

Sensitivity of Control Systems of Quadcopters

Oleg Gasparyan¹; Armand Karapetyan²; Azatuhi Ulikyan³; Liana Buniatyan⁴;
Ovsanna Ohanyan⁵; Mariam Darakhchyan⁶; Vahan Manukyan⁷;
Gohar Melkonyan⁸; Sona Mnatsakanyan⁹

^{1;2;3;4;5;6;7;8;9}National Polytechnic University of Armenia, Yerevan, Armenia

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Abstract

This paper presents a method for analyzing the parameter sensitivity of multivariable control systems in multirotor unmanned aerial vehicles (UAVs) subject to partial efficiency degradation of their DC motors. Quadcopter dynamics with identical channel controllers are formulated within the framework of uniform multi-input multi-output (MIMO) systems. Using canonical representations and the method of characteristic transfer functions (CTFs), the sensitivity of the closed-loop system is reduced to calculating the first-order perturbations of the eigenvalues and canonical basis eigenvectors of the cross-connection matrix. A numerical simulation of a quadcopter control system with uncompensated kinematic cross-connections demonstrates the analytical evaluation of system sensitivity under small motor efficiency degradations.

Keywords: Quadcopter, Multivariable Control System, Uniform System, Characteristic Transfer Functions, Canonical Basis, Sensitivity, Parameter Perturbation, Motor Efficiency Degradation.

I. INTRODUCTION

Multirotor unmanned aerial vehicles (UAVs) serve a broad range of military and civilian applications [1]. In actual flights, unforeseen operating conditions can cause failures in control system components, with consequences that may include a serious accident and the complete loss of the aircraft. Flight safety has therefore motivated extensive research on fault-tolerant control [2], and numerous advanced methods have been proposed for handling component faults. Robust control provides one suitable framework because it permits a system to accommodate a partial loss of component efficiency rather than only a complete failure. This issue is especially important for DC motors and propellers: unlike electronic units and sensors, these components cannot readily be duplicated to provide hardware redundancy.

The method developed in this paper evaluates the sensitivity of a quadcopter control system to a possible partial reduction in motors efficiency. Its application is demonstrated by a numerical example.

II. CONTROL SYSTEM OF QUADCOPTERS

Consider the control systems of a quadcopter in Fig.

1.



Fig 1 Quadcopter

Regardless of the number of rotors (motors), multirotor UAVs are underactuated systems in which the flight altitude z and three attitude angles - roll ϕ , pitch θ , and yaw ψ - are commonly selected as the four controlled variables [1-3].

Throughout the subsequent analysis, the UAV angles and angular velocities are assumed to be sufficiently small for the nonlinear terms in the rotational equations of motion to be neglected. The multirotor dynamics can then be written in the following linearized form [1-3]:

$$\frac{d^2 z(t)}{dt^2} = \frac{1}{m} T_\Sigma(t) - g, \quad (1)$$

$$J \frac{d\omega(t)}{dt} = \tau(t). \quad (2)$$

Here, m denotes the UAV mass, g is the gravitational constant, and J is the diagonal inertia tensor with the principal components I_x , I_y , and I_z . The vector $\omega(t)$ contains the angular velocities expressed in the body-fixed frame, while $\tau(t) = [\tau_x, \tau_y, \tau_z]^T$ collects the principal non-conservative forces and moments acting on the airframe by the aerodynamics of four rotors.

$$T_\Sigma = \sum_{i=1}^4 T_i \quad (3)$$

Is the total thrust at hover, where T_i denotes the thrust produced by the i th rotor.

Let $\bar{T}$ be the four-dimensional vector of T_i ($\bar{T} = [T_1, T_2, T_3, T_4]^T$). The transformation from $\bar{T}$ to $[T_\Sigma, \tau]^T$ may be expressed in matrix form as:

$$\begin{bmatrix} T_\Sigma \\ \tau \end{bmatrix} = D_M \Lambda_M \bar{T}, \quad \Lambda_M = \text{diag}\{\lambda_i^M\}, \quad (4)$$

In (4), D_M is the invertible 4×4 numerical matrix whose entries are determined by the UAV geometry, and λ_i^M ($0 < \lambda_i^M \leq 1$) are the motors' efficiency degradation parameters. With all motors operating normally, the matrix Λ_M reduces to the identity matrix I . Therefore, the matrix D_M represents the kinematic cross-connections among the individual control channels.

The matrix block diagram of the UAV control system is presented in Fig. 2 [2,3].

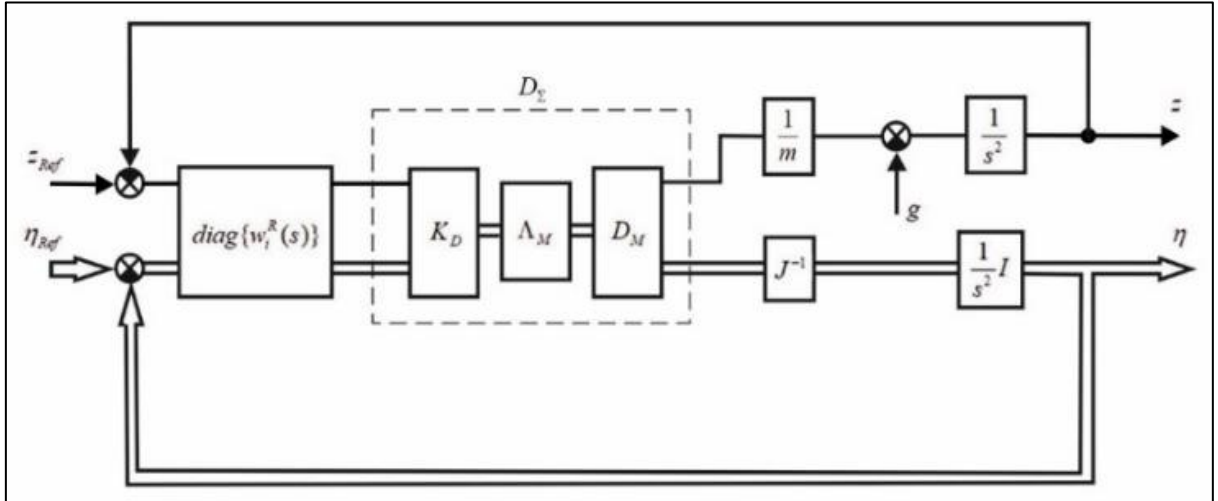


Fig 2 Matrix Block Diagram of the Linear Control System of the Quadcopter

The matrix controller $K_{\text{Reg}}(s)$ used in this system generally has the form:

$$K_{\text{Reg}}(s) = K_R \text{diag}\{w_i^R(s)\}. \quad (5)$$

Here, K_R is a constant matrix and $w_i^R(s)$ are the scalar transfer functions of the individual channel controllers. In practical applications, the functions $w_i^R(s)$ in (5) are usually implemented as conventional PID

controllers [3]. For simplicity, all controllers $w_i^R(s)$ are assumed to be identical, so that $w_i^R(s) = w^R(s)$.

The block diagram in Fig. 2 can be rearranged into the equivalent configuration shown in Fig. 3. In that representation, $\zeta(s)$ and $\rho_{\text{Out}}(s)$ are vectors of dimension 4×1 , and the diagonal matrix M_Σ has size 4×4 . These quantities are defined by:

$$\zeta(s) = \begin{bmatrix} z_{\text{Ref}}(s) \\ \eta_{\text{Ref}}(s) \end{bmatrix}, \quad \rho_{\text{Out}} = \begin{bmatrix} z(s) \\ \eta(s) \end{bmatrix}, \quad M_{\Sigma} = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & I_x & 0 & 0 \\ 0 & 0 & I_y & 0 \\ 0 & 0 & 0 & I_z \end{bmatrix}, \quad (6)$$

The three components of η that appear in the four-dimensional vector $\rho_{\text{Out}}(s)$ are the roll ϕ , pitch θ , and yaw ψ angles; hence, $\eta = [\phi, \theta, \psi]^T$.

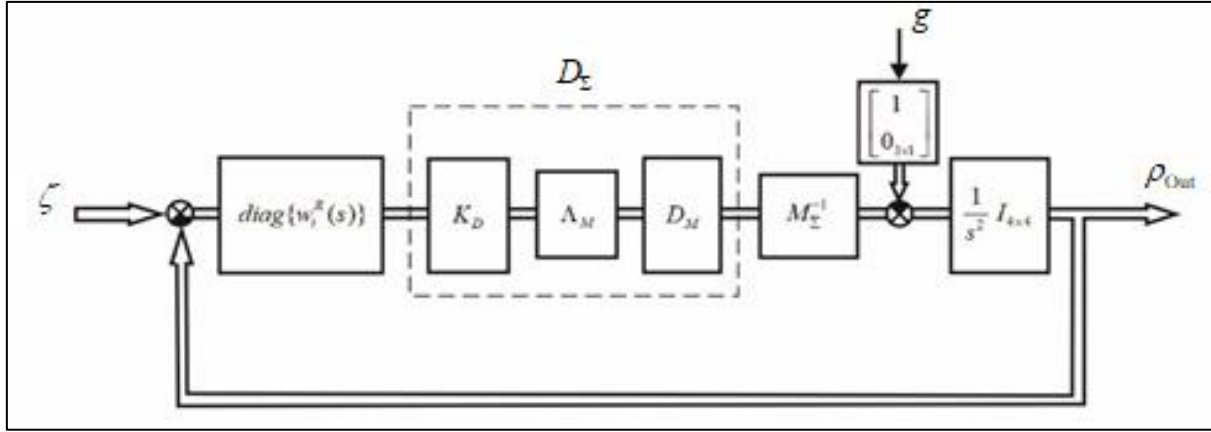


Fig 3 Transformed Block Diagram of the Quadcopter Control System

Introduce the numerical matrix R defined by:

$$R = M_{\Sigma}^{-1} D_M \Lambda_M K_R. \quad (7)$$

When $\Lambda_M \neq I$, the open-loop transfer matrix $W(s)$ for the system in Fig. 3 is given by

$$W(s) = w(s) R, \quad (8)$$

Where

$$w(s) = \frac{w^R(s)}{s^2}. \quad (9)$$

Thus, the quadcopter control system belongs to the class of uniform systems [4].

A customary choice for the matrix K_R in (7) is:

$$K_R = D_M^{-1} M_{\Sigma}. \quad (10)$$

For ideal motors ($\Lambda_M = I$), equations (7) and (10) give $R = I$. The kinematic cross-connections among the four channels in Fig. 3 are then compensated, and the overall system decomposes into four identical, independent SISO systems, as shown in Fig. 4.

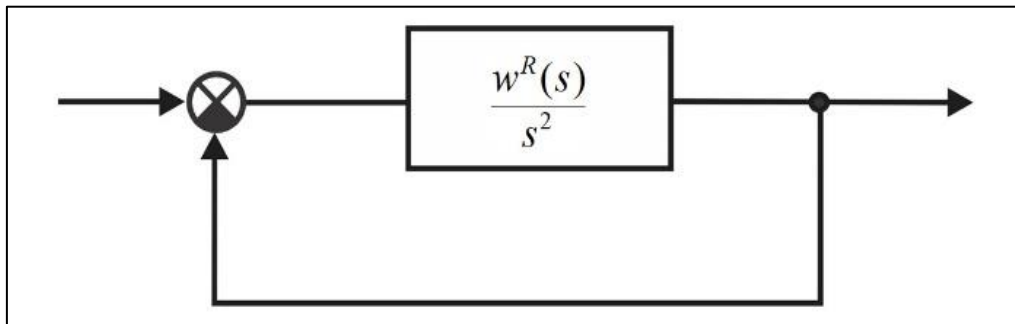


Fig 4 Block Diagram of Isolated Separate Channels in Case of Ideal Motors

However, if motor efficiency is degraded ($\Lambda_M \neq I$), the matrix R in (7) is no longer the identity matrix. The UAV control system then retains the structure of a uniform system, but its channels remain coupled.

III. CANONICAL REPRESENTATION OF UNIFORM CONTROL SYSTEMS

This section develops the canonical representation of uniform multi-input multi-output (MIMO) systems. Fig. 5 shows the matrix block diagram of an N-dimensional uniform MIMO system [4, 5].

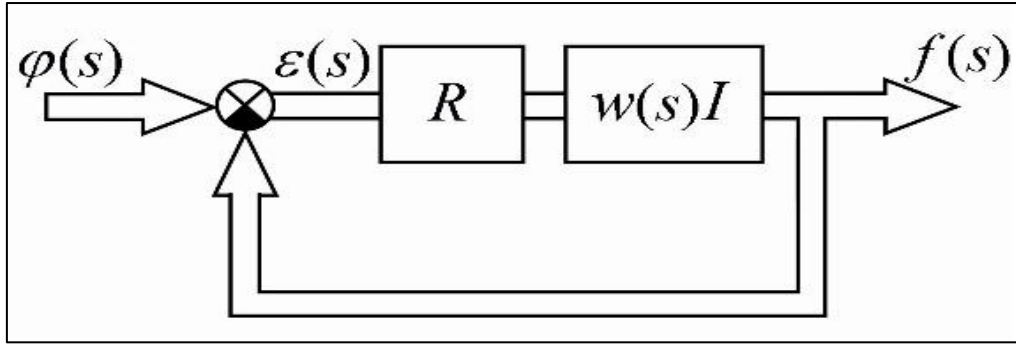


Fig 5 Matrix Block Diagram of a Uniform MIMO System

In Fig. 5, $\varphi(s)$, $f(s)$, $\varepsilon(s)$ represent, respectively, the input, output, and error vectors. The scalar channel transfer function $w(s)$ is a proper rational function of the complex variable s , whereas the numerical matrix R , of size $N \times N$, specifies the cross-connections.

For the open-loop uniform system in Fig. 5, the transfer matrix $W(s)$ is:

$$W(s) = w(s)R. \quad (11)$$

The output vector $f(s)$ and error vector $\varepsilon(s)$ are related to the input vector $\varphi(s)$ by:

$$f(s) = T(s)\varphi(s), \quad \varepsilon(s) = S(s)\varphi(s), \quad (12)$$

Where

$$T(s) = [I + w(s)R]^{-1} w(s)R, \quad (13)$$

$$S(s) = [I + w(s)R]^{-1} \quad (14)$$

Equations (13) and (14) define the closed-loop transfer matrices from the input to the output and error, respectively. The matrix $T(s)$ in (13) is the complementary sensitivity matrix, and $S(s)$ in (14) is the sensitivity matrix [4-8].

Using the characteristic transfer functions (CTFs) method, the open-loop transfer matrix $W(s)$ in (11) admits the following canonical representations [4]:

$$W(s) = \sum_{i=1}^N c_i > q_i(s) < c_i^+ = C \text{diag}\{q_i(s)\} C^{-1}, \quad (15)$$

Where the scalar functions:

$$q_i(s) = \gamma_i w(s) \quad (16)$$

$$i = 1, 2, \dots, N.$$

Are the open-loop CTFs. In these expressions, γ_i are the eigenvalues of R ; c_i are linearly independent eigenvectors of R and constitute the open-loop canonical basis; c_i^+ are the vectors dual to c_i ; and the columns c_i form the modal matrix C .

Substitution of the canonical representation $W(s)$ from (15) into the complementary sensitivity matrix $T(s)$ in (13) and the sensitivity matrix $S(s)$ in (14) gives [4]

$$T(s) = \sum_{i=1}^N c_i > \frac{\gamma_i w(s)}{1 + \gamma_i w(s)} < c_i^+ = C \text{diag} \left\{ \frac{\gamma_i w(s)}{1 + \gamma_i w(s)} \right\} C^{-1} \quad (17)$$

$$S(s) = \sum_{i=1}^N c_i > \frac{1}{1 + \gamma_i w(s)} < c_i^+ = C \text{diag} \left\{ \frac{1}{1 + \gamma_i w(s)} \right\} C^{-1} \quad (18)$$

Equations (15), (17), and (18) show that the closed-loop and open-loop uniform systems have the same canonical basis. Furthermore, the closed-loop CTFs are related to $q_i(s)$ by the same relations that connect the ordinary open-loop and closed-loop transfer functions of a SISO system. The roots of the following characteristic equation determine the stability of the uniform system in Fig. 5 [4-8]:

$$\det[I + w(s)R] = \prod_{i=1}^N [1 + \gamma_i w(s)] = 0.$$

IV. SENSITIVITY OF UNIFORM CONTROL SYSTEMS

Following [3], this section summarizes a general method for evaluating the sensitivity of CTFs to small perturbations in the parameters of a uniform system. The resulting formulas are applied in the next section to a quadcopter whose DC motors experience small efficiency reductions.

Suppose that the open-loop transfer matrix $W(s)$ depends continuously on m variable parameters α_r ($r = 1, 2, \dots, m$), collected in the vector α . To display this dependence explicitly, write the matrix as

$W(s, \alpha)$, with $W(s)$ depending on α . Let α_o denote the nominal value of the parameter vector α , and let $\Delta\alpha$ be the perturbation vector, so that $\alpha = \alpha_o + \Delta\alpha$. Assume that the CTFs and canonical basis are known at the nominal point α_o . After the parameters are perturbed, the transfer matrix $W(s, \alpha_o)$ can be written as:

$$W(s, \alpha) = W(s, \alpha_o) + \Delta W(s, \alpha), \quad (19)$$

Where $\Delta W(s, \alpha)$ denotes the change in $W(s, \alpha_o)$ produced by the parameter perturbations $\Delta\alpha$ [3]. Because $W(s, \alpha)$ depends continuously on α_r , its variation $\Delta W(s, \alpha)$ has the following Taylor expansion for sufficiently small $\Delta\alpha_r$:

$$\Delta W(s, \alpha) = \sum_{r=1}^m U_r^W(s) \Delta\alpha_r + \dots, \quad (20)$$

Where

$$U_r^W(s) = \left. \frac{\delta W(s, \alpha)}{\delta \alpha_r} \right|_{\alpha = \alpha_o} \quad (21)$$

$r = 1, 2, \dots, m$

Are the first-order sensitivity matrices of $W(s, \alpha)$ with respect to the parameter variations $\Delta\alpha_r$, evaluated at the nominal vector $\alpha = \alpha_o$. The dots in (20) represent terms of higher order than $\Delta\alpha_r$, which are neglected in the first-order approximation.

The assumed differentiability of $W(s, \alpha)$ with respect to α_r also permits the CTFs $q_i(s, \alpha)$ and canonical-basis axes $c_i(s, \alpha)$ to be expanded as follows:

$$q_i(s, \alpha) = q_i(s, \alpha_o) + \sum_{r=1}^m S_{ir}^q(s) \Delta\alpha_r + \dots \quad (22)$$

And

$$q_i(s, \alpha) = q_i(s, \alpha_o) + \sum_{r=1}^m S_{ir}^q(s) \Delta\alpha_r + \dots, i=1, 2, \dots, N, \quad (23)$$

Where

$$S_{ir}^q(s) = \left. \frac{\delta q_i(s, \alpha)}{\delta \alpha_r} \right|_{\alpha = \alpha_o}, \quad \Upsilon_{ir}^q(s) = \left. \frac{\delta c_i(s, \alpha)}{\delta \alpha_r} \right|_{\alpha = \alpha_o} \quad (24)$$

$r = 1, 2, \dots, m$

Are the unknown first-order sensitivity functions associated with $q_i(s, \alpha)$ and the sensitivity vectors associated with $c_i(s, \alpha)$.

Because feedback does not change the canonical basis, expansion (23) applies to the closed-loop system as well. The closed-loop CTFs sensitivity functions $S_{ir}^S(s)$ are related to the corresponding open-loop sensitivities $S_{ir}^q(s)$ by:

$$S_{ir}^S(s) = - \frac{1}{[1 + q_i(s, \alpha_o)]^2} S_{ir}^q(s) \quad (25)$$

$i = 1, 2, \dots, N; \quad r = 1, 2, \dots, m.$

As established in [3], evaluation of $S_{ir}^S(s)$ and $\Upsilon_{ir}^S(s)$ requires the matrices

$$M_r(s) = C^{-1}(s, \alpha_o) U_r^S(s) C(s, \alpha_o) \quad (26)$$

$r = 1, 2, \dots, m$

Where

$$U_r^S(s) = \left. \frac{\delta S(s, \alpha)}{\delta \alpha_r} \right|_{\alpha = \alpha_o} \quad (27)$$

$r = 1, 2, \dots, m$

Are the first-order sensitivity matrices of the transfer matrix $S(s, \alpha)$ in (14) with respect to variations of the r th parameter α_r . The diagonal entries $m_{ii}^r(s)$ of $M_r(s)$ in (26) equal the sensitivity functions $S_{ir}^S(s)$ in (25). For the off-diagonal entries $m_{ki}^r(s)$, division by the corresponding differences $[S_i(s, \alpha_o) - S_k(s, \alpha_o)]$ ($k = 1, 2, \dots, N, k \neq i$), Where

$$S_i(s, \alpha) = \frac{1}{1 + q_i(s, \alpha)}, \quad i = 1, 2, \dots, N, \quad (28)$$

Are the closed-loop CTFs, gives the coordinates of the sensitivity vector $\Upsilon_{ir}^S(s)$ for the i th closed-loop canonical-basis axis.

V. SENSITIVITY TO SMALL DEGRADATION OF MOTORS EFFICIENCY

We now examine the sensitivity of a quadcopter control system to small reductions in DC-motor efficiency. The perturbed quantities are the coefficients λ_i^M in (4), whose nominal values are unity ($\lambda_i^M = 1$). All these coefficients enter through the numerical cross-connection matrix R in (6), namely.

$$R = R(\Lambda_M). \quad (29)$$

This is a special case, since the transfer functions $w(s)$ of separate channels do not depend on λ_i^M ($i = 1, 2, 3, 4$). Consequently, the degradations of λ_i^M will result in changes of the canonical basis axes and “factors” γ_i (eigenvalues of $R(\Lambda_M)$). This means that the problem is reduced to the sensitivity analysis of eigenvalues and eigenvectors of the cross-connections matrix R .

Let us introduce the following notations for sensitivities of eigenvalues γ_i and eigenvectors c_i of the perturbed matrix $R(\Lambda_M)$ (29):

$$\beta_{ir} = \frac{\delta \gamma_i(\bar{\lambda}^M)}{\delta \lambda_r^M}, \quad \Upsilon_{ir} = \frac{\delta c_i(\bar{\lambda}^M)}{\delta \lambda_r^M}, \quad r = 1, 2, 3, 4, \quad (30)$$

Where $\bar{\lambda}^M$ is a vector with components λ_i^M .

Following the derivation given in [3], it can be shown that for calculation of the sensitivity functions β_{ir} and Υ_{ir} (30), it is sufficient to determine the representation.

$$N_r = C^{-1}(\bar{\lambda}^M) U_r^R C(\bar{\lambda}^M) \quad (31)$$

$$r = 1, 2, 3, 4$$

Of the sensitivity matrices U_r^R :

$$U_r^R = \frac{\delta R(\bar{\lambda}^M)}{\delta \lambda_r^M} \quad (32)$$

In the canonical basis of the unperturbed control system (control system with ideal DC motors). The diagonal elements n_{ii}^r of the matrix N_r (31) coincide with the sensitivity functions β_{ir} in (30), whereas the off-diagonal elements n_{ik}^r , after division by the corresponding eigenvalues differences $[\lambda_i^M - \lambda_k^M]$, give the coordinates of the sensitivity vectors Υ_{ir} in (30) in the same basis [3].

VI. NUMERICAL EXAMPLE

Consider the control system of a quadcopter with the so-called *I4* scheme of the motors' allocation and the following parameters: $m = 2.5 \text{ kg}$, $I_x = I_y = 0.5 \text{ kg} \cdot \text{m}^2$, $I_z = 1.5 \text{ kg} \cdot \text{m}^2$. Matrices D_M and M_Σ in this case are equal to:

$$D_M = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 0.1 & 0 & -0.1 \\ -0.1 & 0 & 0.1 & 0 \\ -0.3 & 0.3 & -0.3 & 0.3 \end{bmatrix}, \quad M_\Sigma = \begin{bmatrix} 2.5 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 1.5 \end{bmatrix} \quad (33)$$

And the matrix K_R (10) is

$$K_R = D_M^{-1} M_\Sigma = \begin{bmatrix} 0.625 & 0 & -2.5 & -1.25 \\ 0.625 & 2.5 & 0 & 1.25 \\ 0.625 & 0 & 2.5 & -1.25 \\ 0.625 & -2.5 & 0 & 1.25 \end{bmatrix}. \quad (34)$$

The identical proportional-derivative (PD) regulators [9] with the first-order filter $w^R(s)$ in separate channels are taken in the form.

$$w^R(s) = 0.00559 + \frac{0.639s}{0.00875s + 1}. \quad (35)$$

The Nyquist plots of the CTFs and step responses of the separate channels in case of ideal motors (when $R = I$) are shown in Fig. 6 and Fig. 7. The black line in Fig. 6 is the graph of the plant, the blue line represents the PD regulator (35), and the transfer function of the resulting open-loop channel is shown by the brown line.

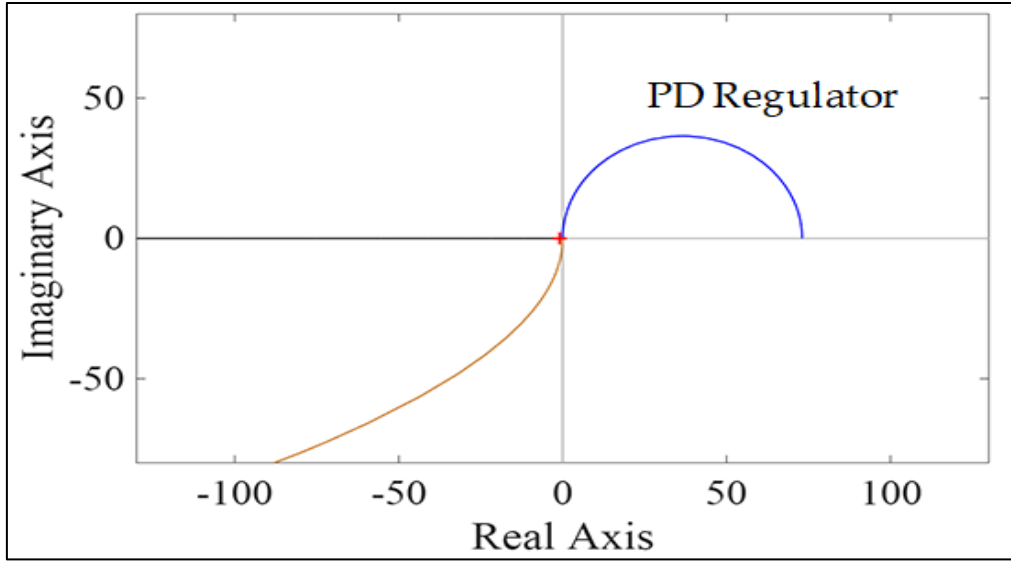


Fig 6 Nyquist Plots of the Isolated Channels ($\Lambda_M = I$)

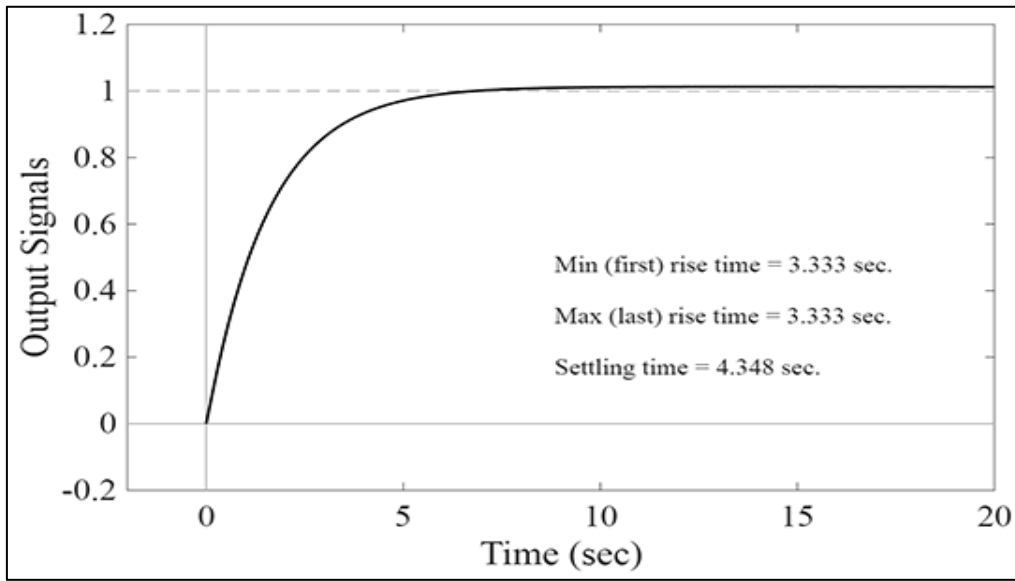


Fig 7 Step Response of the Isolated Channels in Case $\Lambda_M = I$

Suppose now that the matrix Λ_M in (7) has the following form:

$$\Lambda_M = \begin{bmatrix} 0.85 & 0 & 0 & 0 \\ 0 & 0.9 & 0 & 0 \\ 0 & 0 & 0.75 & 0 \\ 0 & 0 & 0 & 0.8 \end{bmatrix}. \quad (36)$$

Suppose also that the matrix K_R in $K_{\text{Reg}}(s)$ (5) is the identity matrix I . Practically, this means that the cross-connections between separate channels are not compensated and are described by the matrix.

$$R_0 = M_{\Sigma}^{-1} D_M = \begin{bmatrix} 0.4 & 0.4 & 0.4 & 0.4 \\ 0 & 0.2 & 0 & -0.2 \\ -0.2 & 0 & 0.2 & 0 \\ -0.2 & 0.2 & -0.2 & 0.2 \end{bmatrix} \quad (37)$$

The eigenvalues of this matrix are complex-conjugated and equal to:

$$\lambda_{1,2} = 0.1798 \pm j0.4150, \quad (38)$$

$$\lambda_{3,4} = 0.3202 \pm j0.1504.$$

The Nyquist plots of the CTFs and step responses of the quadcopter control system with the cross-connections matrix R_0 (37) are shown in Fig. 8 and Fig. 9.

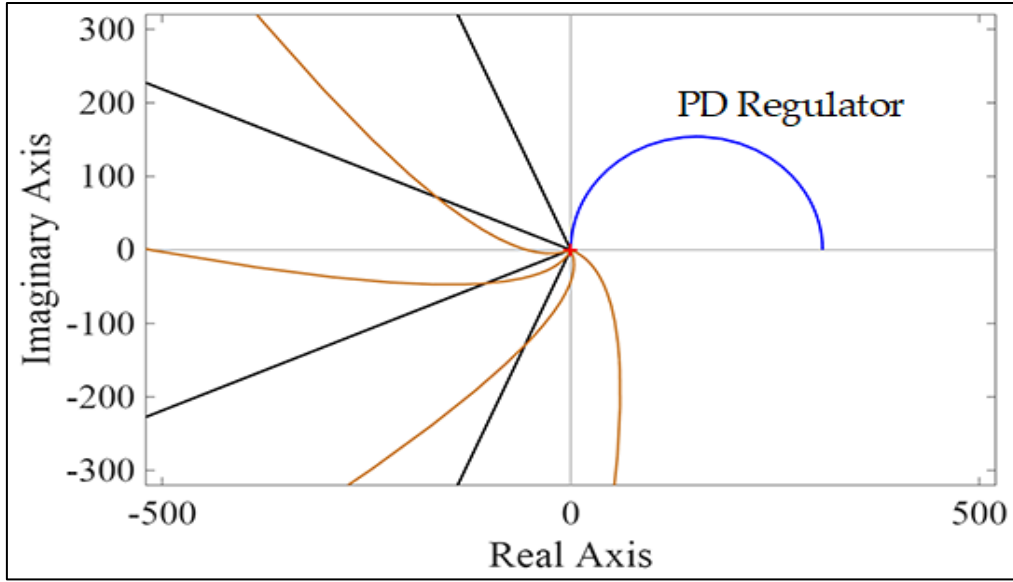


Fig 8 Nyquist Plots of the CTF

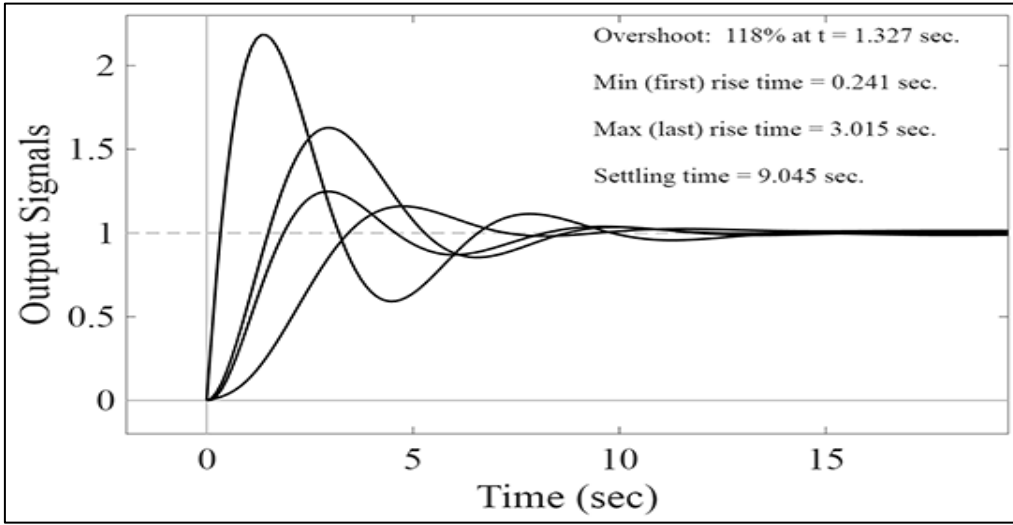


Fig 9 Step Responses of the Control System ($\Lambda_M \neq I_{6 \times 6}$)

In case $\Lambda_M = I$ and $K_R = I$

In Fig. 8, the four black lines are the graphs of the plant's CTFs, the blue line represents the identical PD regulators (35) in separate channels, and the gain loci of the corrected system are shown by brown lines.

Let us now analyze the sensitivity of the closed-loop control system with the cross-connection matrix R_0 (37) to small degradations of the motors' parameters λ_i^M . For brevity, below we present the results only for the sensitivities β_{i1} and Υ_{i1} of the eigenvalues λ_i and eigenvectors c_i of the matrix R_0 (37) with respect to small efficiency degradations of the first motor (i.e., with respect to small negative perturbations of λ_1^M).

The calculations yield the following results:

$$\beta_{11} = 0.3238 - j0.2012 = 0.3812 \exp(-j31.86^\circ),$$

$$\beta_{21} = 0.3238 - j0.2012 = 0.3812 \exp(j31.86^\circ),$$

$$\beta_{31} = 0.1762 - j0.2012 = 0.1767 \exp(-j3.98^\circ),$$

$$\beta_{41} = 0.1762 - j0.2012 = 0.1767 \exp(j3.98^\circ)$$

$$\Upsilon_{11} = \begin{bmatrix} 0 \\ -0.07 - j0.37 \\ 0.02 + j0.18 \\ -0.14 + j0.11 \end{bmatrix}, \quad \Upsilon_{21} = \begin{bmatrix} -0.07 + j0.37 \\ 0 \\ -0.14 - j0.11 \\ 0.02 - j0.18 \end{bmatrix},$$

$$\Upsilon_{31} = \begin{bmatrix} -0.18 - j0.33 \\ -0.37 + j0.06 \\ 0 \\ 0.098 + j0.15 \end{bmatrix}, \quad \Upsilon_{41} = \begin{bmatrix} -0.37 - j0.06 \\ -0.18 + j0.33 \\ 0.098 - j0.15 \\ 0 \end{bmatrix}.$$

The sensitivity functions with respect to loss of efficiency of the other motors are determined analogously.

VII. CONCLUSIONS

The study establishes a framework for evaluating the performance and stability robustness of quadcopter control systems under partial actuator faults. By representing the linearized quadcopter dynamics as a uniform MIMO system, the analysis confirms that motor efficiency degradations alter only the numerical cross-connection matrix, leaving the single-channel transfer dynamics unchanged. Consequently, the sensitivity of the closed-loop CTFs and canonical basis axes is analytically determined through first-order perturbations of the cross-connection matrix's eigenvalues and eigenvectors. The numerical example validates that this approach provides an efficient computational tool for assessing fault tolerance and designing robust compensators against non-redundant motor degradation in multirotor UAVs.

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