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REVIEW ARTICLE

NONLINEAR CONTROL STRATEGIES AND PLANNING FOR UNDERACTUATED OVERHEAD CRANES

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ABSTRACT

Underactuated overhead cranes play an important role in engineering and construction, which also make nonlinear control strategies and planning on this basis become the current focus of academic research. Based on scholarly research findings, this paper carries out a theoretical study on nonlinear control strategies and planning for underactuated overhead cranes. To begin with, the underactuated system, underactuated overhead cranes and its nonlinear control are elucidated. Afterwards, the stabilization methods for front actuators are analyzed, and finally two nonlinear control methods are explored in the hope of providing some references for research in related fields.

KEYWORDS

Underactuated, overhead crane, nonlinear control, strategy, planning

1. INTRODUCTION

Underactuated overhead cranes cannot explain that underactuated systems have a narrow scope of applicability. Instead, underactuated overhead cranes are just a trivial example of underactuated systems in actual production. From a shallower perspective, underactuated systems mean that the number of control inputs is fewer than its degrees of freedom. Underactuated systems have been applied in many fields like aerospace and robotics that we are familiar with. As the name implies, a fraction of actuators is unneeded, which have enormously reduced design complexity and saved a portion of manufacturing and installation costs for those actuators from an economic point of view. At the same time, however, we cannot deny the fact that, due to a smaller number of actuators, underactuated systems should have more complicated interior design, thus making it difficult to grasp its design technology. Therefore, while overhead cranes have been an important machine in building design, nonlinear control strategies and planning for underactuated overhead cranes in this regard have become an important proposition. In view of this, standing on the shoulders of our predecessors, this paper has carefully consulted the research findings and reference materials in this respect, based on which a study is performed on nonlinear control strategies and planning for underactuated overhead cranes. Although theoretical statements make up a sizable portion in this paper, research of nonlinear control strategies herein has practical significance because the author has observed the use and operation process of related equipment in reality for multiple times. Hence, this study can provide references for research in related fields, as well as enlightening the manufacturing and transformation of construction equipment.

2. UNDERACTUATED SYSTEMS, UNDERACTUATED OVERHEAD CRANES AND THEIR NONLINEAR CONTROL

2.1 Underactuated systems

An underactuated system refers to a system in which the number of control inputs is fewer than its degrees of freedom. In this case, since its control inputs denote the system's driving force, it has an inadequate driving force. However, this does not mean that underactuated systems cannot operate normally. In contrast, after strengthening the design of other parts, underactuated systems can not only work normally but also save a lot of workload and design and manufacturing costs [1].

Here is a simple example to illustrate underactuated systems, to make the problem clearer:

$$\begin{cases} x = f\,(x, \mu) \\ y = x \end{cases} \text{where}, x \in R^n, \mu \epsilon R^m, 1 \leq m < n$$

Underactuated systems can be traced back to the eighteenth century, when European noted mathematicians Euler and Lagrange began a study of mechanical systems. Euler put forward basic equations of motion of a rigid body, while Lagrange published the famous work *Analytical Mechanics*, which has preliminary laid the foundation for mechanical systems [2]. A century later, Watt, who was renowned for improving steam engines, made a substantial contribution to mechanical systems, as the invention of the steam engine has marked the official birth of the mechanical control system.

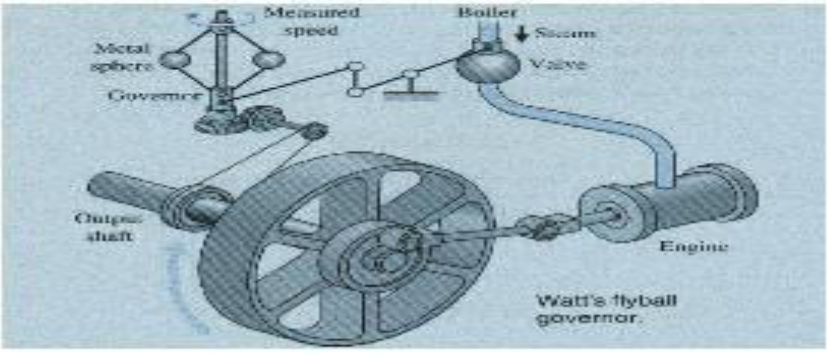

Figure 1: watt invented the steam engine

In the last century, a large number of underactuated mechanical systems began to appear, which have substantially affected human life and production on a largescale. They were used in lunar exploration robots, airplanes, robots, aircraft carriers, and construction machinery and equipment. In the new century, with the further development of human society, nonlinear control of underactuated systems has become a hot issue.

So why systems are underactuated? After making a summary, the author has found these four major reasons. First, it is caused by system dynamics. Because of the entire system design requirements, under actuation is the state that must exist. For instance, the designs of spacecraft, spaceship and helicopters lead to systems with under actuation. Second, in some design and manufacturing process, an underactuated state of the system is provoked deliberately in order to save some expenses or for other practical purposes. For example, some satellites only have two thrusters [3]. Third, the actuators fail. In other words, there are multiple actuators in some designs, and some actuators may not operate normally for various reasons. Fourth, intricate low-order nonlinear systems are created artificially with the purpose of further studying higher-order underactuated system control, such as two-stage inverted pendulum sand ball-beam systems.

We can tell from the above discussions that under actuated systems exist widely in our everyday lives. In actual construction engineering design, we should always consider the economic factor, which is to take measures to improve effectiveness at the lowest cost or reduce cost with maximal effectiveness. Undoubtedly, it is a really challenging attempt to use underactuated systems to reduce the number of actuators so that systems can operate properly [4].

2.2 Underactuated overhead cranes and nonlinear control

An underactuated overhead crane is a brand-new device formed by applying underactuated systems to an overhead crane. When designing such a device, system modeling is generally required, during which the trolley and its load are abstracted as a particle mainly for reducing the complexity of system analysis. Moreover, in practical applications, the quality and flexibility of lifting ropes as an influential factor is neglected in modeling [5]. In accordance with the author's research, there are two major kinds of modeling in underactuated overhead cranes: the simplified model and the expansion model [6].

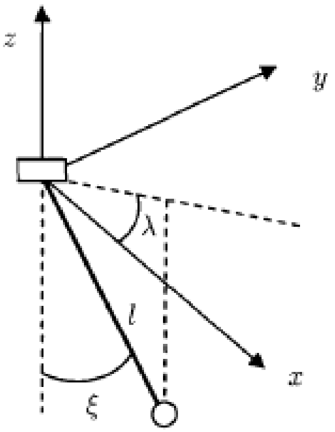

Figure 2: owe drive axle simplified model of the crane

An overhead crane is mainly responsible for delivering goods to specified locations. To achieve this, two standards must be met. First, overhead cranes can have accurate and comprehensive positioning capabilities, so that they can identify the location of the trolley at any time, and this is the basis for overhead cranes to deliver goods at high efficiency. Second, some degree of swing is inevitable in the process of carrying load, which is not a good thing for both safety and quality assurance of goods, so we need to design a system that can effectively control the swing [7].

With the deepening of basic scientific research, nonlinear control strategies have gradually become mainstream in the field of automatic control. A large number of scholars shift the research emphasis from pure science to nonlinear control strategy applications that connect with practice, so it has become a critical issue regarding how to apply nonlinear control strategies in overhead cranes to enhance their performance.

3. STABILIZATION OF UNDERACTUATED SYSTEMS

An underactuated system is essentially a nonlinear system, because if asset point in the model linearizes it, the whole system cannot be controlled by designers. We know that in the smooth, unchanged steady-state, no feedback stabilization law will be able to put an underactuated ship in its equilibrium point. Of course, the ship necessarily refers to the one on the water surface [8]. Hence, the current nonlinear control theory cannot directly address the stabilization problem of underactuated ships in real life. Therefore, overhead cranes as a variant to the stabilization problem of surface ships are bound to be solved by new tools and methods.

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First, this problem can be tackled by using the non-continuous feedback control law, which lets the whole system gradually converge to the equilibrium point. Usually we can use σ constructor to complete this process. Since it is relatively simple and commonly used, it is not described in detail due to the limited space.

Second, this problem can be tackled by the continuous time-varying feedback stabilization method, which is composed of two types: smooth and non-smooth. For the former, there are two specific implementation techniques: the average and backstepping methods. They have an advantage of being able to connect with practice at a higher level, thereby making it easier to realize the theory [9]. However, this technique is generally complex in the design phase. When using the backstepping technique, we can first construct a function and design the periodically time-varying feedback control law, then the system can be stabilized gradually.

In addition, we can also blend the average and backstepping methods when applying the continuous time-varying feedback stabilization method. This is also to construct a special function. On this basis, the overhead crane control system index is converged within the arbitrarily small adjacent area around the original point. When using the backstepping method to design the overhead crane control system, actions must be taken which are sensitive to outside reactions, but for external interference factors including magnitude and scope which we have no idea about, we can adopt a self-adaptive control method. The final results show that the system state will not vary with the addition of the self-adaptive control methods.

3.1 Nonlinear control strategies for underactuated overhead cranes

When controlling the trajectory of an underactuated overhead crane, the most difficult point is that the system that we study, and design is underactuated. That is to say, we do not create an underactuated system in compromise to the objective environment but take the initiative to do that; the equation of motion of overhead cranes is essentially nonlinear, and there are many factors affecting overhead cranes in motion, most of which are external factors. These have exerted a great influence on the system design. In the design process, we need to always grasp the system status, so that we can evaluate its entire effect and proceed to the next stage of work. Nevertheless, the result turns out contrary to expectations: when investigating nonlinear control strategies for underactuated overhead cranes, we can only understand the system state through noise detection, while we do know not all of the system state; before designing an underactuated system, we need to research the chain system, and that cannot be directly applied in subsequent underactuated systems [10]. For the present study on nonlinear control of underactuated overhead cranes, two methods are worth learning, one is backstepping and the other is differential smoothing.

3.2 Backstepping

Backstepping corresponds to a nonlinear system, and this system is linked together by the integrator. Therefore, we can take the Lyapunov function for the first subsystem and add quadratic terms to the state variables of the second sub-system, thus forming an initial structure of the system.

Backstepping is often used to handle the stabilization problem for underactuated systems. Through a given system state equation, it sets virtual control and constructs the appropriate Lyapunov function to obtain the control law. The controller designed by using the Backstepping technique is well traceable, adjusts time quickly, responds to system without overshoot, has not only choice of controlling the Lyapunov function or the control law and is suitable for online control. However, it needs to calculate huge amounts of data, so is complicated [11].

$$\begin{cases} x_1 = f_1(x_1) + x_2 \\ x_{2=}f_2(x_1, x_2) + x_3 \\ x_{3=}f_3(x_1, x_2, x_3) + \mu \end{cases}$$

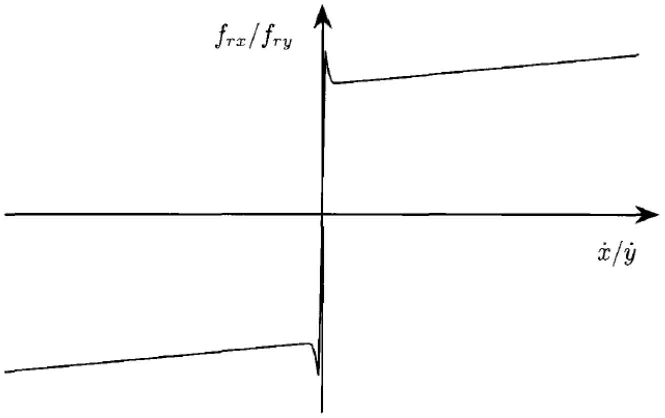

Figure 3: Friction relationship with the vehicle speed

Equation structures which are similar to this one is called the feedback structure. That is to say, the coefficient before each independent variable must be relevant to all independent variables before. Essentially the core idea of this design method is to regard each independent variable uncontrollable to coefficients in each subsystem of the system as virtual control, and then the system can reach a steady state in the process of determining reasonable virtual control, and then the so-called equilibrium point can be attained. Due to some legal shortcomings of the traditional structure, often an error variable must be introduced in order to achieve the stability of the whole system [12]. In this sense, backstepping substantially can implement the design process from front to back and connect state coordinate changes and other relevant parameters in every design step, and the algorithm can be optimized in the design process so as to realize the stabilizing controller.

From another perspective, virtual control in backstepping is to apply the static compensator theory in this field. In this system, subsystems in the front are controlled by those in the back, and only through such control can the intended objective of the entire control system be achieved. A reasonable virtual controller can eliminate the influence of uncertainty in large part. Therefore, it also brings massive changes to non-linear control.

3.3 Differential smoothing

Simply put, if we can find an output set in a system and its dimension number is equivalent to the system input number, and all system states and inputs can be denoted as output functions without no need of integral calculation, the system can be handled by differential smoothing. In mathematical language, it is expressed as:

Set the system status $x \in R^n$. If input $\mu \in R^m$,we can find the corresponding output $y \in R^m$, in the form $y=y$ ($x, \mu, \mu, \ldots, \mu^{(p)}$, which meets $x=x$ ($y, y, \ddot{y}, \ldots, y^{(p)}$, $\mu=\mu$ ($y, y, \ddot{y}, \ldots, y^{(p)}$.

Then the system can be handled by using differential smoothing.

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In nonlinear control system design, using a highly precise explicit method is different from conventional thinking. For a very long period of time, it was an effective and highly efficient approach. However, the conditions for linearization are pretty harsh, and its precision requirement stops plenty of designers in the design process. Thus, people begin to consider whether they can improve the relative order by some means, so that more state components can be linearized on the original basis, and eventually the whole structure system can be streamlined. In view of this demand, differential smoothing came into being.

The differential smoothing method can be applied to nonlinear systems that can generally be converted in to a generally integrator. From another perspective, differential smoothing is an important process of dynamic feedback linearization. Almost all systems have to go through this process when implementing dynamic feedback linearization. For now, differential smoothing is mostly employed in the industrial sector, such as following systems installed in automobiles and satellites. However, in these applications, we need to understand that the smooth output is a more complex variable, and it is not made up by a random combination between configuration and speed of the entire system. The core of differential smoothing is smoothing. Taking advantage of this feature, the equivalent expression for the nonlinear control model of underactuated overhead cranes can be determined. Then, after dynamic feedback linearization, the entire system can be decomposed into two linear systems that are controlled by certain mechanisms.

4. CONCLUSION

Underactuated overhead cranes play an important role in industrial construction, and the control strategies for cranes are directly related to whether they can work properly and are safe enough during operations. Hence, this paper analyzes nonlinear control strategies and planning for underactuated overhead cranes, hoping to supplement research in this regard and also provide some references for later researchers.

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