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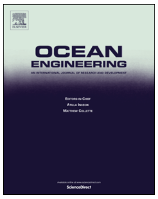

Model-based control designs for offshore hydraulic winch systems ☆

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ABSTRACT

Model-based control designs have an advantage in controlling complex systems, and in assuring global system stability, in comparison to ordinary linear controllers such as PID controllers. This paper attempts to promote the use of model-based control designs in industrial applications, particularly in the marine system industry. A simple pendulum system is used as an example help to compare a backstepping sliding mode controller with a PID controller, and to display the main steps in deriving such a model based control design in a consistent manner, and to highlight the benefits using model-based control laws in comparison to standard PID based control laws. The results from this example indicate that the model based controller is barely affected by changes in system parameters in comparison to the PID controller which must be retuned each time the system parameters are changed. This indicates that a lookup table of controller gains and interpolation is needed if a PID controller is to be used for controlling a system with changing system parameters and/or highly nonlinear dynamics. Furthermore, an offshore hydraulic winch system is used as an in-depth case study in which the system is thoroughly analyzed. Based on simple fluid dynamics, mechanics and dynamics in general, a simplified state space model, but a highly nonlinear model that only describes the main characteristics of the hydraulic system is developed and used in the derivation of a speed controller and a torque controller for the hydraulic winch system. A process plant model describing the hydraulic winch system, together with a lumped wire-load model, is used in simulations to test and verify the derived control laws, which seem to be well-suited for controlling the hydraulic system. Based on the observations and results obtained in this work, it is indicated that a PID controller would not be able to control the hydraulic winch system with a large stability region, as well as a model-based controller, if a huge amount of work was not done in tuning and making lookup tables and interpolation algorithms for controller gains. This argues for the use of model-based control designs in industrial applications containing nonlinear dynamics and/or varying system parameters.

1. Introduction

Model-based control designs and advanced control algorithms have been developed and studied in the academic field of control for several decades, and the advancement of control designs has been propagated along with the technological development of computers. However, model-based control designs have not been fully adapted from academia to the marine industry, even though the performance of model-based controllers usually exceeds the performance of standard controllers, such as PID controllers. Model-based control designs are usually only considered in the industry when the objective is to control highly nonlinear dynamical systems operating in a wide range, and not just close to a preset reference point, since the stability region in such systems when using a linear control law would be limited. Examples of such applications can be found in both the aerospace industry and guidance and control applications.

In the marine industry, more advanced control designs have been applied to guidance and dynamic positioning, DP and control of marine vessels, but have not been fully utilized in the industry supplying inboard systems such as winch systems. In general, the marine industry is good at analyzing the systems dynamics, which is done in the design process when creating new products. Since this dynamical analysis of the system is already being carried out within the industry, resulting in knowing the main dynamical characteristics of the system, it is often less work to design a model-based control law than merely tuning a simple linear control law and guaranteeing stability in all relevant cases, especially if the system contains some nonlinear dynamics which are

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☆ Based on the master thesis Skjong (2014).

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usually present in real systems.

This work aims at promoting the use of model-based control designs in the industry, and to highlight some of the primary benefits such designs have in comparison to ordinary control laws. This is done through an example that compares a model-based control design with an ordinary PID control law. In particular, this paper focuses on the backstepping sliding mode control design (Zihober and Rios-Bolivar, 1994), because of its robustness, while a hydraulic winch system for offshore operations is used as an in-depth case study. One of the reasons for choosing a hydraulic system is that it often includes highly nonlinear dynamics due to nozzles, hydraulic losses and compressibility, which in general is difficult to control by standard PID-based control laws. In general, the marine industry has lots of examples of systems showing nonlinear dynamical characteristics, e.g. marine vessels including propulsion systems (Yum et al., 2016; Rokseth et al., 2016; Pedersen, 2012), marine power plant systems (Pedersen and Pedersen, 2012; Bo et al., 2015) and main engines (Aesoy and Pedersen, 2011), crane systems and manipulators (Rokseth and Pedersen, 2014; Rokseth et al., 2016), top tensioned risers (Rustad and Larsen, 2008) and hydraulic power systems as the one presented in this paper. The performance of such systems would highly benefit from the use of model-based controllers, as will be indicated in the case study, which is good candidate for representing nonlinear dynamical characteristics in the field of marine engineering. Hence, the promotion of the use of model-based control designs in the marine industry will be emphasized through the procedure of deriving model-based control laws and through the study of the resulting simulation results.

The robust model-based control design used in this paper, which includes both sliding mode and backstepping control techniques, has been applied to various systems in the literature, for example in relation to controlling pneumatic systems (Smaoui et al., 2006; Lu et al., 2010), robust control of a hydraulic driven flexible arm (Li and Khajepour, 2005), control of induction motor drives (Shieh, 1999), tracking control objectives (Davila, 2013; Swaroop et al., 2000; Lu et al., 2011), controlling quadrotors (Bouabdallah and Siegwart, 2005) and hydraulic valve control (Choi, 2011). However, a stepwise procedure of developing such a control design is not often given in the literature, and the designs may vary quite a bit. This is mostly because model based control designs are based on general ideas, e.g. such as canceling unwanted dynamics, which is hard to generalize. Nonetheless, this paper attempts to display the main steps in deriving a backstepping sliding mode control law through examples and the in-depth case study in a consistent manner.

The most basic control theory used in this paper will not be explained in any detail other than through the case study, and the reader is instructed to read the given references when suitable. However, the example and the case study presented in this work shows how the control theory is used to derive the model-based control design, which is also quite applicable to other systems. This is, because the ideas behind the model-based controller are quite general and clearly presented in the literature. Even so, much focus will be given to the development of the simplified state space model describing the hydraulic winch system. The reason for this is because it is often harder to develop a good control plant model of a physical system than to develop a model-based control law, and the capabilities of the derived control law highly depend on it. Also, it is easier to see the benefits of the derived control law by looking at simulation results when understanding the system dynamics and the simplifications made when deriving the control plant model.

This paper starts by presenting model-based control designs in general with a primary focus on backstepping and sliding mode control theory, with a simple example showing the performance of a backstepping sliding mode control law compared to an ordinary PID control law. Next, the hydraulic winch system is presented, and a thorough analysis of the main dynamics in the system is performed in order to derive a control plant model. This model is subsequently used to derive suitable control laws for controlling the hydraulic winch system, and two simulations are performed in order to test and verify the derived control laws using the process plant model of the hydraulic winch system it is derived from (Skjong, 2014).

2. Model-based control designs

Model-based control designs are categorized as control designs derived based on the system dynamics for a system to be controlled. The derivation of the control law is often done through stability analysis such as Lyapunov stability analysis of the system, which also assures stability of the controlled system when using the derived control law. In general, model-based control designs are characterized as state of the art in the field of control because such controllers are tailored for specific systems and control objectives, which is hard to generalize. However, when deriving model-based control laws, there exists many design strategies that can be utilized in order to obtain a suitable control law for a given control objective. Two such strategies are sliding mode and backstepping.

Sliding mode and backstepping control designs are characterized as advanced nonlinear control law designs and are known to be state of the art, among other control laws, in the field of control. Sliding mode control law designs can be used to control most systems in comparison to backstepping control designs which have their strengths in canceling dynamic effects in a system when a state is implicitly controlled, e.g. position control in a pendulum system in which the controller gives a force as input to the controlled system, thereby implicitly affecting the acceleration and position. According to Khalil (2002), sliding mode control designs are robust control designs that force trajectories to reach a sliding manifold in finite time and stay on the manifold for all future time. A sliding mode controller is also designed to achieve the control objective, even though a lower order control model is used to describe the process.

Both sliding mode- and backstepping control designs are model-based control designs and are tailored for their purpose. However in general, sliding mode control designs provide nice convergence properties, and the backstepping control designs provide a nice canceling of unwanted dynamic effects in a controlled system. If a system is implicitly controllable, it is possible to deploy both sliding mode and backstepping control theory into one model-based control law that has the nice properties of both control strategies, which also increases the robustness of the control law (Zihober and Rios-Bolivar, 1994). Both backstepping and sliding mode control theory are thoroughly treated in Khalil (2002), and will not be given more of a focus here.

A nice property of model-based control designs is that the controller gains often tend to be independent of system parameters since the model parameters are included in the control law. This means that one tailored control law can be used in the industry to control a range of dynamical systems as long as the form of the differential equations describing the system are equal, meaning that only system parameters may be different. This is quite useful for a vendor that sells a product in different sizes, since the controller does not need to be retuned for each product size. This is illustrated in the following example, in which a backstepping sliding mode control law is used to control the angle of a simple pendulum, and is compared to an ordinary PID control law.