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Model Predictive Control implementation for MIMO system in Presence of Soft Constraints and Non-linear Disturbance

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*Abstract***— Model Predictive Control (MPC) uses optimization to compute the control signal in presence of system constraints. Therefore, it has gained enormous popularity in various industrial applications because of its constraints management capability. Although, MPC takes large computational time to optimize the control vector and thus it suits for regulating slow-dynamic SISO plants. Here MPC is implemented to regulate fast-dynamic MIMO plant i-e rotors of a quadcopter to exhibit the rotational three degrees of freedom. The performance is evaluated in presence of soft constraints along with linear non-linear sinusoidal external disturbance in terms of percentage overshoot and steady-state error. The simulations are presented by driving the mathematical model of DC motor and after that it is simulated in MATLAB as a MIMO system for four quad rotors. The results are presented in three modes i-e roll, pitch and yaw with four cases each i-e without constraints, with constraints, with constraints and linear disturbance and with constraints and non-linear disturbance. The simulation results have proved that MPC controls the MIMO system comprehensively without breaching the soft constraints.**

Keywords— DC motor, MPC, MIMO, Non-Linear Disturbance, Quadcopter, Simulink, Soft Constraints

I. INTRODUCTION

Control system has a wide spectrum of applications in all fields of commercial ventures i-e industrial control, Aerospace, robotics, power system and transportation systems etc. Proportional Integral Derivative (PID) controller is the most famous and classical control technique in literature and used in more than 90% of the plants to regulate their outputs. However, with continuous advancements in technology the performance requirements of the controlled processes have also been increased and they require more sophisticated control algorithms to meet the desired outputs [1]. One of the challenging requirements is that most of the systems operate at operational constraints and PID does not consider the constraints in calculating the control signal [2] Moreover, PID gains have to be tuned frequently to get the desired output under dynamic environment [3]. The best solution to these limitations of PID is MPC control technique, as it handles both input and output constraints effectively. In control theory these two constraints are named as hard and soft constraints respectively [3]. MPC is an optimal control technique that uses the plant model to optimize the control vector by minimizing the cost function at every sampling instant in presence of operational constraints [4]. Its performance depends on the selection of two key parameters i-e prediction horizon N_P and control horizon N_C and the accuracy with which the dynamics of a system have been captured in mathematical form [5]. The common approaches available in the literature to perform mathematical modeling of the physical systems i-e differential equation, transfer function and state space modeling etc [6]. Differential equation modeling is the most basic way to model a physical system and it is famously known as the language of nature but for high order systems it becomes complex and cumbersome to segregate the input, output and the system. Similarly, the transfer function can model only linear time invariant (LTI) and single input single output (SISO) systems. State-Space modeling (SSM) has numerous advantages over the other two techniques. it has the ability to model both linear and non-linear time variant (LTV)

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systems and multiple input multiple output (MIMO) systems as well [6]. In this research work, SSM has been used to model the DC motor used as a rotor of quadcopter. However, the only limitation associated with the MPC is the high computational time required to optimize the control vector as it uses the system matrices in the cost function and sizes of these matrices have direct relation with the selection of N_C and N_P parameters of MPC. The situation becomes worst for systems with low sampling time [7]. Therefore, MPC is famous to control the slow-dynamic systems with large bandwidths i-e petrochemical, temperature control, fluid catalic cracking, , paper industries, pulp industries and crude atmospheric distillation etc [8,9]. In the last decade a lot of research has been done to investigate the MPC performance for SISO systems [5], [8] and [10]. Though, from few years back scientists and researchers have been evaluating MPC for MIMO systems as well [11,12]. In [11], authors have presented a multiple input single output (MISO) slow-dynamic plant of Newell and Lee forced circulation evaporation model. Similarly, MPC is implemented for quadcopter in [12], but it does not discuss any performance evaluation in terms of constraints handling. [13] has presented the performance evaluation of MPC for MIMO system i-e quadcopter rotors in presence of input constraints. However, soft constraints have not been considered in simulations and moreover, no disturbance profile is taken in to account for evaluation purpose.

This paper presents implementation of MPC for fast-dynamic MIMO system of quadcopter rotors and evaluates the controlled performance in presence of soft constraints, linear and non-linear disturbances. The MIMO system outputs roll, pith and yaw are controlled by regulating the speeds of DC motors at different set-points. The results are presented both in the absence & presence of output constraints and with linear, non-linear disturbances as well. MPC performs effectively well under all these scenarios.

The whole research work is distributed in four sections. In section 2 the mathematical modeling and implementation of MPC is presented. Section 3 shows the simulation results. Finally conclusion and recommendations have been summarized in section 4.

II. Implementation of MPC

The performance of MPC heavily depends on the system dynamics captured through mathematical modeling, as it uses the model equations to predict the output after every instant. The block diagram of MPC is shown in Fig. 1

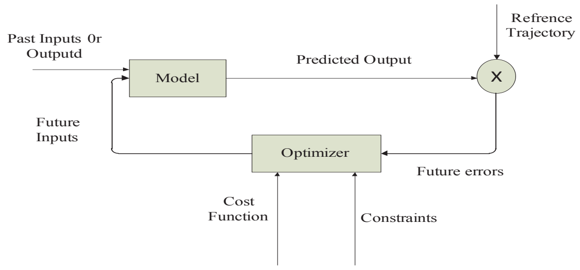


Fig. 1Block Diagram of MPC

The working of MPC mainly depends on optimizer and the model block. The optimizer performs mathematical operation of minimizing the cost function of MPC in presence of applied system constraints and the errors to get optimized control signal. The control signal is applied to the mathematical model of the plant along with any initial values to get the predicted output and which is compared with the desired set-point. The difference between the two quantities in the form of error is given back as feedback to the optimizer and this procedure remains continuing [14]. The mathematical modeling and implementation of MPC according to above figure is presented in following sections:

A. System Modeling

The schematic of Permanent Magnet DC motor (PMDC) is shown in Fig. 2

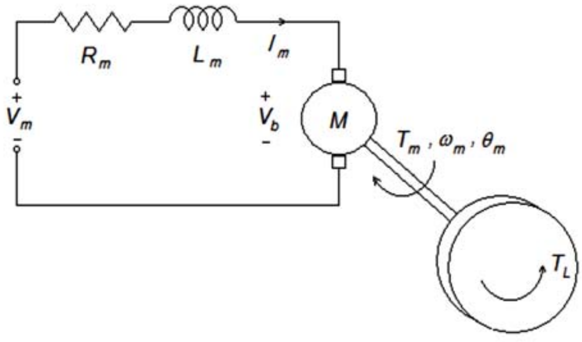


Fig. 2 Schematic Representation

Where, V_m is the applied armature voltage, R_m, L_m and I_m are the resistance, inductance and current respectively. V_b is the back emf voltage generated by the motor. As DC motor is electromechanical device its mechanical terms and components are moment of inertia, damper, motor torque, load torque and angular velocity which are represented as J_m, B_m T_m, T_L, and ω_m respectively. The mathematical modeling of DC motor is done by applying both electrical and mechanical laws as shown below:

Perform kirchoff's voltage law on the above figure to find electrical equation given below:

$$V_m = R_m i_m(t) + \frac{L_m di(t)}{dt} + k_m \omega_m(t) \quad (1)$$

Where $V_b = k_m\omega_m$ and k_m is the torque constant.

The newton's law of motion is applied on DC motor to find the following equation of motion

$$\frac{Jd\omega_m(t)}{dt} = T_m - T_L - B_m\omega_m \quad (2)$$

Here $T_L = 0$ is assumed and $T_m = k_m I_m$.

Apply Laplace transform to above equations and solve them to obtain the transfer function as shown in Eq. (3)

$$\frac{\omega_m(s)}{V_m(s)} = \frac{k_m}{[(L_m J_m)S^2 + (R_m J_m + B_m L_m)S + (k_m^2 + R_m B_m)]} \quad (3)$$

Substitute the physical parameters of DC motor shown in Table 1 in above equation to get the finalized transfer function as shown in Eq. (4)

$$\frac{\omega_m(s)}{V_m(s)} = \frac{18.0766}{[(108.459)S^2 + (72.270)S + 1]} \quad (4)$$

Table 1. Parameters of DC motor[13]

Parameter	Value
Inertia	J_m = 0.15 Nm/rad/s2
Damper	B_m = 0.0002 Nm/rad/s
Resistance	R_m = 1.33 Ω
Inductance	L_m = 2mH
Torqueconstant	k_m = 0.05 Nm/A
RatedVoltage	V_m= 12 V
RatedSpeed	r/min = 2000 RPM

The obtained transfer function is converted to discrete state-space model using sampling interval of 3 ms directly through MATLAB and this time of 3 ms is chosen because of the electrical time constant $\tau_e = 1.5$ ms of the DC motor and sampling time must be double of τ_e [15]. The obtained state space model of DC motor is shown in Eq. (5)

$$x_m(k+1) = \begin{bmatrix} 1.0000 & 0.0030 & 0 \\ -2.757\,10^{-05} & 0.9980 & 0 \\ 1.0000 & 0.0030 & 0 \end{bmatrix} x_m(k) + \begin{bmatrix} 7.4920\,10^{-07} \\ 4.9930\,10^{-04} \\ 7.4920\,10^{-07} \end{bmatrix} u(k) \quad (5a)$$

$$y(k) = [0 \quad 0 \quad 1]x_m(k) \quad (5b)$$

In the above equations 5a represents the system state equations in the form of matrices and 5b represents the output equation. This obtained state-space model is used in Fig. 1 for MPC implementation

B. Optimizer

The cost function used in optimizer block of MPC is shown in Eq. (6) [1].

$$J = (R_s - Y)^T (R_s - Y) + \Delta U^T \bar{R} \Delta U \quad (6)$$

The cost function consists of two terms. The first term minimizes the difference between set-point (R_s) and actual output (Y) while, other term put some check on the change in magnitude of the control signal ΔU through the variable $\bar{R}$. $\bar{R}$ is a diagonal matrix and $\bar{R} = r_w I_{N_c \times N_c}$. $r_w \geq 0$ is a user defined tuning parameter for desired closed loop performance and $I_{N_c \times N_c}$ is a identity matrix of order N_C If r_w=0, no attention is given to the variation of control signal. However, if r_w is large a serious check is present on the change in the magnitude. The control vector after optimization is given in Eq. (7) [5].

$$\Delta U = (\phi^T \phi + \bar{R})^{-1} \phi^T \left(R_s F x(k_i)\right) \quad (7)$$

Where F and ϕ are the vectors shown below

$$F = \begin{bmatrix} CA \\ CA^2 \\ \cdot \\ \cdot \\ CA^{N_p} \end{bmatrix} \text{and } \phi = \begin{bmatrix} CB & 0 & 0 & 0 & \ldots & 0 \\ CAB & CB & 0 & 0 & \ldots & 0 \\ \vdots & CAB & CB & 0 & \ldots & 0 \\ CA^{N_p-1}B & CA^{N_p-2}B & CA^{N_p-3}B & \ldots & \ldots & CA^{N_p-N_c}B \end{bmatrix}$$

There are two types of constraints one of them is applied on the magnitude of manipulated variable or rate of change of manipulated variable and the second type is applied on the output. These two constraints are known as hard and soft constraints and they are presented in Eq. (8) [1]

$$\Delta U^{min} \leq \Delta U(k) \leq \Delta U^{max} \quad (8a)$$

$$u^{min} \leq u(k) \leq u^{max} \quad (8b)$$

$$y^{min} \leq y(k) \leq y^{max} \quad (8c)$$

The constraints can be shown in the form of vector ΔU as shown in Eq. (9)

$$\begin{bmatrix} u(k_i) \\ u(k_i+1) \\ u(k_i+2) \\ \vdots \\ u(k_i+N_c-1) \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} u(k_i-1) + \begin{bmatrix} 1 & 0 & 0 & \ldots & 0 \\ 1 & 1 & 0 & \ldots & 0 \\ 1 & 1 & 1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \ldots & 0 \\ 1 & 1 & \ldots & 1 & 1 \end{bmatrix} \begin{bmatrix} \Delta u(k_i) \\ \Delta u(k_i)+1 \\ \Delta u(k_i)+2 \\ \vdots \\ \Delta u(k_i)+N_c-1 \end{bmatrix} \quad (9)$$

The above equations are summarized in a compact matrix form by linking C1 and C2 to appropriate matrices then imposed constraints can be shown as Eq. (10)

$$-\left(C_1 u(k_i-1) + C_2 \Delta U\right) \leq -U^{min} \quad (10a)$$

$$\left(C_1 u(k_i-1) + C_2 \Delta U\right) \leq U^{max} \quad (10b)$$

Where U^{min} and U^{max} are column vectors with Nc number of elements of u_{min} and u_{max}. Similarly, for the constraints imposed on the rate of change of control signal are shown in Eq. (11)

$$-\Delta U \leq -\Delta U^{min} \quad (11a)$$

$$\Delta U \leq \Delta U^{max} \quad (11b)$$

Again ΔU^{min} and ΔU^{max} are column vectors with Nc number of elements. Similarly, output constraints can be written in the form of ΔU as shown in Eq. (12)

$$Y^{min} \leq Fx(k_i) + \phi \Delta U \leq Y^{max} \quad (12)$$

The optimized control vector ΔU is subjected to the inequality constraints by Eq. (13)

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \Delta U \leq \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} \quad (13)$$

$Where, M_1 = \begin{bmatrix} -C_2 \\ C_2 \end{bmatrix}$; $N_1 = \begin{bmatrix} -U^{min} + C_1 u(k_i-1) \\ U^{max} - C_1 u(k_i-1) \end{bmatrix}$; $M_2 = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$; $N_2 = \begin{bmatrix} -\Delta U^{min} \\ \Delta U^{max} \end{bmatrix}$;

$$M_3 = \begin{bmatrix} \phi \\ \phi \end{bmatrix};\ N_3 = \begin{bmatrix} -Y^{min} + Fx(k_i) \\ Y^{max} - Fx(k_i) \end{bmatrix}$$

Transform the above equation in more compact form as shown in Eq. (14) below and use it to find an optimized control vector without violating the constraints [1].

$$\mathrm{M}\Delta U \leq \gamma \tag{14}$$

Where, M is a vector of constraints with its rows equal to nu mber of constraints and columns equal to dimension of ΔU.

III. Simulation Results

The MPC is rgulating MIMO system of quad rotors and they are controlled at specific angular velocities according to the roll, pitch and yaw motions. The performance of MPC is evaluated in presence of soft constraints. Moreover, its robustness is tested by adding predefined linear and non-linear disturbances at the control signal. The working principle of a quadcopter is presented in the following section.

A. Quadcopter Dynamics

A quadcopter is an under actuated system, as it has four input forces generated through four rotors to regulate total six degrees of freedom. These dofs are controlled through vertical, horizontal and rotational forces by changing the angular velocities of four motors as shown in Fig. 3

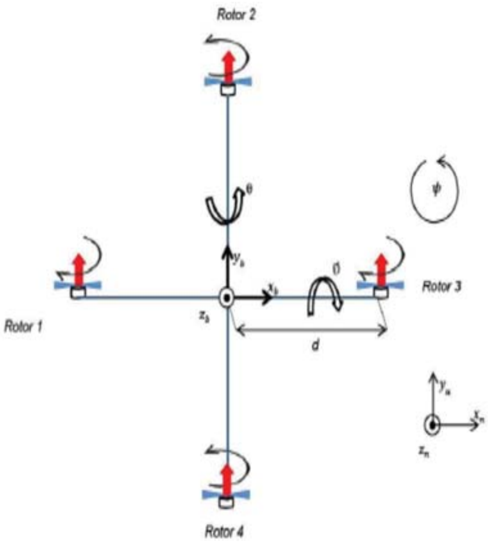


Fig. 3Quadcopter Dynamics

The roll, pitch and yaw movements are about OX, OY and OZ axis. The roll motion is obtained by decreasing the velocity of rotor 4 and increasing velocity of rotor 2. Similarly, pitch movement is achieved by decreasing velocity of rotor 1 and increasing velocity 3. To obtain yaw movement imbalance between the rotating propellers is achieved [16].

B. Simulations Based Analysis

The simulation results are presented in three modes. In mode 1angular velocities of motors are controlled according to roll movement. Similarly, mode 2 and 3 shows the regulation of DC motors according to pitch and yaw movements. The performance analysis is done by testing each mode in four cases i-e without constraints, with soft constraints, with linear disturbance in presence of constraints and with non-linear sinusoidal disturbance in presence of constraints. The simulation parameters along with the desired set-points of four DC motors in three modes are shown in Table 2.

Table 2. Simulation Parameters

Mode	N_P	N_C	r_w	Velocity (rad/sec)	Linear Disturbance	Non-Linear Disturbance
1	10	2	0.1	Rotor 1 100 rad/sec	0.001*u(t)	0.001*sin(t)
				Rotor 2 200 rad/sec		
				Rotor 3 100 rad/sec		
				Rotor 4 50rad/sec		
2				Rotor 1 50 rad/sec		
				Rotor 2 100 rad/sec		
				Rotor 3 200 rad/sec		
				Rotor 4 100 rad/sec		
3				Rotor 1 200 rad/sec		
				Rotor 2 100 rad/sec		
				Rotor 3 200 rad/sec		
				Rotor 4 100rad/sec		

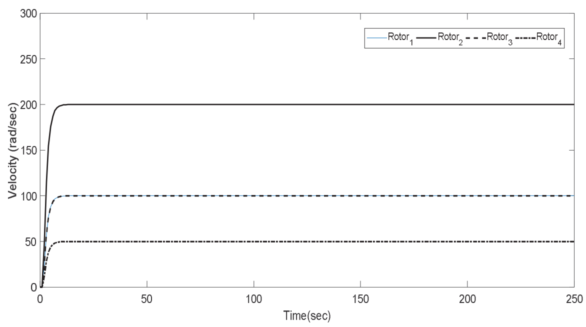
The output constraints imposed in all three modes are also summarized in Table 3

Table 3. Constraints imposed in different modes

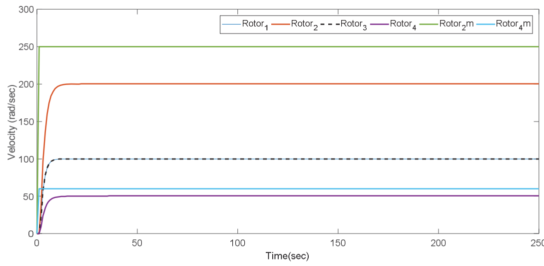
Mode	Output Constraints	Mistaken Set-Points
1	$R2_{max}$=200 rad/sec $R4_{max}$=50 rad/sec	$R2_m$= 250 rad/sec $R4_m$= 65 rad/sec
2	$R1_{max}$=50 rad/sec $R3_{max}$=200 rad/sec	$R1_m$ = 65 rad/sec $R3_m$= 250 rad/sec
3	$R1_{max}$=200 rad/sec $R3_{max}$=200 rad/sec	$R2_m$= 250 rad/sec $R3_m$= 250 rad/sec

Mode 1: Roll Movement

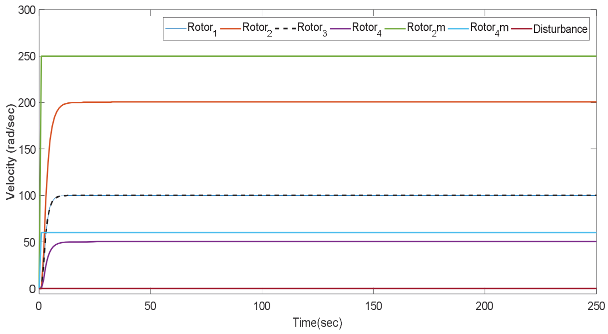
The results of mode 1 in all four cases are shown in Fig. 4



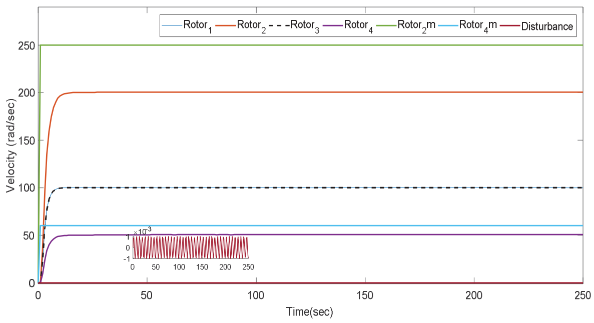
(a) Outputs of four rotors without constraints



(b) Outputs of four rotors with output constraints



(c) Outputs of four rotors with output constraints and linear disturbance



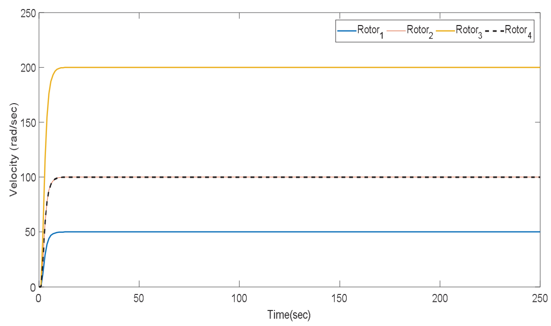
(d) Outputs of four rotors with output constraints and non-linear disturbance

Fig. 4 Velocities controlled at given set-points for roll motion in presence of output constraints and disturbance

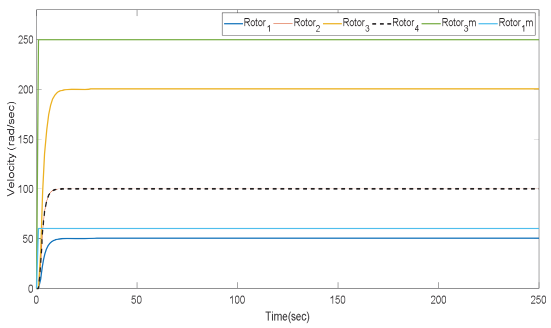
In the above figure it is clear that MPC effectively regulates the velocities of DC motor in all the cases and requirement to achieve roll movement has been achieve efficiently and none of the constraints are violated and thus rotor 2 and rotor 4 does not exceed the constraint limits of angular velocities.

Mode 2: Pitch Movement

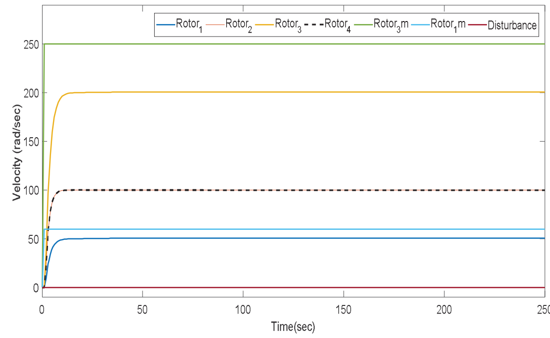
The results of mode 2 in all four cases are shown in Fig. 5



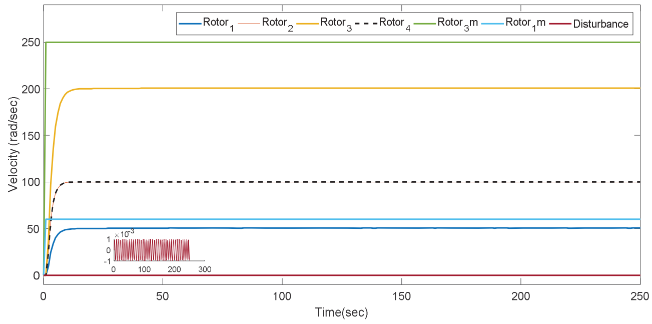
(a) Outputs of four rotors without constraints



(b) Outputs of four rotors with constraints



(c) Outputs of four rotors with output constraints and linear disturbance



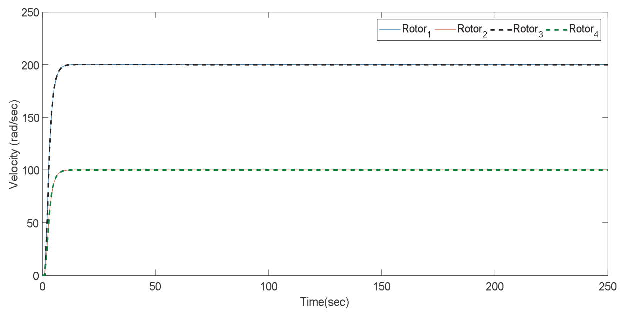
(d) Outputs of four rotors with output constraints and non-linear disturbance

Fig. 5 Velocities controlled at given set-points for pitch motion in presence of output constraints and disturbance

Similarly, in mode 2 MPC performs efficiently and regulated the velocities without violating the constraints.

Mode 3: Yaw Movement

The results of mode 3 in all four cases are shown in Fig. 6



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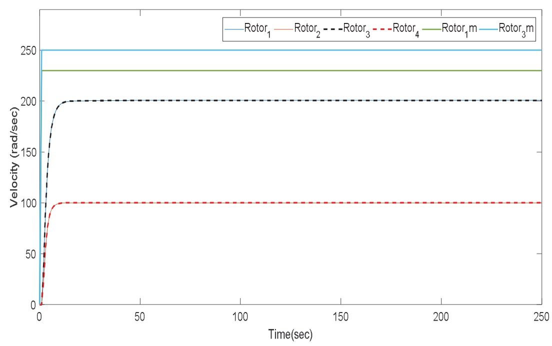
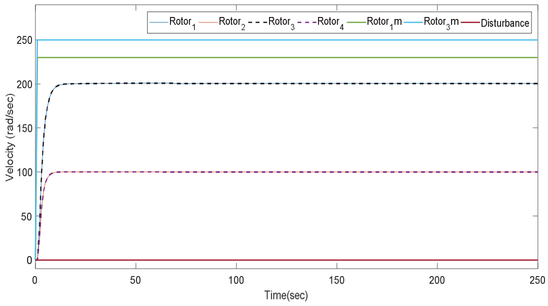
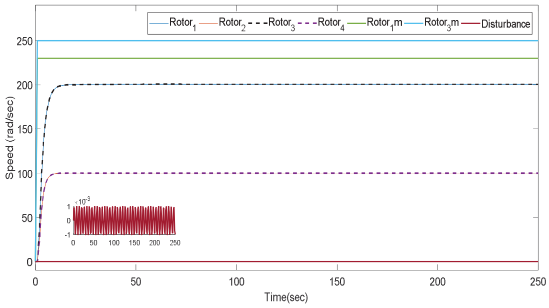
(a) Outputs of four rotors without constraints



(b) Outputs of four rotors with constraints



(c) Outputs of four rotors with output constraints and linear disturbance



(d) Outputs of four rotors with output constraints and non-linear disturbance

Fig. 6 Velocities controlled at given set-points for yaw motion in presence of output constraints and disturbance

MPC again efficiently controlled the velocities of DC motors without violating the constraints. The performance results in terms of %OS and steady-state error are summarized in Table 4

Table 4. Performance Analysis

Mode	Percentage Overshoot %(OS)				Steady-State Error			
	Case1	Case2	Case3	Case4	Case1	Case2	Case3	Case 4
1	R1=0 R2=0 R3=0 R4=0	R1=0 R2=0.3 R3=0 R4=1.2	R1=0 R2=0.3 R3=0 R4=1.2	R1=0 R2=0.3 R3=0 R4=1.2	R1=0 R2=0 R3=0 R4=0	R1=0 R2=0.6 R3=0 R4=0.6	R1=0 R2=0.6 R3=0 R4=0.6	$R1=10^{-3}$ R2=0.6 $R3=10^{-3}$ R4=0.6
2	R1=0 R2=0 R3=0 R4=0	R1=1.2 R2=0 R3=0.3 R4=0	R1=1.2 R2=0 R3=0.3 R4=0	R1=1.2 R2=0 R3=0.3 R4=0	R1=0 R2=0 R3=0 R4=0	R1=0.6 R2=0 R3=0.6 R4=0	R1=0.6 R2=0 R3=0.6 R4=0	R1=0.6 $R2=10^{-3}$ R3=0.6 $R4=10^{-3}$
3	R1=0 R2=0 R3=0 R4=0	R1=0.3 R2=0 R3=0.3 R4=0	R1=0.3 R2=0 R3=0.3 R4=0	R1=0.3 R2=0 R3=0.3 R4=0	R1=0 R2=0 R3=0 R4=0	R1=0.6 R2=0 R3=0.6 R4=0	R1=0.6 R2=0 R3=0.6 R4=0	R1=0.6 $R2=10^{-3}$ R3=0.6 $R4=10^{-3}$

In the above table it is evident that there exists symmetry in performance in all modes. A little %OS of 0.3 and 1.2 occurs in the constrained outputs of rotors and steady-state error of 0.6 occurs. However, disturbance effect is rejected in the outputs of rotors on which constraints are applied. Though, the rotors on which constraints are not imposed the disturbance causes steady-state error of magnitude only 10^{-3}.

IV. Conclusion and Recommendation

In this research work, MPC is implemented for MIMO system i-e simultaneously regulating velocities of quad rotors in presence of soft constraints along with both linear and non-linear disturbances. The simulations are performed in MATLAB/SIMULINK by first doing the state-space modeling of DC motor. The results are presented in three modes to demonstrate roll, pitch and yaw scenarios and every mode is analyzed in four cases i-e without constraints, with constraints, with constraints and linear disturbance, with constraints and non-linear disturbance. In all cases of each mode it is clear that MPC regulate the velocities of DC motor effectively with good performance metrics.

For future work, MPC performance can be analyzed by using four motors with different internal mechanical parameters.

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