Computers and Electronics in Agriculture 109 (2014) 36–45

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Nonlinear model predictive control of hydraulic forestry crane with automatic sway damping

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ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 27 August 2014
Accepted 14 September 2014

Keywords:
Anti-sway control
Path tracking
Hydraulic systems
NMPC

ABSTRACT

Forest machines are used in many tasks and come in various designs. They can be used for cutting down trees, collecting logs and in different forest cleaning operations. Currently, in the commercial machines the level of automation is still relatively low, and they require a professional operator for good work efficiency. Nonlinear model predictive control (NMPC) is an optimal control strategy based on a dynamic model of the system. NMPC algorithms require quite a lot of computational power, but are becoming a more viable option as the performance of computers has increased. We demonstrate how an NMPC can be used for controlling a hydraulic forestry crane that has a freely hanging tool or processing head attached. The goal of the control is to follow a predefined path while simultaneously damping the undesired oscillations of the tool. Three different reference paths with velocities of 0.5 m/s to 1.0 m/s are tested. The average tracking error in these tests is between 0.02 m and 0.11 m. Anti-sway control can reduce the amplitude of sideways oscillations between 2% and 64% and longitudinal oscillations between 59% and 76%. The impact of anti-sway control on the tracking accuracy or the velocity is negligible.

1. Introduction

Forest machines are efficient machines that can do many of the operations required in silviculture. For many decades, forestry machines have been used in the Nordic countries for felling and cutting trees and transporting them from the forest. These machines are usually called forest harvesters and forwarders, respectively. With the goal to mechanize the operations even further, new forest machine concepts for nontraditional tasks have been developed (Hallongren and Rantala, 2012). As current machines require an experienced operator for efficient work and driving the machines is demanding, introducing more automation in to forestry machines could be a logical step. Hellström et al. (2009) discuss the feasibility of autonomous forest machines and state that the main motivation is to increase the productivity in forestry. However, Billingsley et al. (2008) note that forestry is a demanding area for robotics.

One way to automate forest machines would be to automatically control the boom of the machine. Mettin et al. (2009) suggest that taking advantage of the kinematic redundancy of a forestry crane in path planning and control can speed up the motions of the boom when compared with the motions generated by the operator. Hydraulic forestry logging crane has been controlled with individual joint PID-controllers by Ortiz Morales et al. (2014). They report an average Euclidean error of 0.028 m in closed-loop control. They have also tested the accuracy of the control when no feedback from the position of the boom is available.

Generally, the goal of anti-sway control is to reduce the swaying of the load that the crane is lifting. Anti-sway control can be used in manually operated machines to help the user or as a part of automatic control of cranes. It has been studied for example in connection with gantry cranes (Sorensen et al., 2007) and large harbor cranes (Neupert et al., 2010). However, to our knowledge, implementations of anti-sway control in hydraulic forestry cranes do not exist.

In this paper, we are using nonlinear model predictive control (NMPC) to accomplish the boom control. NMPC is a control strategy based on solving an optimal control problem sequentially on-line. This is a so-called moving horizon control, where each time only the first control signal is actually implemented (Allgöwer and Zheng, 2000). The optimization is then repeated once new measurements have been received. The optimization is based on minimizing a given objective function that usually has quadratic costs on state and controls compared to reference trajectories.

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http://dx.doi.org/10.1016/j.compag.2014.09.006
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What makes NMPC attractive is that it can take into account possible constraints in control and state variables. As the name suggests, the future state of the system is predicted. Therefore, the controller does not only take into account the current state but also the future states when calculating the optimal control trajectory. The prediction is based on the dynamic state-space model of the system in question. However, NMPC requires quite a lot of computational power. This makes it difficult to achieve high control rates and long prediction horizons for complex systems.

Schindele and Aschemann (2011) have used NMPC to control an overhead traveling crane on a small-scale test-rig. The sampling time was 10 ms, and the length of the prediction horizon was 140 steps, which equals 1.4 s. They use only the final state error in the objective function. Vukov et al. (2012) also used NMPC to control an overhead crane with a prediction horizon of only 12 steps. In their test, the worst case execution time was 1.1 ms, which is significantly lower than the 10-ms sampling time that was used.

The objective of this research is to study the viability of NMPC for controlling hydraulic forestry crane with a freely hanging tool attached. Another objective is to test how much an anti-sway control damps the oscillations and whether it has an adverse effect on the accuracy of the control. Tests utilizing a hydraulic crane, with a few different control trajectories and velocities, will be conducted.

The rest of the paper is organized as follows: Section 2 presents the methods and models that are used. Section 3 presents data from the actual tests and discusses these results. Some final conclusions will be drawn in Section 4.

2. Methods

2.1. Hardware

A Kesla 305T forestry crane that is designed for loading tree trunks was used in this research. The crane was fixed to a modified Valtra T132 agricultural tractor providing the hydraulics. The forestry crane has four controllable degrees. These four joints are called slew, lift, transfer, and extension. All of them are actuated by hydraulic cylinders. The whole research platform is shown in Fig. 1.

The hydraulic valves of the tractor are controlled via the ISO 11783 CAN bus. The hydraulic valves are regular load-sensing Sauer Danfoss PVG 32 valves used in commercial agricultural tractors. The load-sensing hydraulic system controls the pump so that the hydraulic pressure is at a level slightly higher than the maximum pressure measured from each of the active hydraulic lines. The pressure difference over each hydraulic valve is kept constant. Ideally, the load sensing makes the system insensitive to changes in load, and a constant control of the valve will cause a constant cylinder velocity regardless of the load or external forces.

Fig. 1. Test platform consisting of an agricultural tractor and instrumented forestry crane. A freely hanging arm with a mass at the end is attached to the tip of the boom to simulate a tool.

The hydraulic valves are connected to the crane via a hydraulic block that has shock valves to protect the crane against pressure shocks and overloading situations. The block has suction valves to prevent suction of air to the hydraulic system and cavitation whenever there is large negative load in the direction of the movement.

Fig. 2 shows the different hardware components installed to enable automatic control of the boom. All degrees of freedom of the boom were instrumented. The slew angle was measured directly with a magnetic sensor. The lift and transfer cylinders lengths were measured with magnetostrictive sensors. The length of the extension boom was measured with a draw wire sensor. The sensors were connected to two separate electronic controller units (ECUs) for processing, filtering and transmitting the data.

The swaying of the tool attached to the tip of the boom was measured using two sets of gyros and accelerometers. One of the sets was installed at the tip of the boom and the other one on the tool. Two swaying angles, one rotation angle and angular velocities of the tool were estimated using an extended Kalman filter (EKF) (Kalmari et al., 2013a). The EKF was running on an ECU installed on the tip of the boom. The measured crane and tool angles were transmitted from different ECUs via a separate measurement CAN bus installed on the boom. Position and velocity messages were sent at the rate of 100 Hz.

2.2. Software

Two different programs were used during the tests: a controller program and a user interface program. The controller program included the main control loop running at 10 Hz. At each control step, the controller program read the inputs from the measurement CAN bus, runned the filters and, using the NMPC solver, calculated the outputs and then sent the hydraulic valve commands to the ISO 11783 CAN bus. The user interface program was used to visualize the current state of the machine to the operator, allow to tune the parameters, select the reference path and start the automatic control sequence. The controller and user interface programs ran on a laptop computer with a Core i7-3820QM processor and 8 GiB of memory. The operating system was 64-bit Ubuntu 12.04.

A toolkit called VIATOC (Kalmari, 2013) was used for generating a solver in C code for a given control problem. Its optimization is based on a gradient projection method of Rosen (1960) that has been modified to use a Barzilai–Borwain (Barzilai and Borwein, 1988) style step length selection. Matlab Simulink was used for connecting the developed filters and the NMPC and calculating the required kinematic transformations. C code exported from the Simulink model was included in the controller program.

2.3. Kinematic model of the crane

The crane has four degrees of freedom and the swaying tool has three joints. These joints and the base coordinate system can be seen in Fig. 3. Of these altogether seven degrees of freedom, only the first six are of interest in this study. The last joint, the rotator, should only be taken into account if an unsymmetrical tool is used to perform a given task. In this paper, we are using the tip of the boom as the point that is controlled relative to a reference path. To calculate the position of the tip of the boom relative to the base coordinate system only the first four joints are required.