MINISTRY OF EDUCATION AND TRAINING
THAI NGUYEN UNIVERSITY
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RESEARCHING AND DEVELOPING ADAPTIVE, SUSTAINABLE CONTROL METHODS OF EULER-LAGRANGE SYSTEM WITHOUT ACTUATOR AND APPLIED FOR OVERHEAD CRANE

Speciality: Control Engineering and Automation
Code: 62. 52. 02. 16

ABSTRACT OF DOCTORAL THESIS ON TECHNOLOGY

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Thesis is completed in Thai Nguyen University

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Opponent 3: ……………………………………

The thesis will be defended before The Thai Nguyen University at College of Technology

On .... Date ..../2016

The thesis can be studied more at Thai Nguyen University – Learning Resource Center

INTRODUCTION

1. Introduction on the study, reasons for topic selection

The Euler-Lagrange system (EL) in general and the overhead crane in particular with joint-variable model is the most common system in mechanics and mechatronics. Like the systems with status model, the Euler-Lagrange system adequately expresses objective properties but there's no absolute accuracy and it's often idealized as having no interference when the model is established. Therefore, the design and establishment of a good-quality controller for the EL system under the model's inaccuracy and interference's impacts, always bring significant meanings of application.

The overhead crane is a widely used industrial equipment in reality. When the overhead crane moves so quickly, the loads can be pendulated and accordingly, the loads control can be lost during the overhead crane's operation. Over the past decades, the researchers have made a lot of various studies on controlling the loads as a pendulum; however, in Vietnam, the popular application is still an open-loop control. Until now, the overhead crane is mainly operated by manual method under experience of the operator. However, when the overhead crane's size is larger and the transportation speed needs to be faster, the manual operation will be difficult.

The overhead crane is characterized by the underactuated system when it is unable to directly intervene to control the deflection angle between the overhead cable and vertical direction in the load's swinging status. And the equation system of control state for the overhead crane system with variable cable length is nonlinear and highly-connected. In addition, the uncertain components causing many difficulties for designing a good-quality controller. In order to improve efficiency and ability to satisfy the above-mentioned strict requirements, the writer presents the design of a sustainably adaptive controller for the overhead crane in the thesis.

The purpose of theoretical research on the underactuated system; and the design of a high-level sliding controllers for the overhead crane system is to promote the sliding controller's advantage known as sustainable asymptotic stability for uncertain objects, and to improve the disadvantage of sliding controller using the relay, namely the phenomenon of chattering generation during sliding process.

The topic focuses on studying a sustainable adaptive controller for the underactuated Euler-Lagrange system with undetermined model parameters and interference impacts, thereby, gives the proposals on the sustainably trackinged controllers for the system and applications for the 3D crane system in particular.

2. The theme's objectives

The objectives of the thesis is to develop the sustainable adaptability for the controllers of the underactuated Euler-Lagrange so that this system can track the desired joint-variable trajectory although the system's model has uncertain parameters and interference impacts at the input. Adaptation of the controller is defined as the quality is not affected by clinging parameters can not be determined in the model. The controller's adaptability is defined by the tracking quality which isn't affected by undetermined parameters at the input of the system. For this objective, the thesis has given the following tasks:

- Analyzing the mathematical model of underactuated system and accordingly, establishing a sustainable adaptive controller for this system based on the method of sliding control combined with ISS control principle. And then the study's results will be applied for the control of 3D crane system, simulation and evaluation of the ontroller's quality for a specific object.

- Developing and improving the high-level sliding control method for the control of the underactuated Euler-Lagrange system. Assessing the controller's quality by the application to the control of 3D crane and simulation by Matlab/Simulink software.

In addition, the thesis is aimed at establishing a experimental model of 3D crane system to do initial tests and assess the quality and theoretical results of the thesis through the experiments on a particular object. The details are presented as follows:

- The quality of control towards a preset position, carrying the load from the beginning to the preset end in short time.

- The deflection angle is limited in a small scale and gradually eliminated.

- Improving the vibration effect in the terms of reducing the back-sliding distance in a original neighboring point.

3. The study's subjects

The overall model of Euler-Lagrange system and 3D crane are specific objects for application, verification of results and furthermore, there is the underactuated motion system.

4. Study Methods

- Theoretical study on adaptive control of nonlinear system in the model of joint-variable. Establishing an ISS adaptive based on Lyapunov theory.

- Studying the method of high-level sliding control to reduce the vibration. Establishing a sustainable adaptive controller based on the theory of high-level sliding control.

- Experimental method: Simulation of assumptions and collection of results on experimental model.

5. The study's contents

- The mathematical model of 3D crane system is an object for studying the underactuated Euler-Lagrange systems.
- Developing a sustainable adaptive controller for underactuated system based on the ISS adaptive control.
- Giving an overview of control method for crane system. Applying the results of theoretical research on ISS adaptive control for the overhead crane system.
- Studying on the methods of sliding control (basic sliding, two-level sliding, two-level sliding with output response (super-twisted sliding).
- Designing the controllers of two-level sliding and super-twisted sliding for the Euler-Lagrange system in general and 3D crane system in particular. Verifying by the simulation using the Matlab/ Simulink software.
- Establishing laboratory table, verifying theoretical results through experimental study.

6. Study scope

Theoretically studying on sustainable adaptive control for the underactuated Euler-Lagrange system. Giving additional proposals and completing the available methods in theoretical aspect. Applying the proposed methods of ISS and high-level sliding control for 3D crane.

7. Scientific and practical meanings

The thesis provides the methodology and proposes the establishment of a sustainable adaptive controller under the principles of ISS and two-level sliding control, contributing to the improvement and enrichment of knowledge about the nonlinear system control for the underactuated Euler Lagrange systems. The thesis's study results could support the design of a sustainable adaptive controller for the underactuated Euler Lagrange systems, including the overhead cranes in reality; The application of high-level sliding method for promoting the advantages of sliding controller aren't much dependent on the accuracy of the model, not too complex and it's so convenient for the programming and calculation of the microcontroller or computer; therefore, many applications are brought into reality.

Chapter 1: AN OVERVIEW OF THE METHODS OF UNDERACTUATED SYSTEM CONTROL

Currently, many control methods are being simultaneously applied to the control of underactuated system in general and the system of overhead cranes, tower cranes in particular. It is difficult to determine which method is better because every control problem is always related to different working conditions and environment. As a result, in overall review of technical and economic aspects, each method has its advantages and disadvantages. In this chapter, the writer summarizes his methods of the underactuated & underactuated system control as follows:

1) Partial linearization control

2) Feedforward control (input shaping).

3) Backstepping method

4) Sliding control

5) Fuzzy interpolation control

The underactuated system in general is the system in which Euler-Lagrange model is in the uncertain overall structure, affected by interference and described by:

$$M(\underline{q},\underline{\theta})\ddot{\underline{q}}+C(\underline{q},\dot{\underline{q}},\underline{\theta})\dot{\underline{q}}+\underline{g}(\underline{q},\underline{\theta})=G\left(\underline{u}+\underline{n}(t)\right) \quad (1.1)$$

Conclusion of Chapter 1

Chapter I presents some methods of underactuated system control. Regarding on controlling this system, there've been many different methods, from simple ones to more complex ones such as adaptable & sustainable control with many tools combined for use. However, in this chapter, the writer only gives an overview of direct control methods in joint-variable space, except the methods of status space.

In addition, the thesis orientates the use of the sustainable adaptive control methods established for the actuated EL system to control the underactuated system with the appropriate additions and interventions on the base of Spong system separation tool and the underactuated EL system control methods by many previous writers.

Chapter 2: SOME PROPOSALS FOR IMPROVEMENT OF ADAPTABILITY, SUSTAINABILITY FOR THE UNDERACTUATED SYSTEM

Based on the presented and analyzed results on the underactuated system control methods in previous chapter, some methods are proposed to improve the adaptability and sustainability for two specific controllers. The details are presented as follows:

1.Improving the adaptability and sustainability for the available partial linearization controller. The adaptability is established on the principle of clear assumptions. The sustainability is enhanced by the principles of ISS control known as the actual stability control.

2. Completing the method of high-level sliding control. A high-level sliding controller for the 3D crane system has been introduced in an

international journal under the study of a group of South Korean scientists. This quadratic controller can be applied for the underactuated system in general, not only the overhead crane system, however, it isn't really complete. The incompleteness is expressed as follows:

- The controller can only make the system's trajectory asymptotic toward the sliding surface, not reach sliding surface after a limited time. As a result, the element which controls to keep the system on the controller's sliding surface becomes useless.

- The system's stability hasn't been affirmed when the sliding surface is asymptotic to 0.

The thesis will propose the methods of completing the high-level sliding controller in the direction of making the joint-variable trajectory of underactuated system in general and 3D overhead crane system in particular moves toward sliding surface after a limited time. In addition, the conditions for parameters will be added so that when sliding surface is 0, the system will slide on the sliding to reach the coordinate origin.

2.1.The ISS stable, adpative tracking control by the offset signal

In this thesis, the ISS stability control method is established on the combination of Spong's partial linerialization method (applied for uncertain system with interference impacts) with the method of accurate linerialization control to handle the uncertain constant component $\underline{\theta}$ in the actuacted system. A new point of this method is that in order to limit influences of interference component $\underline{n}(t)$, the offset signal vector $\underline{s}(t)$ will be added instead of applying the principle of sliding control often used for the control of undeactuated EL system, accordingly, the undesired vibration in the system won't happen.

2.1.1. The ISS adaptability controller with the offset signal

Model:

$$\begin{cases} D\ddot{\underline{q}}_1 + C_{11}\dot{\underline{q}}_1 + \underline{f}^{/} = \underline{u} + \underline{n} \\ M_{21}\ddot{\underline{q}}_1 + M_{22}\ddot{\underline{q}}_2 + \underline{f}_2 = \underline{0} \end{cases} \tag{2.3}$$

Assuming $\left\| \underline{n}(t) \right\|_\infty = \sup_t \left| \underline{n}(t) \right| = \delta$ (2.4)

is a finite value.

The left side of model (2.3) can always be written in details as follows :

$$\begin{cases} D(\underline{q},\underline{\theta})\ddot{q}_1 + C_{11}(\underline{q},\dot{\underline{q}},\underline{\theta})\dot{q}_1 + \underline{f}^{/}(\underline{q},\dot{\underline{q}},\underline{\theta}) = F_1(\underline{q},\dot{\underline{q}},\ddot{\underline{q}})\underline{\theta} \\ M_{21}(\underline{q},\underline{\theta})\ddot{\underline{q}}_1 + M_{22}(\underline{q},\underline{\theta})\ddot{\underline{q}}_2 + \underline{f}_2(\underline{q},\dot{\underline{q}},\underline{\theta}) = F_2(\underline{q},\dot{\underline{q}},\ddot{\underline{q}})\underline{\theta} \end{cases} \tag{2.5}$$

Theorem 1: *Considering the uncertainty system* (2.3) *satisfies the assumptions* (2.4) *and* (2.5). *Then a sustainable adaptive controller*:

$$\underline{u} = D(q,d)\left[\ddot{\underline{q}}_r + K_1\underline{e} + K_2\dot{\underline{e}}\right] + C_{11}(\underline{q},\dot{\underline{q}},\underline{d})\dot{\underline{q}}_1 + \underline{f}^{/}(\underline{q},\dot{\underline{q}},\underline{d}) + \underline{s}(t) \tag{2.6}$$

In which:

$$\underline{e} = \underline{q}_r - \underline{q}_1,\ K_1 = diag(a),\ K_2 = diag\left(\sqrt{(a+1)a}\right),\ a > 0 \tag{2.7}$$

the vector of constant $\underline{d}$ *in* $D(\underline{q},\underline{d})$, $C_{11}(\underline{q},\dot{\underline{q}},\underline{d})$, $\underline{f}^{/}(\underline{q},\dot{\underline{q}},\underline{d})$ *is replaced for parameter vector of uncertain constant* $\underline{\theta}$ *for:*

$$\max_{1\le i\le n} \sum_{j=1}^{n} \left| d_{ij}(\underline{q},\underline{d}) \right| \le \gamma,\ \forall \underline{q} \tag{2.8}$$

γ *is a determined finite value,* $d_{ij}(\underline{q},\underline{d})$ *are the elements of the matrix* $D(\underline{q},\underline{d})^{-1}$ *and*:

$$\underline{s}(t) = F_1(\underline{q},\dot{\underline{q}},\ddot{\underline{q}}) \int_0^t \left[\left(D(\underline{q},\underline{d})^{-1} F_1(\underline{q},\dot{\underline{q}},\ddot{\underline{q}}) \right)^T (K_1\ ,\ K_2)\underline{x} \right] d\tau \tag{2.9}$$

In which, $\underline{x} = col\left(\underline{e}\ ,\ \dot{\underline{e}}\right)$ *is the symbol of tracking error vector, always taking the tracking error vector* $\underline{x}$ *to neighboring area of origin point* O *determined by*:

$$\text{O} = \left\{ \underline{x} \in \mathrm{R}^{2m} \,\middle|\, |\underline{x}| < \frac{\delta\gamma}{a} \right\} \quad (2.10)$$

Proving that:

$$\underline{\dot{x}} = A\underline{x} + B\left[F_1\left(\underline{\theta} - \underline{d}\right) - \underline{s} - \underline{n}\right] \quad (2.12)$$

In which $\underline{x} = \begin{pmatrix} \underline{e} \\ \underline{\dot{e}} \end{pmatrix}$, $A = \begin{pmatrix} 0 & I_m \\ -K_1 & -K_2 \end{pmatrix}$, $B = \begin{pmatrix} 0 \\ \hat{D}^{-1} \end{pmatrix}$ (2.13)

K_1, K_2 in the (2.7) are two definite positive symmetric matrices making the matrix **A** defined in (2.13) become a durable matrix which has all its own values located on the left side of conjugate axis and accordingly, the system with no interference:

$$\underline{\dot{x}}_m = A\underline{x}_m \quad (2.14)$$

is a stable equation. Therefore, the trajectory $\underline{x}_m(t)$ doesn't depend on initial value $\underline{x}_m(0)$, when $t > 0$ is always bounded and asymptotic to the origin when $t \to \infty$.

After that, prove that the additional controller (2.9) stated in the theorem will deviate $\underline{x} - \underline{x}_m$ to be bounded and move toward the neighboring area of origin point as defined by (2.10), thereby, affirm the property of being bounded and moving the asymptotic point toward neighboring position O of error trajectory $\underline{x}(t)$.

$$\dot{V} = -a^2 |\underline{x}|^2 - \underline{x}^T PB\underline{n} \le -a^2 |\underline{x}|^2 + \|PB\| \delta |\underline{x}| \le a\left[-a|\underline{x}| + \gamma\delta\right]|\underline{x}| \quad (2.18)$$

This states that when: $\frac{\gamma\delta}{a} < |\underline{x}|$, the error trajectory $\underline{x}(t)$ is located out of neighboring point O in the formila (2.10), then $\dot{V} < 0$, accordingly, $|\underline{x}(t)|$ monotonously reduces (đ.p.c.m).■

When $\underline{q}_1 \to \underline{q}_r$, $\underline{q}_r$ is a constant, we have:

$$\underline{\ddot{q}}_2 = -M_{22}^{-1}(\underline{q}_2, \underline{q}_r, \underline{d})\underline{f}_2(\underline{q}_2, \underline{q}_r, \underline{\dot{q}}_2, \underline{d}) \quad (2.20)$$

Theorem 1 provides the steps to design a sustainable adaptive controller for the underactuated subsystem which is uncertain, affected by interference and able to track the sample trajectory with asymptotic $\leq \gamma\delta/a$.

In addition, it can easily be seen that:

- The bigger the value a is, the smaller neighboring point is.
- $\underline{d}$ always exists to satisfy the assumption (2.8).
- The controller (2.6) with offset singal $\underline{s}(t)$ stated in (2.9) has the same function as the sliding controller's –handling the influence of uncertain element of function $\underline{n}(\underline{q},t)$ mixed in the input signal. However, its difference from sliding controller is that it doesn't use the sliding surface and doesn't need to keep the status trajectory on the sliding surface, accordingly, the system's vibration won't occur.

2.1.2. Elemental quality of second subsystem

For the second subsystem to obtain $\underline{q}_2 \to \underline{0}$, we choose $\underline{d}$ for the system's stability, then we have $\underline{q}_1 \to \underline{q}_r$ thanks to the controller stated in theorem 1, (2.6), (2.9) and we have $\underline{q}_2 \to \underline{0}$. However, how to choose $\underline{d}$ appropriately depends on the specific structure of (2.20) and typical characteristics of each system. For the overhead crane system, it's so easy to choose $\underline{d}$ appropriately for the equation (2.20) to be stable for all values of $\underline{d}$.

2.2. High-level sliding control

The high-level sliding controller is known as an anti-vibration solution in sliding control. However, the given solution hasn't been complete, namely:

- It hasn't expresses the trajectoryal time of the system moving toward the sliding surface is limited. This aspect is very necessary because even the system can be asymptotic to the sliding surface, it can still be unstable.
- Lacking strict conditions for the system sliding on the sliding surface to move to the origin of coordinate.

Therefore, in addition to the ISS control method, in order to complete two aforementioned shortcomings, the thesis will propose the quadratic controller and super-twisted sliding controller to solve the sustainable adaptive control problem for the underactuated EL system.

2.2.1. Concepts of basic sliding control and high-level sliding control

2.2.2. Design the quadratic controller for the uncertain underactuated EL system

In an international journal under the study of a group of Korean scientists introduced an application of the quadratic sliding controller to the sustainable tracking controller of the overhead crane system. However, this controller is incomplete because it just states that the trajectory of overhead crane system is asymptotic to sliding surface but it hasn't proved that it will be back to the sliding surface within a finite time. Moreover, it hasn't yet given the conditions for the trajectory of the system to slide on sliding surface toward the origin of coordinate.

To overcome these shortcomings, the thesis will expand the methods presented in this paper, which is specifically designed for 3D overhead crane system, as follows:

- Expanding to the underactuated EL system with a lot of independent joint variables (1.1) in a general way.

- Adding the contents proving that the controller always move the system's trajectory toward the sliding after a a finite time.

- Adding conditions for the system to slide on sliding surface toward the origin of coordinate.

Controller Design

Considering the underactuated EL system in an implicit model, under the effects of interference, and independent variables $\underline{q}_1$ is more dependent joints $\underline{q}_2$, described by:

$$M(\underline{q},\underline{\theta})\underline{\ddot{q}} + C(\underline{q},\underline{\dot{q}},\underline{\theta})\underline{\dot{q}} + \underline{g}(\underline{q},\underline{\theta}) = \begin{pmatrix} \underline{u} + \underline{n}(t) \\ \underline{0} \end{pmatrix} \tag{2.39}$$

Model

$$M(\underline{q})\underline{\ddot{q}} + C(\underline{q},\underline{\dot{q}})\underline{\dot{q}} + \underline{g}(\underline{q}) = \begin{pmatrix} \underline{u} + \underline{\varsigma} \\ \underline{0} \end{pmatrix} \quad (2.41)$$

Applying the system separation method used by Spong, we will have the elements of underactuated subsystem corresponding to (2.41) as follows:

$$\underline{u} + \underline{\varsigma} = D(\underline{q})\underline{\ddot{q}}_1 + \underline{h}(\underline{q},\underline{\dot{q}}) \quad (2.43)$$

When expanding the sliding surface t $\underline{s} = \underline{\dot{s}} = \underline{0}$, with the task of tracking control $\underline{q}_1 \to \underline{q}_r$, in which $\underline{q}_r$ is a sample trajectory in the form of preset constant, we'll have the sliding surface expanded as follows:

$$\underline{s}(\underline{q},\underline{\dot{q}}_1) = \underline{\dot{q}}_1 + \Lambda\underline{e} + \Gamma\underline{q}_2,\ \underline{e} = \underline{q}_1 - \underline{q}_r \quad (2.44)$$

We will proceed to establish a quadratic sliding controller for the EL system of many independent jointvariables. When being extended for the equation (2:43), the sliding controller will be in the following form:

$$\underline{u} = \underline{u}_{eq} - K\ \mathrm{sgn}(\underline{s}),\ K = diag(k_i) \in \mathrm{R}^{m\times m} \text{ và } k_i > 0,\ \forall i, \quad (2.45)$$

In which: $\underline{u}_{eq} = \underline{h}(\underline{q},\underline{\dot{q}}) - D(\underline{q})\left[2\Lambda\underline{\dot{q}}_1 + \Lambda^2\underline{e} + \Gamma\underline{\dot{q}}_2 + \Lambda\Gamma\underline{q}_2\right]$ (2.46)

The duration for moving toward the sliding surface is limited.

We need to prove the control rules (2.45), (2.46) to take the system from any point of initial status under a compact set in the space of joint variables $\left(\underline{q}(0),\underline{\dot{q}}_1(0)\right) \in \mathbf{C}$ toward the sliding surface $\underline{s}(\underline{q},\underline{\dot{q}}_1) = \underline{0}$ after a definite time.

Theorem 2: *If a constant vector* $\underline{d}$ *exists and when it is repaced for the uncertain parameter vector* $\underline{\theta}$ *in equation* (2.39) *without changing the independent joint varible's vector* $\underline{q}_1$ *, the quadratic sliding controller* (2.45), (2.46) *is able to take the equation* (2.39) *from any point of initial status* $\left(\underline{q}(0),\underline{\dot{q}}_1(0)\right) \in \mathbf{C}$ *under a domain of compact* $\mathbf{C}$ *to reach the* *sliding surface* $\underline{s}(\underline{q},\underline{\dot{q}}_1)=\underline{0}$ *with* $\underline{s}(\underline{q},\underline{\dot{q}}_1)$ *given by* (2.44) *and the trajectory sets* $\underline{q}_r$ *as a constant*, *after a limited time* T .

Prove:

$$V(t) < V(0) - \frac{\delta^2}{\lambda_{\max}} t \tag{2.49}$$

The last inequality (2.49) confirms the existence of a limited time T to reach $V(T)=0$, meaning that the joint variable trajectory of the system will be back to sliding surface after a limited time (đ.p.c.m). ■

Such as, in theorem 2, the quadratic sliding controller is able to take the system back to the sliding surface after a limited time.

Conditions for the system to slide on the sliding system toward the origin of coordinate.

Necessary and sufficient condition for the system to slide on the sliding system toward the origin of coordinate is that the system:

$$\underline{\dot{x}} = \begin{pmatrix} -\Lambda\underline{x}_1 - \Gamma\underline{x}_2 \\ \underline{x}_3 \\ \underline{h}(\underline{x}) \end{pmatrix} = \underline{\vartheta}(\underline{x}) \text{ với } \underline{\vartheta}(\underline{x}) = \begin{pmatrix} -\Lambda\underline{x}_1 - \Gamma\underline{x}_2 \\ \underline{x}_3 \\ \underline{h}(\underline{x}) \end{pmatrix} \tag{2.52}$$

needs to get a stable proximity, meaning that when and only when a positive definite function $V^{/}(\underline{x})$ *exists so that*

$$\frac{\partial V^{/}}{\partial \underline{x}} \underline{\vartheta}(\underline{x}) < 0, \ \forall \underline{x} \neq \underline{0} \tag{2.53}$$

is a negative definite function (According to the Lyapunov converse theorem).

2.3. Conclusion of Chapter 2

The thesis provides some proposals on establishing a sustainable and adaptive controller for the underactuacted system with uncertain constant parameter $\underline{\theta}$ in model and affected by interference $\underline{n}(\underline{q},t)$ on the input $\underline{u}$, described by general model (1.1), namely:

1) Firstly, already establishing a ISS adaptive controller (stated in theorem 1) for the system (1.1). This controller has applied to the system which contains the uncertain constant parameters and affected by interference at the input. Unlike sliding controller, the ISS adaptive controller doesn't cause vibration in the system, accordingly, the applicability in reality is higher.

In addition, the ISS adaptive controller has the disadvantage, namely: it isn't able to take the system's tracking error to origin O; it just takes the system's tracking error to neighboring points of origin O defined by (2.10), however, this isn't so important, because the size of the neighboring area of origin can always be adjusted to be smaller in an arbitrary way via parameter a of the controller.

2) Secondly, already generalizing the quadratic sliding controller for 3D overhead system in explicit form, introduced in an international journal of a group of Korean scientists, to the underactuated EL system (1.1) with uncertain parameter in the model and under the influence of interference at the input. Furthermore, the thesis states that the time for the system to back the sliding surface is always finite (theorem 2) and adds conditions for the error system to slide on the sliding surface toward the origin of coordinate.

Finally, there is a problem unresolved in the thesis. Particularly, for the EL systems with the self-sustainable subsystem, it's needed to determine parameters $\underline{d}$ instead of uncertain parameter $\underline{\theta}$ in initial system (1.1) in a general way so that the subsystem (2.20) is asymptotically stable. In reality, it's based on the characteristics of each system to appropriately select $\underline{d}$, not necessarily defining in the general case.

Chapter 3: APPLICATION IN 3D OVERHEAD CRANE SYSTEM CONTROL

3.1. Overhead crane system modeling

3.1.1. Physical structure of overhead crane system

3.1.2. EL model of 3D overhead crane system

$$M(\underline{q})\underline{\ddot{q}} + B\underline{\dot{q}} + C(\underline{q},\underline{\dot{q}})\underline{\dot{q}} + \underline{g}(\underline{q}) = G\underline{u} \quad (3.8)$$

In which $\underline{q} = (x, y, l, \varphi_x, \varphi_y)^T$ is vector of joint variables.

$\underline{u} = (u_x, u_y, u_l)^T$ is force vector lực acting on the system (input signal).

Based on obtained model, it can be seen that :

1) The system is underactuacted when the deflection angles φ_x, φ_y aren't directly controlled and it must indirectly be controlled by the force elements u_x, u_y, u_l.

2) The system of equation describing the 3D overhead crane system is a nonlinear system with high connection. These two factors causes a lot of difficulties in the design of the controller for 3D overhead crane system. It's necessary to take appropriate methods to solve them.

3.1.3. EL model of 2D overhead crane system

$$M(\underline{q})\underline{\ddot{q}} + C(\underline{q},\underline{\dot{q}})\underline{\dot{q}} + \underline{g}(\underline{q}) = (u_1, u_2, 0, 0)^T \quad (3.10)$$

3.2. The ISS adaptive controller

3.2.1. The ISS adaptive controller for overhead system

3.2.2. Simulation results

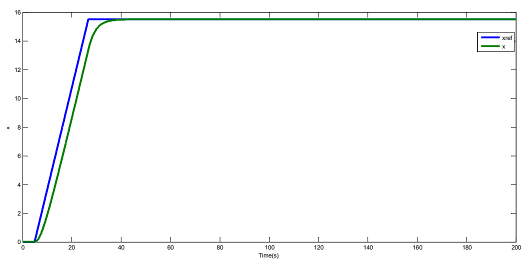

Chart 3.4. The position of overhead crane is satisfied under axis x

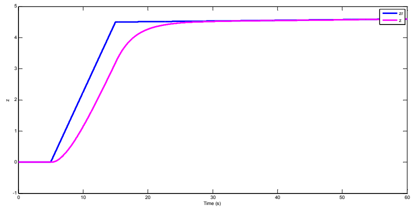

Chart 3.5. The position of overhead crane is satisfied under axis z

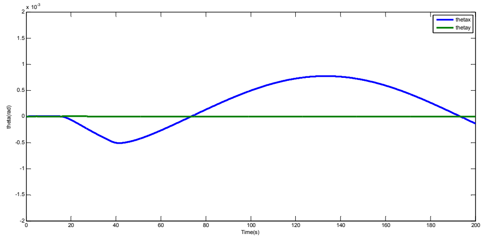

Chart 3.6a. Crab corners of cables are satisfied in the directions x,y when there's no model uncertainty

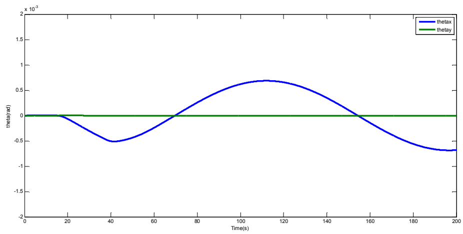

Chart 3.6b. Crab corners of cables are satisfied in the directions x,y when there's no model uncertainty (At 50s).

The above contents affirms that the ISS adaptive control method introduced in Chapter 2 of the thesis is well applied for the overhead crane system. This controller not only ensures the trajectory tacking for movements of overhead crane but also ensures crab angles of the cable to move in the directions toward neighboring point 0. Moreover, the controller proposed in the thesis ensures that the system can well meet loads regardless of the effects of external interference and uncertain parameter of the model. The effectiveness of the controller was proved through simulation results performed on Matlab / Simulink.

3.3. Quadratic sliding control

3.3.1. Quadratic sliding controlfor overhead crane system

The quadratic sliding controller for the underactuated uncertain EL system is also applied to the overhead crane system described by (3.8).

3.3.2. Simulation results

The simulation results show that the system is stable. The system quality can be evaluated to be quite good.

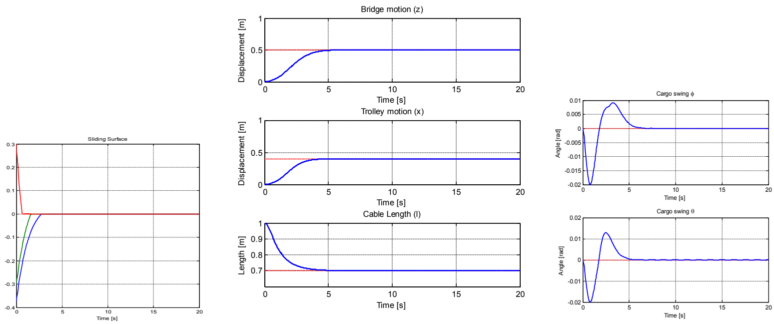

Chart 3.11. Simulation result with $\alpha_1 = \alpha_2 = -4$

3.4. Super-twisting sliding control

3.4.1. Design the super-twisting sliding controller for overhead crane system

The thesis continues to develop the super-twisting sliding controller for only 3D overhead crane system.

Simplification of the model when the system has minor crab angle

Design controller

$$\begin{cases} u_i = -\lambda_i \sqrt{|s_i|}\,\mathrm{sgn}\, s_i + \omega_i \\ \dot{\omega}_i = -\alpha_i\,\mathrm{sgn}\, s_i \end{cases} \text{với } i \in \{x, y, l\} \qquad (3.30)$$

3.4.2. Simulation results

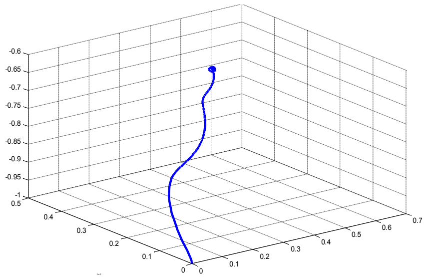

Chart 3.17. Movement trajectory of the load

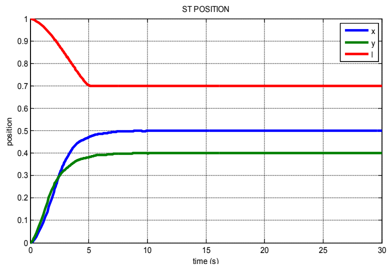

Chart 3.18. The state variables x, y, l are satisfied

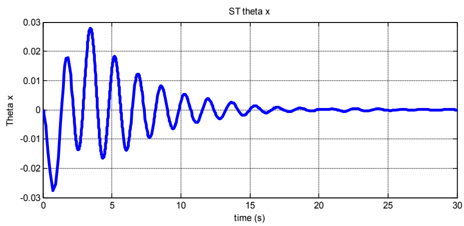

Chart 3.19. Angle φ_x is satisfied

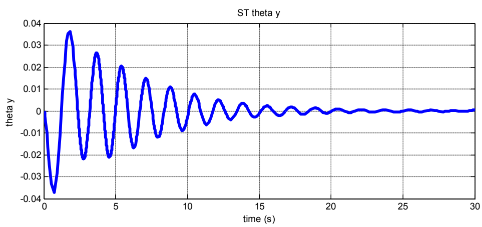

Chart 3.20. Angle φ_y is satisfied

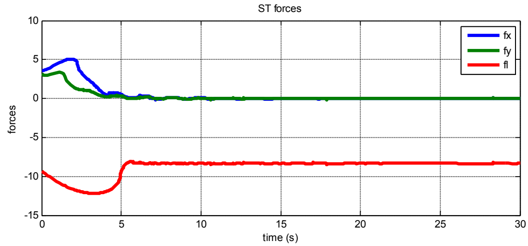

Chart 3.21. Control force

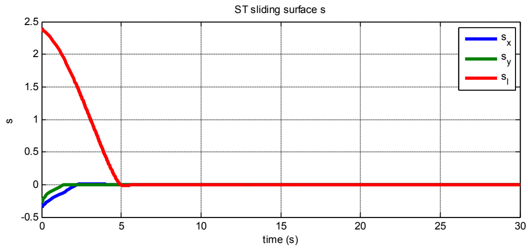

Chart 3.22. Sliding surface $\underline{s}$

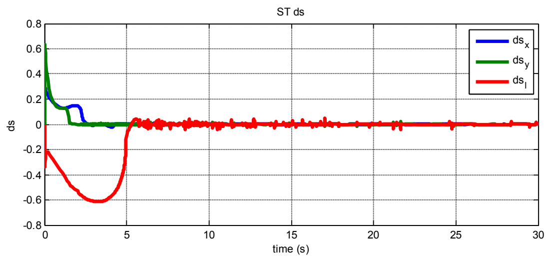

Chart 3.23. The function of sliding surface $\dot{\underline{s}}$

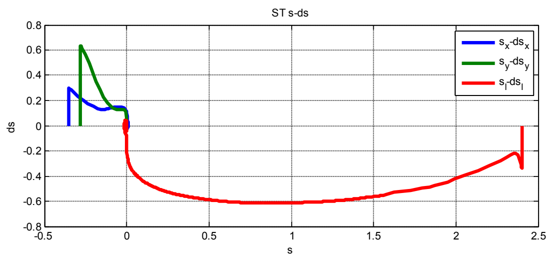

Chart 3.24. Trajectory $\underline{s} - d\underline{s}$

Such as, the designed controller meets requirements of given problem, particularly:

1) Carrying the load from the beginning to the preset end in short time.

2) The deflection angles are limited in a small scale and gradually eliminated. The vibration effects of high-level sliding controller are improved the in the terms of reducing the back-sliding distance in neighboring area of the origin. This result is completely suitable with the theory and becomes the base for the application of controller in reality.

3.5. Construction of 3D crane laboratory table

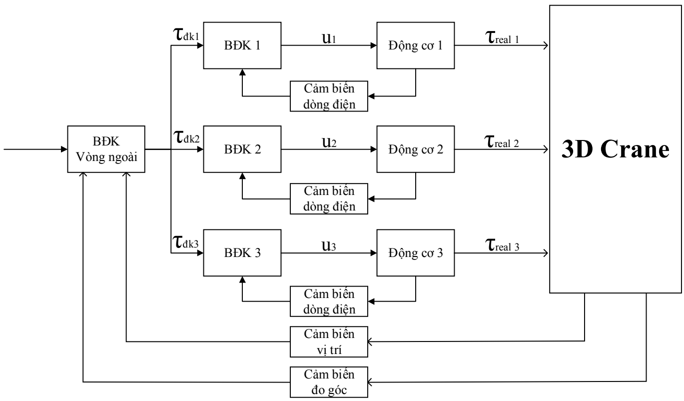

Figure 3.26. Control system

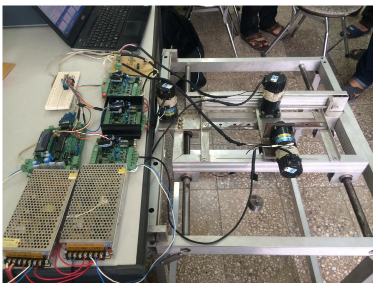

Figure 3.32. Image of experimental system 1

Experiment result

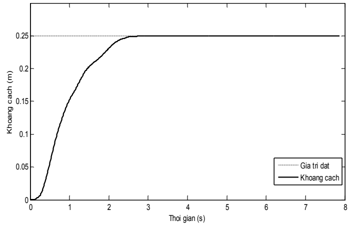

Figure 3.34. Coordinates of the horizontal supporting beams

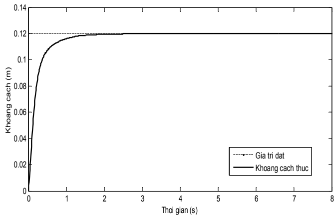

Figure 3.35. Coordinates of crane on the horizontal supporting beams

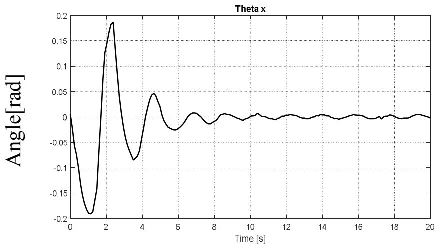

Figure 3.36. Angle φ_x

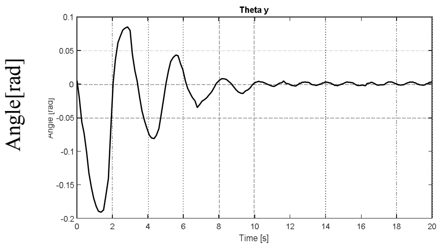

Figure 3.37. Angle φ_y

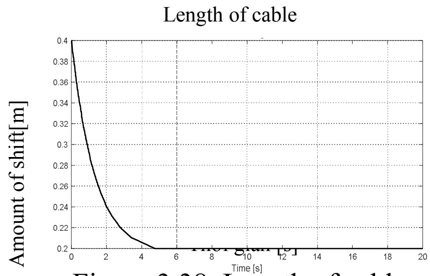

Figure 3.38. Length of cable

Remark

Control system meets the requirement of position control problem, takes the load from the first position to the final position in a short time, adjustment is small. Here, the drawback is the difficulty in assembly of tilt sensor and mechanical structure is not really accurate when fitting between the plastic gear and force transmission bar.

3.6. Conclusion of Chapter 3

In Chapter 3, 3D crane laboratory table was built to verify experimentally the theoretical results of the thesis. Laboratory table was also connected to computer. Control program was installed on computer for super-twisting mode sliding control, which controlled 3D overhead crane system reaching the desired value as requirements. Practically experimental model can be applied in Control Engineering and Automation major to meet the requirements of control problem with fairly good quality control, while the control power must limit the constantly changing phenomenon with great frequency and is the basis for the application in practice.

Experiment result had a small deviation compared with the theoretical simulation results, the main reason is due to the deviation of mechanical structure of the model in the fabrication process. However, it showed properly the nature of the output feedback sliding mode control (super-twisting mode sliding control) and guaranteed the compliance with the parameters of sliding mode control.

Especially state feedback control including ISS adaptive control and quadratic sliding mode control has not been performed with 3D overhead crane laboratory table due to the lack of sensors to feedback the movement value of joint-variable trajectory to computer (controller).

CONCLUSIONS, RECOMMENDATIONS AND PLAN FOR FURTHER STUDY

4.1. General conclusion

The thesis has achieved the following results:

1. Supplementing the adaptability and sustainability of partial linearization. The adaptability supplemented to this control is developed under the certainty equivalent principle. The sustainability is supplemented by input to state stable principle. The results were stated in the dissertation in the form of Theorem 1 in Chapter 2.

2. Improving quadratic sliding mode control method with two controllers (2.45), (2.46) and (2.47) for the system without actuator in general. Concurrently, the dissertation has:

- Supplemented the Theorem 2 in Chapter 2 to confirm that this controller brought the system down to slide surface after a finite time period.

- Supplemented conditions so that (2.53) deviation on the slide surface is 0. This conditions has also been deployed in detail in the dissertation into condition (3.15) on control parameter when applied to 3D overhead crane system

3. Particularly for EL system without actuator, namely 3D overhead crane system, the dissertation has developed a super-twisting

mode sliding control (3.30) in Chapter 3 operating on the principle of output feedback. Concurrently, it's showed in the formulae (3.31) that this super-twisting mode sliding control brought the system down to sliding surface after a finite time period.

4. The dissertation has developed a 3D crane laboratory table, connected this laboratory table to computer and tested the quality of this super-twisting mode sliding control in practical environment.

4.2. Recommendations and plans for further studies

Some problems arising during the implementation of the topic that the dissertation has not completed yet will be seen as the problems Ph.D candidate needs for further studies in future. Those are:

1. For Euler Lagrange system without actuator having sustainable freedom subsystem (2.20), it's necessary to develop sufficient condition for selecting parameter vector $\underline{d}$ of ISS adaptive control that corresponding freedom subsystem (2.20) will be asymptotic stability when this subsystem, in the equivalent form (1.22), does not satisfy the condition presented in paragraph 1.1.2

2. During the construction of 3D overhead crane's laboratory table, there is an enough precious angle sensor However, to compact the model while maintaining the accuracy, the research student has set a task to develop a algorithm for observation of crab angle φ_x, φ_y from measured value of joint variable trajectory $\underline{q}$ and its speed $\dot{\underline{q}}$ replacing angle sensors, but this haven't been able to yet.

LIST OF SCIENTIFIC WORKS RELATED TO THE THESIS

Scientific articles

1. Hoang Duc Quynh, Nguyen Thi Viet Huong, Nguyen Doan Phuoc (2013), "Identify the state of bidirectional overhead crane system by discrete KALMAN observer", *Journal of Science and Technology – Thai Nguyen University,* Volume 106, No. 06, pages 15-21.
2. Nguyen Thi Viet Huong, Dao Phuong Nam, Nguyen Doan Phuoc (2013), "Simulation and emulation using state observer in overhead crane system", *Journal of Science and Technology – Thai Nguyen University,* Volume 110, No. 10, pages 27-36.
3. Nguyen Thi Viet Huong, Nguyen Doan Phuoc, Vu Thi Thuy Nga, Do Trung Hai, (2014), "Control of 3-D overhead crane system using sustainable adaptive controller", *Journal of Science and Technology – Thai Nguyen University,* Volume 128, No. 14, pages 35-41.
4. Nguyen Thi Viet Huong, Dao Phuong Nam, Nguyen Quang Hung (2014), "Study and construction of state observer in overhead crane system ", *Journal of scientific research and military technology,* Special issue TĐH'14, 04 – 2014, pages 25-32.
5. Nguyen Thi Viet Huong, Tran Vu Trung, Dao Phuong Nam (2015), "High-order Sliding Approach for Robust control of a 3-D Overhead Crane System", *Journal of Science and Technology of Technical Universities,* ISSN 2354-1083, No. 108, pages 007-011.

Scientific conference report

6. Vu Thi Thuy Nga, Nguyen Thi Viet Huong (2013), "High-quality sensorless for synchronous motor in the entire speed range", *The 2nd Vietnam Conference on Control and Automation VCCA-2013*, Post No. 145, Summary of page 9.

7. Nguyen Thi Viet Huong, Dao Phuong Nam, Nguyen Doan Phuoc (2013), "**S**imulation and emulation of overhead crane", *The 2nd Vietnam Conference on Control and Automation VCCA-2013-2013*, Post No. 31, Summary of page 33.