0 & 0 \\ 0 & 31.1 & 0 & 0 \\ 0 & 0 & 83.8 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{Q}_{\text{LQIDG}_{\text{pitch}}} = \begin{bmatrix} 546.5 & 0 & 0 & 0 \\ 0 & 311.4 & 0 & 0 \\ 0 & 0 & 2.22 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (34)$$

$$R_{1_{\text{LQIDG}}} = 1, \quad R_{2_{\text{LQIDG}}} = 7.7422$$

Roll-Pitch-Yaw:

$$\mathbf{Q}_{\text{LQIDG}_{\text{roll}}} = \begin{bmatrix} 631.85 & 0.00 & 0.00 & 0.00 \\ 0.00 & 214.28 & 0.00 & 0.00 \\ 0.00 & 0.00 & 7.91 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.01 \end{bmatrix}$$

$$\mathbf{Q}_{\text{LQIDG}_{\text{pitch}}} = \begin{bmatrix} 0.01 & 0.00 & 0.00 & 0.00 \\ 0.00 & 873.93 & 0.00 & 0.00 \\ 0.00 & 0.00 & 9853.09 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.12 \end{bmatrix} \quad (35)$$

$$\mathbf{Q}_{\text{LQIDG}_{\text{yaw}}} = \begin{bmatrix} 0.03 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.17 & 0.00 & 0.00 \\ 0.00 & 0.00 & 1.81 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.45 \end{bmatrix} \times 10^{-4}$$

$$R_{1_{\text{LQIDG}}} = 1, \quad R_{2_{\text{LQIDG}}} = 1.2577$$

TABLE I
PARAMETER ESTIMATION RESULTS

Parameter	Initial Value	Value After Estimation
A_1	7.312	4.152
A_3	1.1×10^{-4}	5.47×10^{-5}
B_1	4.53	4.36
B_3	1.1×10^{-4}	7.13×10^{-5}
C_2	5.45×10^{-5}	1.3×10^{-5}

Before you begin to format your paper, first write and save the content as a separate text file. Complete all content and organizational editing before formatting. Please note sections (IV-D)–(IV-H) below for more information on proofreading, spelling and grammar. Keep your text and graphic files separate until after the text has been formatted and styled. Do not number text heads—LATEX will do that for you.

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Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, ac, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

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- Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as "3.5-inch disk drive".
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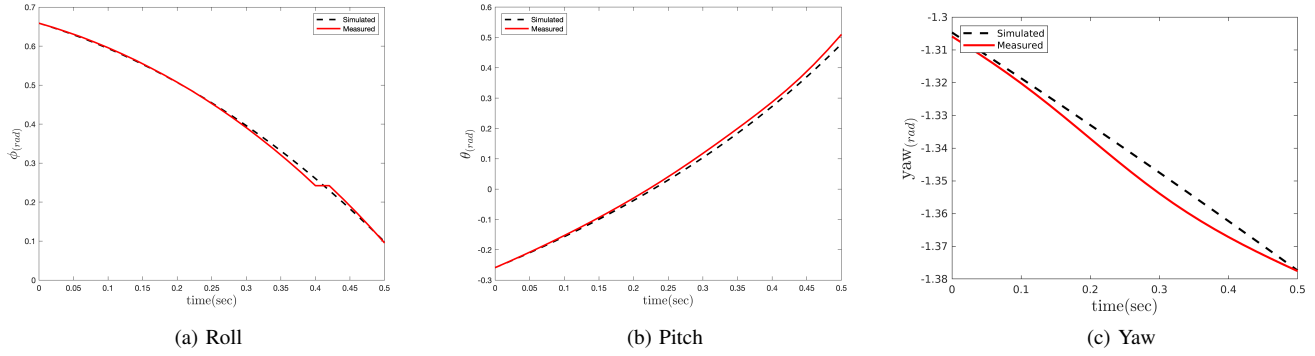(a) Roll   (b) Pitch   (c) Yaw

Fig. 1. Simulation results for the network.

Spell out units when they appear in text: ". . . a few henries", not ". . . a few H".

- Use a zero before decimal points: "0.25", not ".25". Use "cm^3", not "cc".)

F. Equations

Number equations consecutively. To make your equations more compact, you may use the solidus (/), the exp function, or appropriate exponents. Italicize Roman symbols for quantities and variables, but not Greek symbols. Use a long dash rather than a hyphen for a minus sign. Punctuate equations with commas or periods when they are part of a sentence, as in:

$$a + b = \gamma \tag{36}$$

Be sure that the symbols in your equation have been defined before or immediately following the equation. Use "(36)", not "Eq. (36)" or "equation (36)", except at the beginning of a sentence: "Equation (36) is . . ."

G. LaTeX-Specific Advice

Please use "soft" (e.g., \eqref{Eq}) cross references instead of "hard" references (e.g., (1)). That will make it possible to combine sections, add equations, or change the order of figures or citations without having to go through the file line by line.

Please don't use the {eqnarray} equation environment. Use {align} or {IEEEeqnarray} instead. The {eqnarray} environment leaves unsightly spaces around relation symbols.

Please note that the {subequations} environment in LaTeX will increment the main equation counter even when there are no equation numbers displayed. If you forget that, you might write an article in which the equation numbers skip from (17) to (20), causing the copy editors to wonder if you've discovered a new method of counting.

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- The subscript for the permeability of vacuum μ_0, and other common scientific constants, is zero with subscript formatting, not a lowercase letter "o".
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- In your paper title, if the words "that uses" can accurately replace the word "using", capitalize the "u"; if not, keep using lower-cased.
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- Do not confuse "imply" and "infer".
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- There is no period after the "et" in the Latin abbreviation "et al.".
- The abbreviation "i.e." means "that is", and the abbreviation "e.g." means "for example".

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TABLE II
TABLE TYPE STYLES

Table Head	Table Column Head		
	Table column subhead	*Subhead*	*Subhead*
copy	More table copy[a]		

[a]Sample of a Table footnote.

Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when

Fig. 2. Example of a figure caption.

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ACKNOWLEDGMENT

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For papers published in translation journals, please give the English citation first, followed by the original foreign-language citation [6].

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