AN IMPROVED APPROACH FOR MODEL PREDICTIVE CONTROL IN 3-D OVERHEAD CRANE SYSTEMS

MỘT CÁCH TIẾP CẬN CẢI TIẾN CHO MÔ HÌNH ĐIỀU KHIỂN DỰ BÁO TRONG HỆ THỐNG CẦU TRỤC 3 CHIỀU

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ABSTRACT

The Model Predictive Control (MPC) for the 3-D overhead crane (3DOC) system is the main subject of this paper. The crane's underactuated system necessitates a complex controller design. In this paper, the MPC was used to handle the problem of automatic load transportation. With this method, the system can meet many complicated requirements due to the high nonlinear dynamics of overhead cranes, such as anti-vibration, accurate position, and satisfy dynamics constraints in real life. According to the results of our tests, MPC is successfully applied to cranes and many transportation systems similarly.

Keywords: *Model predictive control, Trajectory tracking, 3-D overhead crane, Anti-vibration, Crane control.*

TÓM TẮT

Mô hình điều khiển dự báo (MPC) cho hệ thống cầu trục 3-D (3DOC) là chủ đề chính của bài báo này. Hệ thống cầu trục thiếu tác động đầu vào đòi hỏi thiết kế một bộ điều khiển phức tạp. Trong bài báo này, chúng tôi sử dụng MPC để xử lý vấn đề vận chuyển tải tự động. Với phương pháp này, chúng tôi có thể đáp ứng nhiều yêu cầu phức tạp gây bởi tính phi tuyến cao của hệ cầu trục, chẳng hạn như chống rung, chính xác hoá vị trí, sử dụng nguồn năng lượng thấp và thỏa mãn các ràng buộc trong thực tế. Theo kết quả thử nghiệm của chúng tôi, MPC được áp dụng thành công cho các hệ cầu trục và nhiều hệ thống vận chuyển tương tự.

Từ khoá: *Mô hình điều khiển dự báo, bám quỹ đạo, hệ thống cầu trục 3-D, chống rung, điều khiển hệ thống cầu trục.*

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1. INTRODUCTION

As effective means of transportation, overhead cranes have been used widely in many fields, such as harbour bridge cranes, explosion-proof cranes, and hydropower cranes. The exact delivery of the payload to the intended location and the quick suppression and elimination of the payload swing are two problems with overhead cranes. Due to this, scholars worldwide have conducted much research on crane systems and numerous excellent reports on the topic [1-6].

Over the last forty years, many methods have been used for controlling overhead cranes. In the first years, researchers used approximate linearized models [7] to control the nonlinear dynamics easily. However, the impacts of crane nonlinearities become apparent when the crane operates in rapid motion. As a result, more advanced control strategies have been proposed, primarily based on nonlinear dynamic models created for overhead cranes, including the application of adaptive control [8] and model-free control techniques based on fuzzy logic [9-11]. Other methods, including the neural network predictive control method [12] and time-optimal control [13], have been used successfully to create anti-sway trolley paths based on studying the crane system's natural frequency.

However, it is essential to consider the applicability of control system designs for crane systems in real life. Therefore, this paper introduces a new control approach for 3DOC, based on model predictive control (MPC). MPC technique offers a robust control framework for handling control issues with numerous constraints, many variables, and uncertainty. It works well in dealing with these types of control problems. In most control strategies, the weight was not hoisted up and down (rope length is supposed to be constant), which is often not the case in actual operations.

The main contributions of this paper can be summarized as follows: (1) the crane follows the desired path and reach the goal with minimal load swing (the rope length can be changed); (2) solve the problem of anti-vibration for the crane where the swing angles are limited, besides ensuring tracking problem for the 3DOC under tight ties that hardly mentioned in previous studies; (3) solve the control problem of the underactuated system which is mostly solved by sliding mode control (SMC) (the system has only three control inputs while five state variables need to be controlled).

The rest of this paper is organized as follows: Section 2 introduces a dynamic model of 3DOC together with the MPC formulation. Simulations and results are shown in Section 3. Finally, Section 4 concludes the paper.

2. MODELING AND CONTROLLER DESIGN

2.1. Model of 3-D Overhead Crane

Fig. 1 shows the coordinate systems of a 3DOC, in which m_c, m_t, m_b and m_l are the equivalent masses of cargo, trolley, bridge, and hoist, respectively; x and y are the positions of the trolley; l presents the cable length; Φ and θ denote the swing angles projected onto the Z-X plane and Z-Y plane, respectively. To describe the motion of the system, $q = [x \ \ y \ \ l \ \ \Phi \ \ \theta]^T$ has been defined as the generalized coordination and $F = [f_t \ \ f_b \ \ f_l \ \ 0 \ \ 0]^T$ as the driving forces.

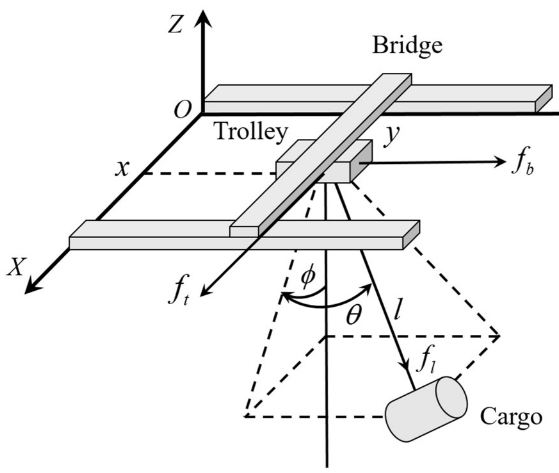


Fig. 1. Coordinate frames of a 3-D overhead crane

Using Lagrange's method, the dynamic model of a 3DOC system can be written in the compact matrix form [14]:

$$M(q)\ddot{q} + D\dot{q} + C(q,\dot{q})\dot{q} + G(q) = F \qquad (1)$$

Where M(q) is the symmetric mass matrix, $C(q,\dot{q})$ is the Coriolis and centrifugal matrix, D is the damping matrix and G(q) is the gravitational force vector, which can be expressed as:

$$M(q) = \begin{bmatrix} m_t + m_c & 0 & m_c S_\Phi C_\theta & m_c l C_\Phi C_\theta & -m_c l S_\Phi S_\theta \\ 0 & m_b + m_t + m_c & m_c S_\theta & 0 & m_c l C_\theta \\ m_c S_\Phi C_\theta & m_c S_\theta & m_l + m_c & 0 & 0 \\ m_c l C_\Phi C_\theta & 0 & 0 & m_c l^2 C_\theta^2 & 0 \\ -m_c l S_\Phi S_\theta & m_c l C_\theta & 0 & 0 & m_c l^2 \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} 0 & 0 & m_c\left(C_\Phi C_\theta \dot{\Phi} - S_\Phi S_\theta \dot{\theta}\right) & m_c\left(C_\Phi C_\theta \dot{l} - l C_\Phi S_\theta \dot{\theta} - l S_\Phi C_\theta \dot{\Phi}\right) & -m_c\left(l C_\Phi C_\theta \dot{\Phi} + S_\Phi S_\theta \dot{l} + l S_\Phi C_\theta \dot{\theta}\right) \\ 0 & 0 & m_c C_\theta \dot{\theta} & 0 & m_c\left(C_\theta \dot{l} - l S_\theta \dot{\theta}\right) \\ 0 & 0 & 0 & -m_c l C_\theta^2 \dot{\Phi} & -m_c l \dot{\theta} \\ 0 & 0 & m_c l C_\theta^2 \dot{\Phi} & m_c l C_\theta\left(C_\theta \dot{l} - l S_\theta \dot{\theta}\right) & -m_c l^2 C_\theta S_\theta \dot{\Phi} \\ 0 & 0 & m_c l \dot{\theta} & m_c l^2 C_\theta S_\theta \dot{\Phi} & m_c l \dot{l} \end{bmatrix}$$

$$D = \begin{bmatrix} D_t & 0 & 0 & 0 & 0 \\ 0 & D_b & 0 & 0 & 0 \\ 0 & 0 & D_l & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad G(q) = m_c g \begin{bmatrix} 0 \\ 0 \\ -C_\Phi C_\theta \\ S_\Phi C_\theta \\ C_\Phi S_\theta \end{bmatrix}$$

in which D_t, D_b and D_l stand for the viscous-damping coefficients along with x, y and l motions, respectively; S and C present the sine function and cosine function, respectively and g indicates gravitational acceleration.

2.2. Model Predictive Control Formulation

MPC is a method of control based on the solution of an online optimal control problem. By constructing a cost function that includes the sum of squares of the error between the desired and actual output and the control signal error between sampling periods, the MPC algorithm optimizes the cost function such that the control signals are optimal. In solving this optimization problem, the constraints such as swing angle limit, wire length limit, and impact force constraints will be combined as mandatory conditions for solving the optimal control signal.

Let $x = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}$ be the state-space vector, $y = [x \ \ y \ \ l \ \ \Phi \ \ \theta]^T$ be the output signal and $\mathbf{u} = [f_b \ \ f_t \ \ f_l]^T$ be the control force. Eq.1 can be rewritten in the first-order differential equation:

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{\mathbf{q}} \\ \ddot{\mathbf{q}} \end{bmatrix} = \begin{bmatrix} \dot{\mathbf{q}} \\ \mathbf{M}^{-1}(\mathbf{F} - \mathbf{G} - \mathbf{D}\dot{\mathbf{q}} - \mathbf{C}\dot{\mathbf{q}}) \end{bmatrix} \qquad (2)$$

Or, in the field of discrete time:

$$\mathbf{x}(k+1) = \mathbf{f}(\mathbf{x}(k), \mathbf{u}(k)) \qquad (3)$$

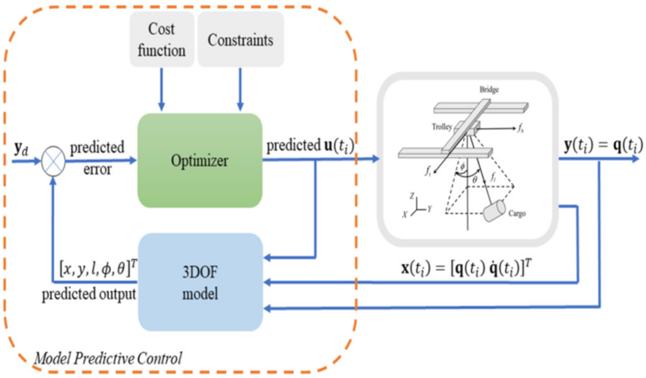


Fig. 2. State feedback model predictive controller

The MPC law of control is obtained by solving the following constrained optimal problem:

$$\text{minimize} \quad J(k) = \sum_{j=1}^{N_p} \left\| \hat{\mathbf{e}}(k+j|k) \right\|_P^2 + \sum_{j=1}^{N_p-1} \left\| \Delta\hat{\mathbf{u}}(k+j|k) \right\|_Q^2$$

$$\text{subject to} \quad \mathbf{x}(k+j|k) = f(\mathbf{x}(k+j-1|k), \mathbf{u}(k+j-1|k)) \qquad (4)$$

$$|\hat{\mathbf{u}}(k+j)| \leq \mathbf{u}_{max} \quad \forall j = 1,2,...,N_p - 1$$

$$|\hat{\mathbf{y}}(k+j)| \leq \mathbf{y}_{max} \quad \forall j = 1,2,...,N_p .$$

Where $\hat{\mathbf{x}}(k+j|k), \hat{\mathbf{y}}(k+j|k)$ and $\hat{\mathbf{u}}(k+j|k)$ are the predicted trajectory vector, predicted output vector and predict control vector at sampling time k + j, respectively and given by the current state $\mathbf{x}(k)$; $\hat{\mathbf{e}}(k+j|k) = \hat{\mathbf{y}}(k+j|k) - \hat{\mathbf{y}}_d(k+j|k)$ and $\Delta\hat{\mathbf{u}}(k+j|k) = \hat{\mathbf{u}}(k+j|k) - \hat{\mathbf{u}}(k+j-1|k)$ are respectively predicted error output and predicted change of input made at time k; N_p denotes the number of steps of prediction horizon. The weighted matrices **P** and **Q** are chosen as positive definite matrices.

The control strategy is summarized in Algorithm 1. This algorithm can be conducted by the usage of *Nonlinear MPC Toolbox* integrated in MATLAB-Simulink, or manually coding in Python.

Algorithm 1 *(MPC Algorithm)*

Step 1: Establish the cost function J(k) and constrains in (4)

Step 2: At sampling time k, measure the current state x(k)

Step 3: Calculate a predicted control sequence that minimizes J(k) initialized by the current state x(k) and satisfies constraints

Step 4: Use the first value of sequence as the input control of crane

Step 5: Move to the next sampling time k → k + 1 then repeat from Step 2

3. RESULTS AND DISCUSSION

3.1. Parameter selection

In this section, the simulation has been illustrated to verify the ability of trajectory tracking problems using MPC. To ensure that the moving cargo follows the trajectory and contemporaneously reduces the vibration during movement, the desired swing angle was chosen to be 0. The desired path is selected as follows: $x_d = 0.5\sin(0.1t)$; $y_d = 0.4\cos(0.1t)$; $l_d = 0.5 - 0.2\sin(0.2t)$; $\Phi_d = 0$; $\theta_d = 0$.

The overhead crane parameters and the MPC parameters is shown in Table 1.

Table 1. Simulation parameters

System Parameters	Control parameters
$m_b = 7kg$, $m_t = 5kg$, $m_l = 2kg$, $m_c = 0.85kg$, $D_b = 30N.m/s$, $D_t = 20N.m/s$, $D_l = 50N.m/s$, $g = 9.81m/s^2$.	$N_p = 10$, $T_s = 0.5s$, $y_{max} = [1, 1, 1, 0.25, 0.25]^T$, $u_{max} = [15, 15, 30]^T$, $\mathbf{P} = diag(100, 50, 50, 25, 25)$, $\mathbf{Q} = diag(1, 1, 1)$, $\mathbf{x}(0) = [0, 0, 0, 0, 0, 1, 0, 0, 0, 0]^T$.

3.2. Simulation Results

Fig. 3 and Fig. 4 show the trajectory tracking result. The red curve indicates the desired trajectory, and the blue curve indicates the output trajectory using the MPC controller. Figs show that the MPC controller generates fast convergence to the desired path. The swing angle fluctuates slightly in the first 10 seconds, then is almost stable to ensure anti-vibration tracking control during cargo movement. The cargo starts moving from an initial point with coordinates [0, 0, 1, 0, 0] and then follows the desired trajectory, as in Fig. 3. The required driving forces are plotted in Fig. 5.

Moreover, the shaking angles are limited by $|\Phi_d, \theta_d| \leq$ 0.2 rad, guaranteeing the vibration of 3doc. After about 20s, the values of the swing angles approach zero, so the vibration of the 3DOC when tracking the orbit is almost non-existent. This further proves that the MPC controller for a complex nonlinear system like 3DOC is possible. MPC guarantees complex constraints when operating a nonlinear system.

The values of the control signal are limited to [-30N; 30N] to avoid high jump control signal causing loss of system control when the setting values change suddenly. But the MPC problem has a periodic nature, after each cycle will solve the optimization problem making the control signal square pulse shape, but with a set period of 0.5s, the change period of the control signal is not high and the error value of the control signal at each cycle is optimized by the constraints of MPC to ensure the operation of the system and the experiment later. After about 10(s) ensure that the system follows the set trajectory, the control signals of the sinusoidal harmonic oscillation are the same as the desired system trajectory, the change is not too abrupt, and the harmonic controlled oscillation helps the system to be optimized in terms of performance. Finally, the force values of the control signal are optimal compared to the parameters of the crane, in line with the actual implementation that we will do after that.

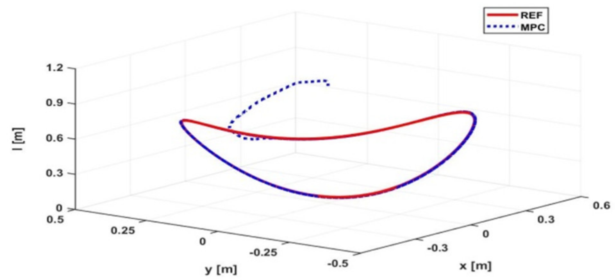
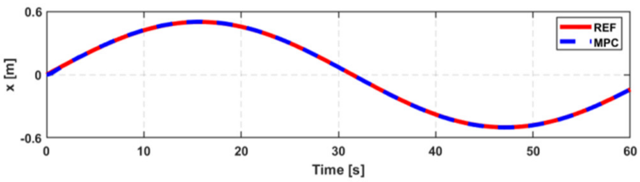


Fig. 3. The 3DOF trajectory tracking in Oxyz



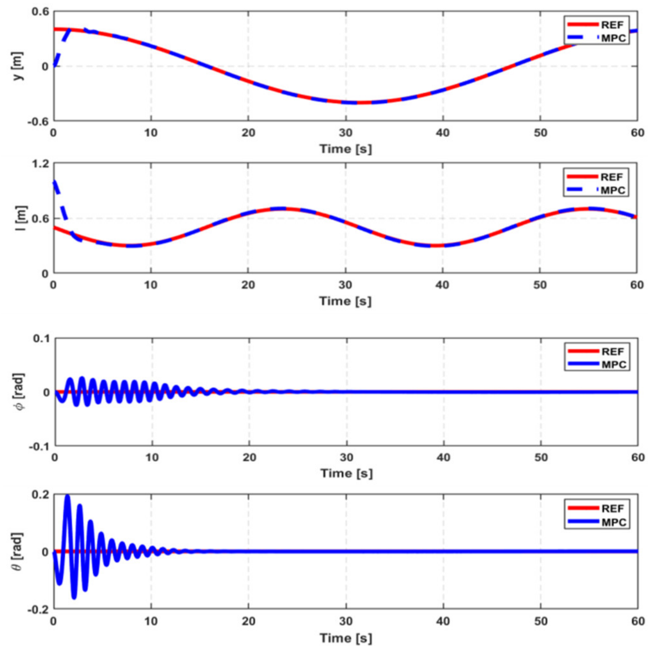


Fig. 4. The output tracking performance

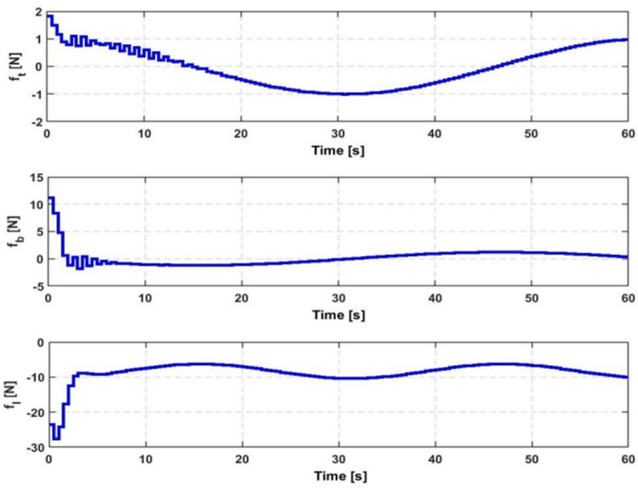


Fig. 5. The control input signals

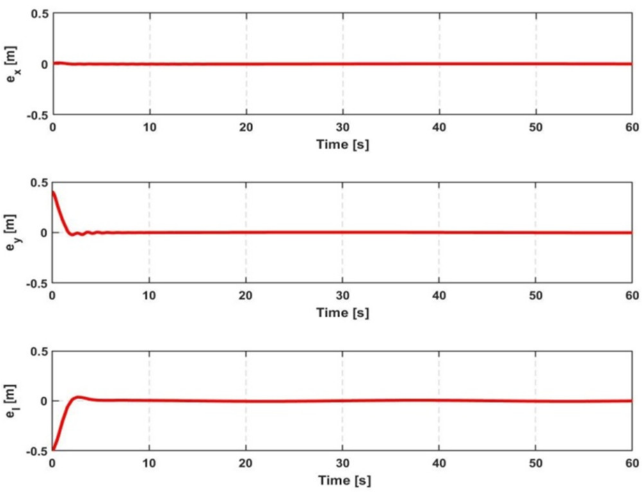


Fig. 6. The errors of trajectory

4. CONCLUSION

The MPC controller is used in this study to control the crane to travel to a predetermined constant destination or to follow a trajectory with safety performance because the states and energies can be constrained. Since each process only takes the first value of the prediction sequence, the system can quickly adapt when there is an impact, so the theoretical impact of the disturbance will not have much of an impact. The MPC controller uses the information of the current states to predict the following states and then computes the necessary input. Because the crane system in this research is simplified by ignoring the impact of outside disturbances like wind and friction, our work, in the future, will evaluate the quality of the MPC controller to the system complex and uncertain crane.

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