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Robust Sliding Mode Control for Novel Type of Parallel Robot

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Abstract: in this paper we present a new control architecture based on the robust sliding mode control applied to control a nonlinear system (parallel cable robot). This approach is widely used to address the uncertainties and disturbances of nonlinear systems and to improve the performance of the robot in terms of tracking a desired path. A dynamic model is presented followed by the description of the control approach used. To do this, numerical simulations were carried out by developing a specific code including a graphical user interface for a user-friendly real time. The simulation results for a dynamic model with sliding mode control are discussed for different trajectories applied to this robot, to confirm the validity of accurate tracking of a desired path before future work description

Keywords: Cable driven robot, Sliding mode control, Modeling, Position control, Robustness.

1. INTRODUCTION

Cable driven parallel manipulators are a special class of parallel mechanisms, whose trusts consist of cables having adjustable length to control the end-effector's position and orientation [1-2]. This last is a fully parallel mechanism in closed chains with N degrees of freedom for the end effector. Cable robots are relatively simple in form, with multiple cables attached to a mobile platform or end-effector. The end-effector is manipulated by motors that can extend or retract the cables [3]. The cables arrangement results in closed chains that can be seen as a parallel mechanism. Considering that cables can only pull, usually a cable driven robot has n-1 degrees of freedom for the end effector with n being the number of cables, since one cable is usually needed to keep the others in tension. Cable-driven robots are a type of parallel manipulators where the end-effector is supported in-parallel by n cables with n tensioning actuators. Indeed, the end-effector is operated by actuators that can extend or retract cables [4]. Cable driven robots have few moving parts with reduced mass and inertia. Accordingly, they are most suitable for tasks requiring high performance such as speed and accuracy, and large workspace, [5-6]. A well-known application of a cable driven system is the Skycam, which can operate a camera in a whole stadium area, [7]. Among other applications of cable-driven robots it is worth to mention haptic interfaces [8], and systems for lifting loads [9]. Some other examples at LARM in Cassino are also reported for rehabilitation applications such as in in [10] and as a passive tracking systems such as reported in[11]. One of the key aspects for cable driven robots is the need of a proper control strategy to achieve proper motions without breaking the cables. The sliding mode method has been designed to improve the robustness of robotic system control, as reported for example in [12]. In particular, an adaptive sliding mode controller can adjust the control torque based on real-time position tracking error in the set-point control of the end-effector. In this paper, a robust sliding mode controller is developed in order to tracking control of the end effector into a closed loop around the cable-parallel robot to ensuring point to point command operations.

2. MODELING AND SYSTEM STRUCTURE

This section proposes a model of a low-cost wire driven robot that has been designed and built at LARM in Cassino. In particular [13], Fig. 1 shows the structure of robot with 8 cables.

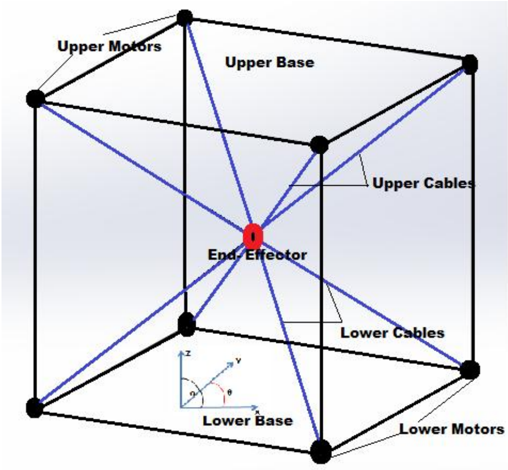


Fig.1 Scheme of a 3D parallel robot.

In order to analyze the input-output behavior of the cable-based robot under consideration, we exploit the study developed and presented in [14] the inverse geometric model, the direct geometric model, the inverse kinematic model, the direct kinematic model are derived as well as the study of static forces and dynamic model. Hereafter, we present the dynamical model which describes the motion of the end-effector. It combines the end-effector and the motor characteristics. It can be represented by a system of two coupled nonlinear differential equations:

$$M(X)\ddot{X} + N(X,\dot{X}) = S(X)\tau \tag{1}$$

where:

$$\tau = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \vdots \\ \tau_i \end{pmatrix} \tag{2}$$

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}, et, N(X,X^{\bullet}) = \begin{pmatrix} N_1(X,X^{\bullet}) \\ N_2(X,X^{\bullet}) \end{pmatrix} \tag{3}$$

The relationship between the applied forces $F = \begin{pmatrix} f_x \\ f_y \end{pmatrix}$ acting on the end-effector and the cable tensions τ i can be expressed as follows:

$$F = S * \tau \tag{4}$$

where S is the jacobian matrix.

$$S = \begin{pmatrix} -\cos\Theta_1 & -\cos\Theta_2 & -\cos\Theta_3 & -\cos\Theta_4 \\ -\sin\Theta_1 & -\sin\Theta_2 & -\sin\Theta_3 & -\sin\Theta_4 \end{pmatrix} \tag{5}$$

To present the dynamical model in the state space representation, we introduce the state variables:

$$x_{12d}(t) = x(t)$$
$$x_{22d}(t) = \dot{x}_{12d}(t)$$
$$x_{32d}(t) = y(t)$$
$$x_{42d}(t) = \dot{x}_{32d}(t) \qquad (6)$$

Therefore, by introducing the state variables, equations (1) can be expressed as follows:

$$\dot{x}_{12d}(t) = x_{22d}(t)$$
$$M_{11}\dot{x}_{22d}(t) + M_{12}\dot{x}_{42d}(t) = u_1(t) - N_{11}x_{22d}(t) - N_{12}x_{42d}(t)$$ and (7)

$$\dot{x}_3(t) = x_4(t)$$

$$M_{21}\dot{x}_{22d}(t) + M_{22}\dot{x}_{42d}(t) = u_2(t) - N_{21}x_{22d}(t) - N_{22}x_{42d}(t)$$
$$M = r * m + S(X)J\frac{\delta\beta}{\delta X}\ ; \qquad (8)$$

$$N(X, \dot{X}) = S(X)(J\frac{d}{dt}\frac{\delta\beta}{\delta X} + C\frac{\delta\beta}{\delta X}\dot{X}) \qquad (9)$$

β :is the angle of rotation of the pulley like represented in Fig.3.

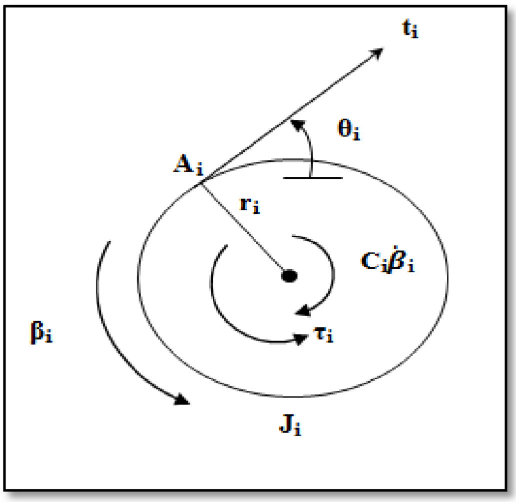


Fig.3 The structure diagram the pulley /shaft

where

$$J\ddot{\beta} + C\dot{\beta} = \tau - rt. \qquad (11)$$

$$J = \begin{pmatrix} J_1 & 0 & 0 & 0 \\ 0 & J_2 & 0 & 0 \\ 0 & 0 & J_3 & 0 \\ 0 & 0 & 0 & J_4 \end{pmatrix}, and C = \begin{pmatrix} C_1 & 0 & 0 & 0 \\ 0 & C_2 & 0 & 0 \\ 0 & 0 & C_3 & 0 \\ 0 & 0 & 0 & C_4 \end{pmatrix}$$

We consider that all the rays (ri) of the pulley are ri = r(i=1.2...8). So

$$t = \frac{1}{r}(\tau - J\ddot{\beta} - C\dot{\beta}) \tag{12}$$

$$\beta = \begin{pmatrix} \beta_1(X) \\ \beta_2(X) \\ \vdots \\ \beta i(X) \end{pmatrix} = \frac{1}{r}\begin{pmatrix} L_{10} - L_1 \\ L_{20} - L_2 \\ \vdots \\ L_{i0} - L_i \end{pmatrix} \tag{13}$$

Substituting (12) we obtain

$$t = \frac{1}{r}\left(\tau - J\left(\frac{d}{dt}\left(\frac{\delta\beta}{\delta X}\right)\dot{X} + \frac{\delta\beta}{\delta X}\ddot{X}\right) - C\frac{\delta\beta}{\delta X}\dot{X}\right) \tag{14}$$

The state space representation can be derived in the general form

$$X(t) = F(X,t) + g(X,t) * U(t) \tag{15}$$

where :

$$U(t) = \begin{bmatrix} 0 \\ u_1(t) \\ 0 \\ u_2(t) \\ 0 \\ u_3(t) \end{bmatrix} \tag{16}$$

X(t) represents the state space vector F(X, t), g(X, t) are nonlinear functions U(t) represents the command vector. The resulting tension at the end effector leads it to move towards a corresponding position on its workspace. However, to working properly, there is an additional constraint that should be fulfilled concerning the dynamical equilibrium of the end-effector. This means that, at any instant, all the cables should be maintained under minimal and positive tensions to avoid the collapsing of any cable [15].

3. CONTROL LAW AND ARCHITECTURE

The robust sliding mode control is to bring the state trajectory to the sliding surface and to switch by means of a switching logic appropriate around it to the balance point. Nevertheless, the SMC requires a switching law of control which has the drawback to generate scattering over the controlled system, [17].The main advantage of sliding mode control is that the system is insensitive to extraneous disturbance and internal parameter variations while the trajectories are on the switching surface.

To define a sliding mode controller we need to determine an appropriate sliding surface along x and y. The sliding surface of a common sliding mode controller for a system is generally defined as:

$$s_{2dx} = C_{12dx} * \left(x_{12d}(t) - x_{1ref}\right) + C_{22dx} * x_{22d}(t) \tag{17}$$

$$s_{2dy} = C_{12dy} * \left(x_{22d}(t) - x_{2ref}\right) + C_{22dy} * x_{42d}(t) \tag{18}$$

C12dx, C22dx, C12dy, C22dy : are parameters to be determined to meet some required performances.

x_{1ref} x_{2ref} : are the set point along X and Y.

By eliminations ˙x4 from the two equations (3) and (4), we can express ˙x22(t) as follows:

$$\dot{x}_{22d}(t)=\frac{\alpha_1 * x_{22d}(t)+\alpha_2 * x(t)+M_{22} * u_1(t)-M_{12} * u_2(t)}{\beta i} \tag{19}$$

And also by manipulating equations (3) and (4), we can express ˙x24 (t)as follows:

$$\dot{x}_{42d}(t)=-\frac{\rho_1 * x_{22d}(t)+\rho_2 * x_{42d}(t)+M_{21} * u_1(t)-M_{11} * u_2(t)}{\beta i} \tag{20}$$

To determine the order of law we worked with a new synthesis method that is the approach to the finish law [16].

$$\dot{s}_{2dx}=-K_{2dx}s_{2dx}-Q_{2dx}sign(s_{2dx}) \tag{21}$$

$$\dot{s}_{2dy}=-K_{2dy}s_{2dy}-Q_{2dy}sign(s_{2dy}) \tag{22}$$

Where:

K2dx, Q 2dx , K2dy, Q 2dy,: are parameters determined by simulation.

Sign(S2dx): is de sign of surface (+1 or -1).

By comparing (19) ,(20) and (21),(22) we obtain the following relationship:

$$u_{2dx}(t)=u_1(t)=-K_{12dx} * x_{22d}(t)-\sigma_x x_{42d}(t)-K_{22dx} * \left(x_{12d}(t)-x_{1ref}\right)-Q_x sign\left(s_{2dx}\right) \tag{23}$$

$$u_{2dy}(t)=u_2(t)=-K_{12dy} * x_{42d}(t)-\sigma_y x_{22d}(t)-K_{22dy} * \left(x_{32d}(t)-x_{2ref}\right)-Q_y sign\left(s_{2dy}\right) \tag{24}$$

This equation U(t) along X and Y represent the command vector of the cable-based robot for applying adequate electrical voltages to the motors in order to generate tensions on the cables. The algorithm of sliding mode in closed-loop case is shown in Fig. 4.

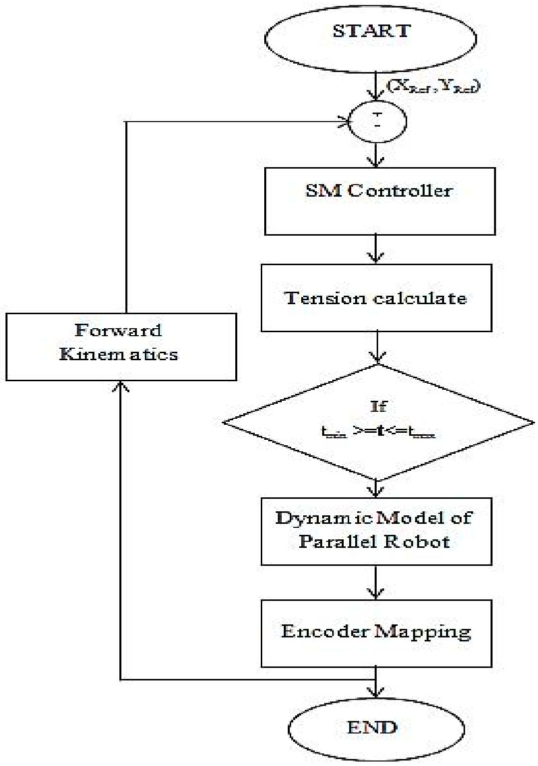


Fig.4 a flow-chart of the sliding mode control algorithm

4. SIMULATION RESULTS

In this part we present the simulation of the response of four cables-based robot which has a non-linear equation system. For this purpose, we use a Runge Kutta method because it's methods as a means of solving non-linear partial differential equations and we then implement a Cartesian of the sliding mode controller method.

In our system, we do not have direct access to Cartesian position of the end-effector. Instead, we get the direct measurements of the rotation angles βi of the pulleys. Then these values are converted into the cable lengths Li, these lengths are then used as inputs to the forward kinematics to obtain the Cartesian position X [17].

The following parameters values that provides an acceptable compromise on performances have been selected by manual trials about errors compared X and Y for our SMC:

C12dx=55000; C22dx=150; K2dx=150; Q2dx=100; C12dy=55000; C22dy=150; K2dy=150; Q2dy=100.

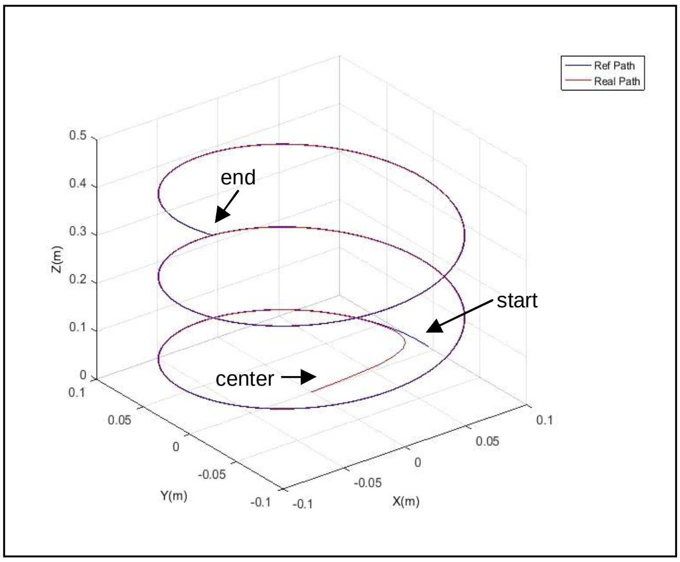
And the parameters for the dynamics equations (15) for our robot with 8 cables are mention in the following table:

Table.1. Initial values for the robot parameters

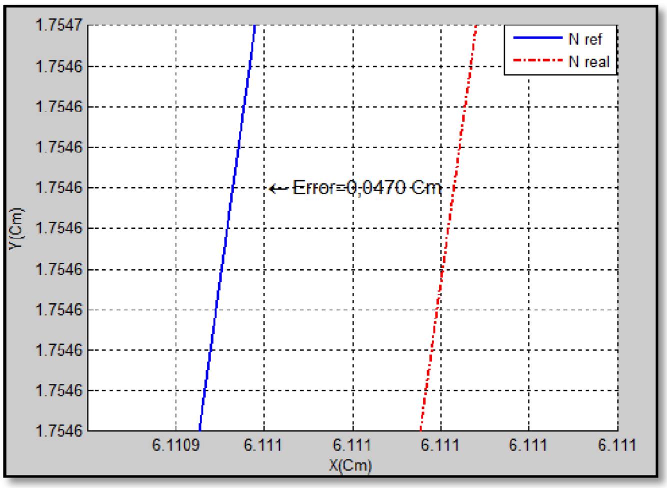
Variables	Initial Value	Unit
M	0.01	Kg
Lb	65.80	cm
C	0.01	Nms
J	0.0008	kgm2
ri	1.5	cm
L(1,2,..,8)	45.25	cm

The input signals are :
Spiral trajectory : $X_{ref}(1,i) = A*\cos(\omega*t)$; $Y_{ref}(1,i) = A*\sin(\omega*t)$; $Z_{ref}(1,i) = 0.22*t$;
Sinusoidal trajectory: $X_{ref}(1,i) = A*\cos(\omega*t)$; $Y_{ref}(1,i) = A*\sin(2*\omega*t)$; $Z_{ref}(1,i) = 0.22*t$;
with : A=10 cm, ω=8 rad/s; t:0:0,006:1,994.

To illustrate the SMC, we present the results concerning the tracking of a spiral trajectory. Figure 5 shows the tracking of a spiral trajectory in the 3D plane and error between the real and the reference paths (E=0,043 with mean squared error) . Figure 6 shows the temporal evolution of the cable lengths.
For the remarks ,we can observe the symmetry on cable lengths and concerning the tensions, it is noted that when the length of the cables (L1,L2,L3,L4) have decreased and the cables (L5,L6,L7 and L8) have increased, i- e the motors in the release position (ensure that always the cables taut with tmin positive), and when the cables have decreased (L1,L2,L3,L4) at the opposite, the necessary tensions have increased (t5,t6,t7 and t8), That is to say the motors in tightening position. Cable's flexibility in such robots is another source of error which has not been considered in our study.



a)



b)

Fig.5 The tracking of a spiral trajectory: a) plot of the end-effector position in 3D plane; b) a zoom view of plot

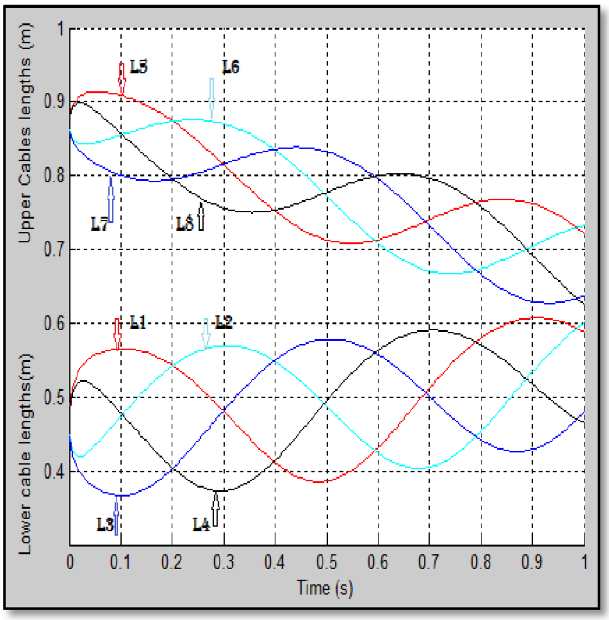


Fig .6 Evolution of cable lengths.

The analysis of previous presented simulation results confirm the possibility to use successfully this controller for curve tracking in case of curves in low speed, because the sliding mode control applied for this robot always cheek the role to requires adequate electrical voltages to the motors in order to generate tensions on the cables.

To illustrate this last situation, we present the tracking of a square trajectory Fig.7, we can also say that this controller is suitable and more effective than PID [18].

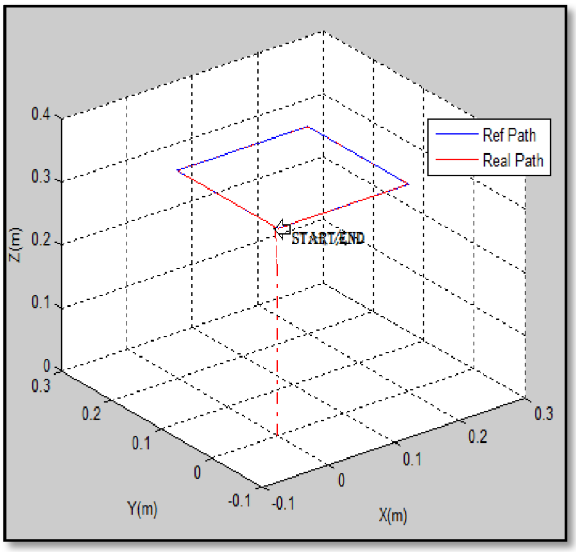


Fig.7 The tracking of a square trajectory.

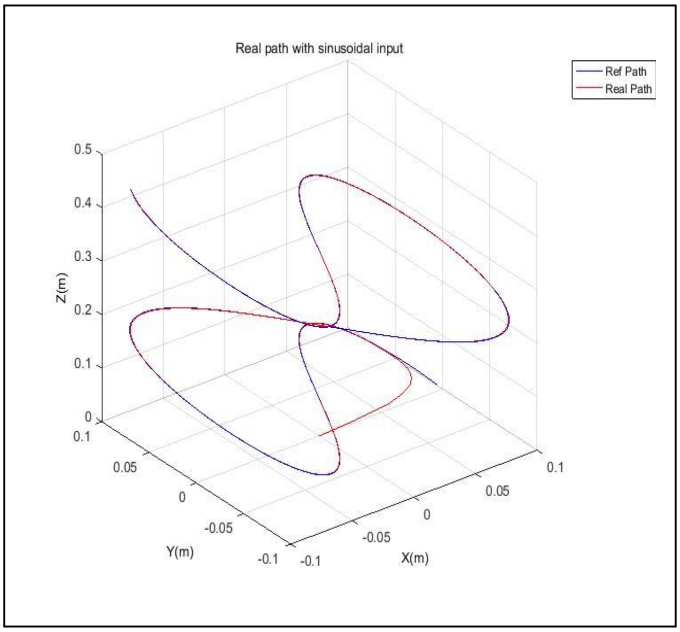


Fig.8 The tracking of a sinusoidal trajectory.

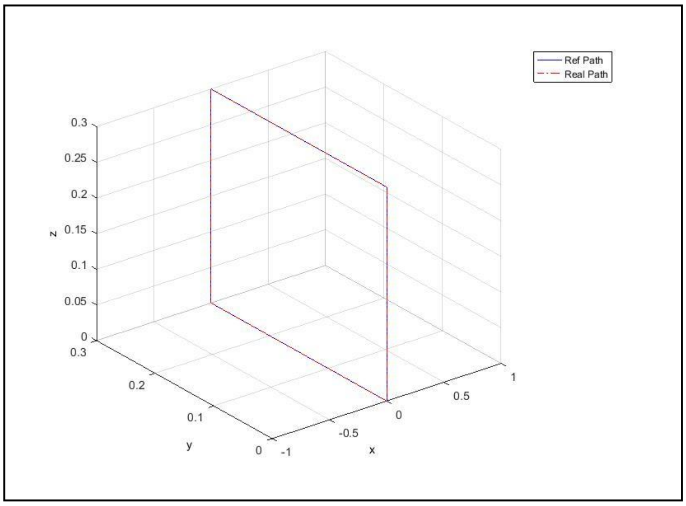


Fig.9 The tracking of a rectangular trajectory.

The following table mention the error performance between sliding mode and the classical controller (PID) [20].

Table 2 The Error performance between sliding mode and PID controllers

Error (Ex)	Sliding mode control	PID control
Sinusoidal trajectory	0,047 (cm)	0,26 (cm)
Triangular trajectory	0,047 (cm)	0,36 (cm)

5. CONCLUSIONS

In this paper, a nonlinear controller based on sliding mode control has been successfully applied for 3D cables based robot. Specific simulations have been carried out in Matlab environment. This last, simulation results (fig.5-fig.9) demonstrated proved that the sliding mode controller have positive stretching influences on the stability of the system in spite of the chattering phenomenon and also the proposed control shows a better performance as comparing with a PID controller in most operation conditions. in the future work, we want use PID controller with PSO and genetic algorithm to optimize the parameters.

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