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ISO 11783 Compliant Forest Crane as a Platform for Automatic Control

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Abstract: ISO 11783 is a communication standard for agricultural and forest machines. This standard allows an implement to command specific functions of a tractor. Agricultural tractors can be equipped for silvicultural work forming small scale forest machine. It could cost-efficiently compete against common forest machines in some tasks. We have developed an ISO 11783 compliant forest crane connected to an agricultural tractor. The combination is designed to work as a test platform for an autonomous forest machine. The dynamics of the system have been studied using first and second-order models. Based on identification tests with no load on the crane, first-order model is sufficient for describing the motion of most of the cylinders. According to the identification results, small controls do not cause motion on the crane, and a non-linear model is required. Currently used hydraulics of agricultural tractors is not entirely adequate for controlling forest cranes. With more intelligent tractor hydraulics, the crane could be more controllable and energy-efficient.

Keywords: identification, hydraulic systems, ISO 11783, forestry, agriculture

1. INTRODUCTION

Forest machines are expensive and complex machines. Traditionally they have been used to harvest and collect trees, but the interest in using them in other silivicultural tasks is increasing (Hallongren and Rantala, 2012). Forest machines are designed to be operated by a professional and lots of effort has been put to increase productivity. The development has led to very expensive and large machines. Most of the silvicultural work is nowadays done using only these large machines. Instead, some silvicultural operations could also be as well done with smaller scale machines. Demand for cost-effectiveness is high and lowering the total costs and increasing the working efficiency are always significant goals.

There are already some agricultural tractors that are used for small scale forestry or forest management operations with additional forest crane implements. The adoption of small scale forest machines could be increased in many ways. One such way is an ISO 11783 compliant forest crane presented in this paper. Second one is to automate part of the work of the operator. In this paper, the forest crane is instrumented and later controlled using a computer to automate some of the operator's work. The ISO 11783 compliant forest crane can also lower the total cost of the system as the hydraulics of the tractor can be used to control the implement.

ISO 11783 is an international standard that specifies a data network for agricultural tractors and forest machines. The goal is to standardize data transfer between and within a tractor and implements that are mounted to or towed by the tractor (ISO, 2009). Tractors that are tested and obey the standard are usually called ISOBUS compatible. The standard makes it possible for the implement to command, for example, the driving speed of the tractor and to use the tractor's hydraulic valves.

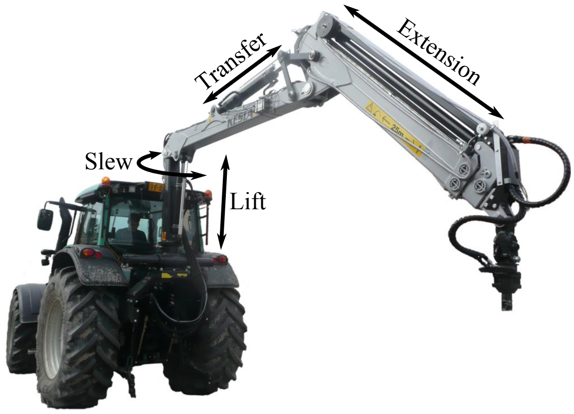

Fig. 1. Tractor and crane used as the platform.

ISO 11783 is widely adopted in the agricultural tractors and implements, but to our knowledge there are no forest machines that are compatible with the standard. However, there are agricultural tractors that are equipped with a forest crane and are capable of doing some silvicultural tasks. These cranes have traditionally been equipped with their own hydraulic valves. These cranes are not ISO 11783 compatible and do not yet use any features provided by the tractor. If the hydraulic valves of the tractor were used, the currently used valves could be left out. Leaving out the crane's own valves would naturally bring some savings.

To increase the working efficiency of the small scale forest crane, one solution is to automate the work. Increasing the level of automation is usually quite challenging. For example, Billingsley et al. (2008) state that forests are a demanding environment for robots. To study autonomous work in forests, it is therefore first relevant to study semi-autonomous forest machines. The aim in this study is to enable the use of ISO 11783 compliant forest crane in an autonomous forest machine. We have built a research platform for the task using an agricultural tractor and a forest crane. By using ISO 11783, it is straightforward to command valves of the tractor and transfer information between the tractor and the implement. Our platform, which is depicted in Fig. 1, consists of a tractor based on Valtra T132 with some modifications. The hydraulic forest crane is Kesla 305T designed for loading tree trunks.

Automatic control of the crane requires closed loop control over ISO 11783 network, which presents some challenges. Oksanen (2010) states that there are a number of parameters of the hydraulic system that can vary between different tractors. These parameters are the process gain, nonlinearity and parameters of the dynamics. As ISO 11783 does not support requesting these physical parameters, Oksanen proposes a procedure for human driven identification. However, he states that identification and adaptive control in changing conditions are very challenging. In this paper, we present an identification method and model nonlinearities in ISO 11783 compliant forest crane implement which is instrumented for automatic control. We also discuss the shortcomings of the current tractor hydraulics when used with a forest crane.

2. ISO 11783 COMPATIBLE FOREST CRANE

The ISO 11783 presents different classes that state what parts of the standard a tractor must implement (ISO, 2012). Currently there are three levels: Class 1, Class 2 and Class 3. There are also different letters (F, G, M, N and P), telling which extra functionality the tractor supports. For example, the letter N tells that the tractor transmits GPS-messages in to the implement bus. Tractor that has Class 1 or 2 capabilities only sends some measurements to the CAN bus. Class 3 makes it possible for the implement to actually command the valves of the tractor.

Fig. 2 shows the network structure and the main components required to make ISO 11783 compatible combination of tractor and forest crane. On the tractor there are two buses: tractor bus and implement bus. The implement bus is the key component defined in the standard that makes it possible to make an advanced implement using the capabilities of the tractor. The operator uses virtual terminal and auxiliary inputs to actually control the crane. The forest crane related computations are done in an implement ECU (electronic controller unit). The implement ECU forwards user requests to valve commands via tractor ECU to auxiliary valves.

An ISO 11783 compatible tractor can have up to 16 auxiliary valves (ISO, 2009). In Fig. 2 the hydraulics valve commands are directed via the tractor ECU. On a class 3 tractor the valves are not usually directly connected to the main implement network due to safety reasons. Thus, the valves are placed in the figure on a separate tractor bus. The ISO 11783 standard does not give any strict orders how the auxiliary valves should be connected to the implement bus.

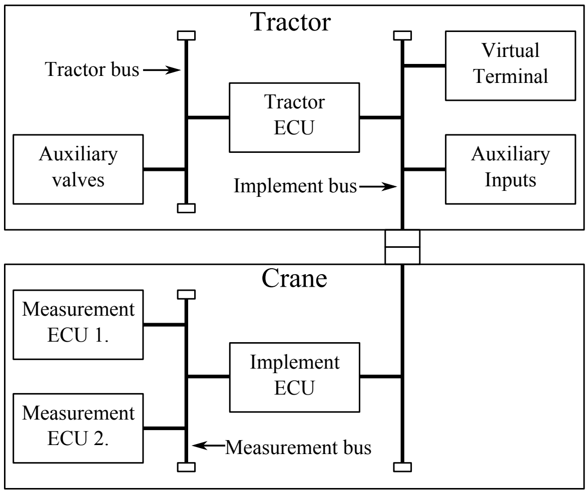

Fig. 2. ECUs and networks of the proposed ISO 11783 compatible crane. Adapted from ISO (2011).

A virtual terminal (VT) is a graphical display used for presenting data to and receiving input from the operator (ISO, 2010). The idea is that instead of having a separate display for every implement, a common standardized display can be used. User interface, called object pool, is loaded from the implement ECU to the tractor's VT using standardized protocol. When the pool loading is ready, the operator can command the implement using VT. As the VT has only few push buttons, we have used it only to set some parameters like pairing of valves and cylinders and setting maximum valve openings. Controlling the crane using only binary buttons of the VT would be too difficult.

An auxiliary input device gives the operator the possibility to control the implement independently of the VT (ISO, 2010). According to ISO 11783 standard, auxiliary input devices can have a wide range of different binary and analog buttons and dials. In our system there are two joysticks that are used as auxiliary controls. In Fig. 2, the auxiliary input device is connected directly to the implement network. Again, the actual location of the auxiliary input device in the networks is not clearly stated in the standard.

2.1 Hydraulics

Forest cranes usually use valve boards that are specially designed for them. In case of cranes that are used as implements to agricultural tractors, the valves are situated on the crane and only the controls are in the tractor. A second hydraulic pump is often used to ensure adequate flow of hydraulic fluid. The cranes have asymmetrical hydraulic cylinders and therefore the flows going in and out of the cylinder are unequal. To compensate for the asymmetry of the cylinders the spools of the valve should be asymmetrical (Viersma, 1979).

The hydraulic cylinders of a forest crane can receive impacts that cause pressure shocks on the hydraulic lines and valves. To prevent such overloading situations, each valve is typically protected with a shock valve with a predefined pressure level. The load can overrun in situations where there is a large force affecting in the direction where the cylinder is moved. The overrunning of the load can cause suction of air into the system or cavitation. Air bubbles sucked through the gaskets of the cylinders cause elasticity and thus oscillations in the hydraulics. Cavitation can cause local high pressure peaks causing damage to the hydraulics. Suction valves that provide oil directly from the tank in a low pressure condition prevent the suction of air and cavitation. A one-way restrictor valve or a counterbalance valve can also be added to prevent load overrunning.

Agricultural tractors have general-purpose valve boards with symmetrical spools. Symmetrical spools can cause unnecessary pressure losses, and thus decrease the energy efficiency. The valves are not equipped with shock valves and there are no suction valves. Without these valves, there is a risk of damage and worse controllability of the system.

Load sensing hydraulics is common in forest cranes. Also the agricultural tractor used in our tests has a load sensing system using Sauer Danfoss PVG 32 valves. The basic idea of the load sensing system is that only the needed amount of flow and pressure is generated with the hydraulic pump. The pressure level that the pump will generate is determined by measuring the maximum pressure of all the ports plus some predefined margin. Each valve is fitted with pressure compensator that keeps a constant pressure drop over the spool of the valve even if the current pressure level is too high. If a constant pressure drop over a spool is achieved, the flow is only dependent on the opening area, not the actual load on the cylinder (Sauer Danfoss, 2012). Load sensing hydraulics bring energy savings compared to constant pressure systems, where the pump always creates a predefined pressure level. Controlling hydraulic cylinders and motors on load sensing system is also easier as the load will not make so considerable effect on the outcome.

2.2 Crane Instrumentation

The combination of the tractor and the forest crane presented is designed as a research platform for autonomous forest machine. Automatic control of the boom requires instrumentation of every joint of the crane. Instrumentation is also required for the identification of model parameters discussed in the following sections.

The crane itself has four degrees of freedom that are called: slew, lift, transfer and extension, which are shown in Fig. 1. The slew angle is measured using a magnetic sensor that is directly taped onto the slew mechanism. The length of the lift and transfer cylinders are measured directly with magnetostrictive sensors. The length of the extension is measured with a draw wire sensor. With the exception of the incremental sensor measuring the slew angle, all the other sensors measure absolute length. Magnetostrictive sensors installed on the lift and transfer cylinders can be seen in Fig. 1. The tool attached to the boom can also have some degrees of freedom that should be measured in a fully autonomous forest machine, but currently we are focusing only on controlling the boom. The measurements were delivered from the instruments to the implement ECU through two measurement ECUs (see Fig. 2).

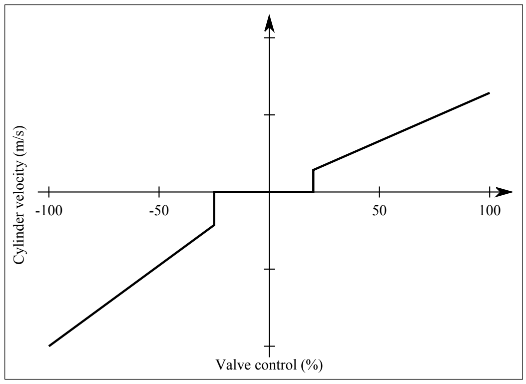

Fig. 3. Model of the nonlinearity between the control value and the actual velocity of the cylinder.

3. METHODS

On an ISO 11783 class 3 compatible tractor, the hydraulic valves are controlled using a command that states the requested flow as a percentage of the maximum flow that the valve can deliver (ISO, 2009). If the characteristics of the valve are not known beforehand, there is no way knowing what is the actual flow and the cylinder velocity that the flow causes. The characteristics of the other hydraulic and mechanical parts connected to the valve can also affect the outcome. Automatic control of the boom requires that there is a model that defines the dynamics of the system in simple but fairly accurate way. Therefore, we have created a model to describe the system and done identification tests to define the parameters for each of the individual valve-cylinder pairs.

Our model consists of two parts: dynamic model and the model describing the nonlinearity. As stated earlier, the hydraulic cylinders have different areas on different sides of the piston. If the spool of the valve is symmetric, this will cause the cylinder shaft to move at a different velocity in different directions. During the tests we found that small controls did not always cause any response. Saturation, where the velocity of the shaft does not increase after a certain point, can happen if the pump cannot generate enough flow. Saturation was left out of the model as it was not encountered during the tests. Fig. 3 shows the nonlinearity model. In total of 6 parameters are used in this model.

The control sequence used in the identification is a triangle wave with a flat top and bottom parts. Square waveform was not used as it might cause too high accelerations in the crane and pressure shocks in the hydraulic system. Examples of the control sequence are depicted in Fig. 5. The nonlinearity parameters are estimated using only the parts where the controls and velocity of the cylinder are nearly constant. After the nonlinearity model is known, the whole data is used for estimating the dynamic parameters.

In reality, the control cannot cause the system to react immediately. There is always some sort of dynamics in the system. Eriksson et al. (2009) use a first-order lag and integrator plus delay (FOLIPD) to describe the dynamics of an auxiliary valve and a hydraulic cylinder on ISO 11783 compatible tractor-implement combination:

$$G(s) = \frac{K_v}{s(1 + sT_F)} e^{-sL}. \tag{1}$$

In our formulation, the nonlinearity model captures the negative and positive gains of the system, and the gain term K_v is not required. As we want to capture the dynamics between the control and the velocity of the cylinder the integrating term is left out. Only two parameters, lag L and time constant T_F , are required to define the dynamics:

$$G_1(s) = \frac{1}{1 + sT_F} e^{-sL}. \tag{2}$$

We could also use a second-order model to describe the dynamics of the hydraulic system. There are flexible parts that act as springs and damping parts that will brake the motion. Elasticity is caused by bending of the crane boom, compression of the hydraulic fluid, flexing of the hydraulic hoses and the tires of the tractor. In some cases, a second-order model is also utilized to describe the dynamics of the spool of the valve (Mettin and La Hera 2005). The parameters of the second-order model are the damping ratio ζ and the natural frequency ω. We assume that the asymmetry of the cylinder does not affect significantly these parameters. Again a delay term L is added because of the delays caused by the electrical buses. Thus the following equation describes the second-order dynamics:

$$G_2(s) = \frac{\omega^2}{\omega^2 + 2\zeta\omega s + s^2} e^{-sL}. \tag{3}$$

Higher order dynamics could also be utilized. For example a third-order model combined of a first-order model for the valve dynamics and a second-order model for the dynamics of the hydraulic system might be intuitive. However, increasing the model complexity is not always a good idea as overfitting should be avoided.

The identified dynamic parameters can be used to design controllers for individual cylinders. Eriksson et al. (2009) propose a PID-controller that can be easily used after the first-order model parameters are known. The actual controllers developed to control the crane are not discussed further in this publication.

4. RESULTS

Identification of the model parameters of the cylinders were done individually, i. e. the cross effects of the cylinders were not studied. The following results were obtained when the crane had no load. Tests with a heavy swinging load were also conducted, but these results are not presented.

The identification procedure was started manually for each cylinder, but the actual control sequence was generated by a program running on a laptop computer. The same program also saved the cylinder position and velocity measurements. In practice, the computer was working as an implement ECU in Fig. 2 as it was connected directly to the implement and measurement CAN buses.

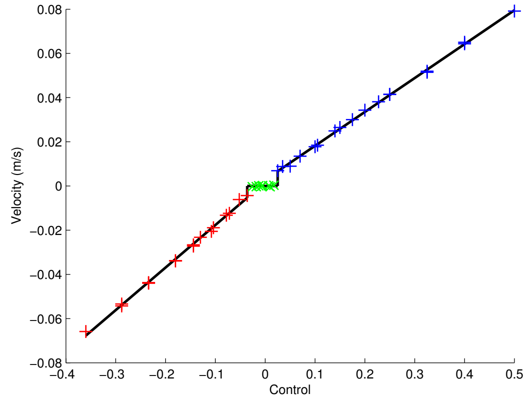

Fig. 4. Estimated nonlinearity of the transfer cylinder dynamics. The points of averaged control to velocity on which the linearization is based on are also drawn.

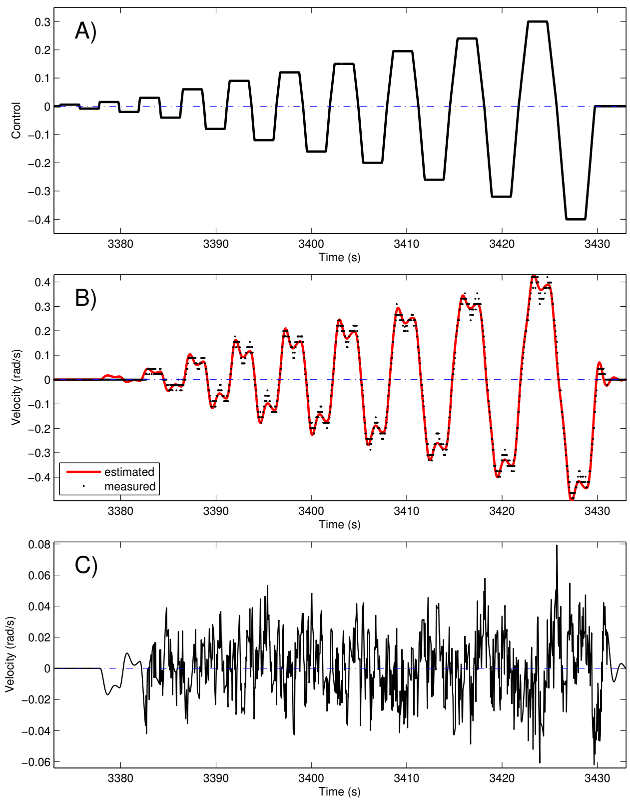

Fig. 5. A) The control sequence used to identify the slew dynamics. B) The estimated and the measured angular velocity of the slew. C) The difference between the estimated and measured angular velocities. A second-order model is used on the estimate.

Fig. 4 shows the estimated linearization model that describes the relation between the valve control and measured cylinder velocity of the transfer cylinder. The linearization models for other cylinders are similar.

The measured responses for each of the angles or cylinder lengths are are shown in Fig. 5, 6, 7 and 8. The estimated velocities using the models are shown in the same figures. Also the model errors are depicted in the bottom figures. The second-order model is used in the slew cylinder in Fig. 5 while the others are shown with first-order model estimates.

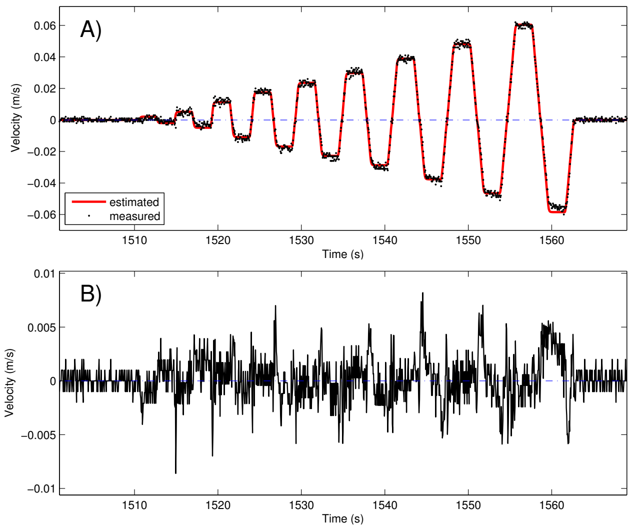

Fig. 6. A) The estimated and the measured velocity of the lift cylinder. B) The difference between the estimated and measured velocities. A first-order model is used on the velocity estimate.

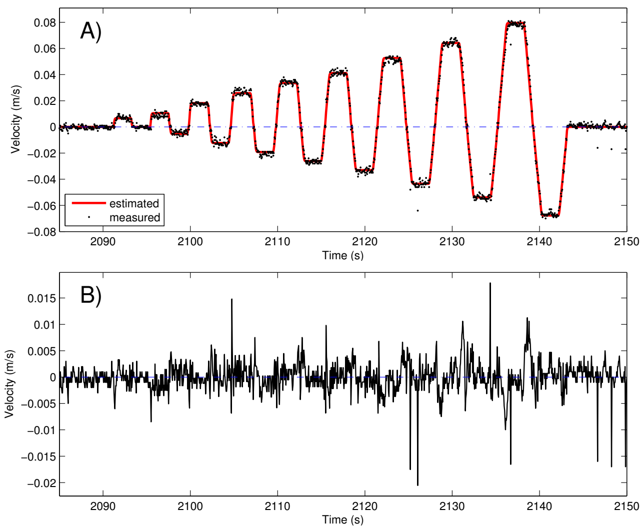

Fig. 7. A) The estimated and the measured velocity of the transfer cylinder. B) The difference between the estimated and measured velocities. A first-order model is used on the velocity estimate.

Table 1. First-order dynamic parameters.

Cylinder	L (s)	T_F (s)	L+T_F (s)
Slew	0.3477	0.0063	0.3539
Lift	0.1500	0.0798	0.2298
Transfer	0.1607	0.0466	0.2073
Extension	0.1370	0.0755	0.2125

Table 1 gives the estimated dynamic first-order parameters of each cylinder. The second-order parameters are shown in Table 2. Regardless of the dynamic model the linearization parameters are always the same.

5. DISCUSSION

From Fig. 5 can be seen that there are significant oscillations in the response of the slew. Therefore, it is clear that the slew cannot be modeled accurately using a first-order model. The low natural frequency of the slew might suggest that swaying is caused by elasticity in the tires and the crane, not in the actual hydraulics. The rest of the cylinders; lift, transfer and extension, don't have clear oscillations in their responses. The high damping values ζ for these cylinders in Table 2 confirm this. An over-damped second-order system, where $\zeta > 1$, has no oscillations and can be divided into two consecutive first-order systems. Based on these results we have decided to use second-order models for the slew and the simpler first-order model for the rest.

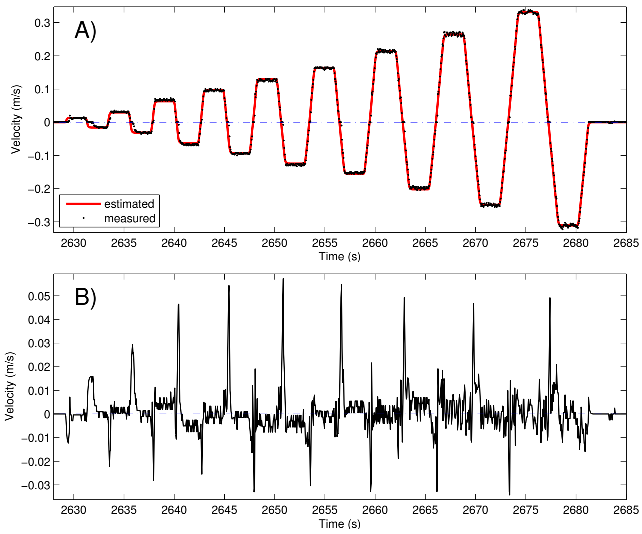

Fig. 8. A) The estimated and the measured velocity of the extension boom. B) The difference between the estimated and measured velocities. A first-order model is used on the velocity estimate.

Table 2. Second-order dynamic parameters.

Cylinder	L (s)	ζ (1)	$\omega(\frac{1}{s})$
Slew	0.0909	0.3154	4.322
Lift	0.1496	10.70	264.8
Transfer	0.1475	14.78	507.3
Extension	0.1256	1.931	41.82

Tables 1. and 2. show the estimated first and second-order parameters. If the slew is left out, the delays in the first-order models are between 137-161 ms. Time constants (T_F) for these cylinders are 47-80 ms. The delays estimated with the second-order models are between 91-150 ms. We suspect that most of the delay is caused by the delays in ECUs and CAN buses that process and deliver the measurement messages and valve commands.

The nonlinear model does not work perfectly. This can be seen in Fig. 8B when the direction of the velocity changes. The measurements indicate that there is a short moment where the cylinder stops completely. The estimate does not stop as in the model the nonlinearity is before the dynamics. A more complex model with nonlinearity both before and after the dynamics might give better results.

The models described in Section 3 are not perfect. There are many phenomena that are not captured. For example, temperature, the load and crane position can affect the response of the hydraulics. The actual goal of the models and the identification is to simulate the system and design controllers that can control the system. Based on the results in Section 4 it seems that the models capture the dynamics and nonlinearity of the system quite well. However, the parameters can change. Identification tests might not be the best way to define the parameters. The parameters should be re-estimated regularly or continuously from actual data generated during automatic control without need for specific tests. Another solution would be to use adaptive controllers that can adapt to the changes in the dynamics of the system.

ISO 11783 makes it possible to add more advanced functions on an ordinary forest crane. Instead of controlling the valves, the operator could control the crane in polar-coordinates. In polar-control mode the directions would be up-down, left-right and forward-backward. It would also be possible to create an active anti-sway control that would damp the oscillations of the tool caused by the controls of the user.

The normal working hydraulics of an agricultural tractor is designed to be general purpose hydraulics, and not specifically adjusted for a certain implement. It could be possible to design more sophisticated working hydraulics. One solution would be to utilize individually controlled four notch valves, instead of 4-way valves. When each notch is opened individually, more accurate and energy efficient control would be achieved. The valves would then be controlled based on pressure measurements.

As a downside, this kind of intelligent working hydraulics would be more expensive and complicated than the current system. For this kind of intelligent hydraulics to be ISO 11783 compatible, the standard should also take into account the advanced functions. The implements should be able to configure valve block parameters such as the maximum load sensing pressure.

6. CONCLUSIONS

An ISO 11783 compliant prototype of a forest crane was instrumented and identified. ISO 11783 makes it possible for the crane to command the valves of the tractor and use the joysticks installed into the tractor to control the crane. The prototype crane is used as a platform for controlling the crane automatically. Therefore, each joint of the crane was instrumented to measure the speeds and lengths of the cylinders.

To model the dynamical behavior, all four motions of the crane were studied individually. The parameters were estimated after identification tests, where a control signal resembling cut saw tooth wave was utilized. The nonlinearity was examined. It was found that a small control value did not cause any response. With larger control values the velocity response was found to be linear. First and second-order dynamic models were used to describe the dynamics. A delay was added to the dynamic models. It was found that the slew action had clear oscillations and requires a second-order model. The lift, transfer and extension can be described using simpler first-order dynamics.

Currently forest cranes that can be attached to agricultural tractors rely on their own hydraulic valve boards. Therefore it is worthwhile to study how tractor hydraulics could be used to control the forest crane. The general-purpose valve boards installed in tractors have symmetrical spools. In addition, the valves usually lack suction or shock valves, which can cause cavitations on some cylinders and possibly damage the hydraulics. If these protections can not be found in the tractor side, they should still be added to hydraulics of the crane. We conclude that currently used tractor hydraulics is not entirely adequate for using forest cranes. With more intelligent hydraulics, the crane could be more controllable, safer to operate and energy-efficient.

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