Closed loop control over ISO 11783 network – challenges of plug-and-play

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Abstract: ISO 11783 is a communication standard for agricultural machines, especially to distribute information between a tractor and implements (agricultural tools) connected to that. The first goal in the standard is manufacturer independent communication, the second is to use the same operating terminal to control all the implements connected to a tractor and the third is related to precision farming and information systems. ISO 11783 standard provides three classification levels for a tractor manufacturer; in Class 1 tractor has to broadcast only the basic measurements to the network, in Class 2 more measurements and in Class 3 tractor is capable of handling requests or commands from implement. This most advanced level, Class 3, enables closed loop control over a network. The implement may command either level of tractor hitch, engage power takeoff, or control auxiliary hydraulic valves. With ISO 11783 Class 3 tractor, a closed loop control over a network can be designed. In the case, the controller resides on the implement while the actuators are in the tractor. The tuning of such a system can be made by hand, for one tractor and one implement. This paper discusses challenges related to implementing closed loop control over ISO 11783 network. The main question is that how the implement has to be designed in order to be compatible with any tractor. Means to tackle the problem are shortly: requesting physical parameters and the gain scheduling, automatic identification of tractor parameters and feasibility of adaptive control. The paper introduces a proposed initial test procedure to be done before closed loop control can be enabled. Nevertheless, the identification and adaptive control of a multi degree-of-freedom system with various unmeasured loads and common hydraulic system is found to be extremely challenging in case of any tractor and any environmental conditions.

Keywords: closed loop control, networks, vehicles, networked control systems, standards, ISO 11783, electro-hydraulic systems, hydraulic actuators, nonlinear gain, agriculture, machinery, tractors, agricultural implements, mechatronics

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1. INTRODUCTION

ISO 11783 is a communication standard for agricultural machines, especially to distribute information between a tractor and *implements* (agricultural tools, like seed drills or sprayers) connected to that. ISO 11783 is the first and the only worldwide-accepted standard for plug-and-play network for agricultural machines. In the market, the products compatible with the standard are called *ISOBUS* compatible. ISOBUS is a market name, but also a specification that sets requirements for the products to be tested compatible. The requirements contain some clarifications but also define a subset of functions that a device has to support; as well as which a version of each part of the standard is used.

The first goal of the standard is manufacturer independent communication, the second is to use the same human-machine interface (HMI) to control all the implements connected to a tractor and the third is related to precision farming and information systems. On the point of view of a farmer, the objectives are the easier operability of the machines, the better exchange of information within the machine and towards the farm; and plug-and-play electronic system. The spirit of the standard is that every compatible product can be connected to the bus *plug-and-play*. (Stone et al. 1999)

ISO 11783 allows control over a network with standard messages, in case the tractor ECU is Class 3 compatible. In this case, an implement of a brand X is capable of commanding all the tractors of brands X, Y or Z. An example of ISO 11783 system is shown in Figure 1, where three implements are connected to a tractor, one in front and two in rear (Auernhammer 2004).

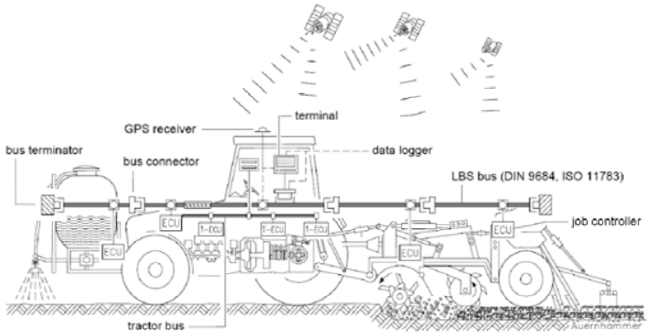

Figure 1. An example of ISO 11783 system (Auernhammer 2004).

The closed loop control over the network can be utilized to realize an automatic depth control; an automatic driving speed based on resistance; or improved navigation on the implement side – just to mention a few possibilities

(Mouazen et al. 2004, Oksanen et al. 2005a, Suomi et al. 2006, Backman et al. 2009). Freimann (2007) presents a concept of headland management through Class 3 interface.

However, great challenges are set for engineers to realize control over a network in case of an open standard network and different manufacturers. The tractor is a pretty well-defined device as well as the *virtual terminal* (HMI device) in the ISO 11783 standard. In case of control over the network with a Class 3 tractor and an implement, the implement is considered acting as a master and therefore especially the implement manufacturers face these challenges. (Oksanen et al. 2005b).

The main challenges are the safety of the system and the stability of the control. The safety issue is related to a new scenario, where a driver of the machine is no more controlling all the resources of the tractor, and what to do if the system goes wild or an external threat is identified. However, this paper concentrates only on the control issue.

2. ISO 11783 STANDARD

ISO 11783 standard provides three classification levels for a tractor; in Class 1 tractor has to broadcast only the basic measurements to the network, in Class 2 more measurements and in Class 3 the tractor is capable of handling requests or commands from the implement. This most advanced level for a tractor, Class 3, enables closed loop control over a network. Practically, the implement may command the level of tractor *hitch*, engage *power takeoff (PTO)*, or control (one or more) *auxiliary hydraulic valves*. The level of hitch is commanded and measured as a percentage between minimum and maximum, and the valve opening is commanded in the same way as a percentage – rather than in an absolute scale. In addition, the standard defines two more additional letters to be used in conjunction with Class numbers: *N* for navigational messages and *F* for front-mounted implements. (ISO 11783-9 2002)

With ISO 11783 Class 3 tractor, a closed loop control over a network can be designed. In the case, the controller resides on the implement while the actuators are in the tractor. Automatic depth control for seed drill is an example of such a control. The tuning of such a system can be made by hand, for one tractor and one implement. However, as noted above, the control of actuators is proportional as a percentage – control problems arise when plugging in another tractor with double sized valves and pump, for instance.

2.1 Hitch and PTO control

To command a hitch (rear or front) and PTO (rear or front), an implement has to transmit a single ISO 11783 message, at least 1 Hz.

In the hitch, the command signal type is a set point as a proportional value or a percentage, where 0% is the lowest position of the hitch and 100% is the highest position from the ground level (ISO 11783-7 2002). The physical values corresponding minimum and maximum depend on a tractor model. The measured values are broadcast by a tractor in the same scale. Typically, the tractor has an internal hydraulic servo control system that drives the hitch to the desired position.

For commanding PTO, the standard defines both the engagement, RPM set point and PTO modes (540/1000/eco).

Both in the hitch and PTO the set points (level or speed) are used to command the tractor. On the point of view of implement, the actuator in the process is stable, as the tractor has an internal servo control system, to control the level of the hitch and the speed of PTO.

2.2 Auxiliary hydraulic valves

The standard supports up to 16 auxiliary valves installed on the tractor. In Class 2 it is required that the tractor has to broadcast either an estimated or a measured flow of each auxiliary hydraulic valve. In both cases, the flow is indicated as a percentage of the maximum flow of the valve (-100% to 100%). In Class 3, the commands to the tractor ECU are also given as a percentage of the maximum flow.

The auxiliary hydraulic valves are not used unconnected, in other words some hydraulic actuator on the implement side is coupled with the valve with hydraulic pipes, usually with a double action cylinder actuator or with a hydraulic motor. In case of hydraulic cylinder control, the goal of control is usually position control, while in the hydraulic motor case the goal is speed control.

Position control by coupling the ISO 11783 hydraulic valve with a hydraulic cylinder forms an integrating process. The resulting unstable process together with control over a network is considered more challenging than commanding a hitch or PTO.

2.3 Navigational control

Navigational control together with Class 3 is labeled as Class *3N*. Navigational control consists of controlling wheel speed and steering, in a wheeled tractor. For the wheel speed, the standard offers both a cruise control mode and a slip control mode with some sub-modes. For the guidance control (steering), the command is given as desired curvature (set point). In both cases, the tractor is responsible for handling lower level servo control; the implement is just giving set points to those controllers. (ISO 11783-7 2002, ISO 11783-7 Amendment 1 2002)

3. ANALYSIS

3.1 Classification of interfaces

As described above, five different types of *subsystem* are available in ISO 11783 command *interface*: a hitch, PTO, auxiliary hydraulic valves, speed control and guidance. On the point of view of implement, the systems beyond the interface are considered as *subsystems*.

Considering the interface in control over network system, the following axes for categorization can be defined:

A: signal type: 1) set point or 2) direct action
B: signal scale: 1) physical or 2) proportional
C: physical process: 1) tractor, 2) tractor+implement
D: the stability of subsystem: 1) stable, 2) unstable

On the point of view of controlling the process, a case of A_1-B_1-C_1-D_1 is the easiest, as the whole process is located on tractor side, the tractor has an internal lower level controller and the set point can be given in physical units instead of proportional. So it should be compatible for each tractor. On the other end, a case of A_2-B_2-C_2-D_2 can be considered the most challenging when a tractor is changed.

ISO 11783 Class 3N command interfaces are classified as:

- PTO speed control: A_1-B_1-C_1-D_1
- wheel cruise or slip control: A_1-B_1-C_1-D_1
- hitch level control: A_1-B_2-C_1-D_1
- guidance control: A_1-B_1-C_1-D_1/D_2
- auxiliary hydraulic valve + motor: A_2-B_2-C_2-D_1
- auxiliary hydraulic valve + cylinder: A_2-B_2-C_2-D_2

For guidance control the action is given as a set point and tractor internal servo control system drives steering wheels to the desired angle, and therefore the interface in itself is D_1. However, the kinematic behavior of a typical tractor makes it unstable from curvature input to heading directional output, which is the most used purposes of this interface, and therefore D_2 classification is also valid. Auxiliary hydraulic valve control together with an implement side hydraulic actuator is considered the most challenging case. Auxiliary hydraulic valves can also be used for other purposes like pressure control, but these special cases are not considered in this paper.

3.2 Process parameters

As discussed above, the ISO 11783 command interfaces are identical on the point of view of control engineering.

The process parameters can be classified into three categories: the process gain, the static nonlinearities of the actuator and the dynamics of the process.

In case of A_1-B_1 interface, the gain is fixed and known, but in other cases it needs to be identified. In cases where hydraulic cylinders are involved, the gain typically depends on the direction of movement and may vary.

Nonlinearities are remarkable only in case of auxiliary hydraulic valves. The properties of a spool cause nonlinearity; e.g. the positive overlap of the spool causes a dead zone (Foster et al. 2005). The other crucial property is a saturation of the hydraulic flow, which happens easily if the hydraulic pump is not able to produce as much flow as requested. With electronically controller proportional valves with the spool position feedback, the dead zone can be compensated as well as load changes, but it may not be assumed to be real in any tractor. Illustration of a rough model describing the nonlinearities is shown in Figure 2.

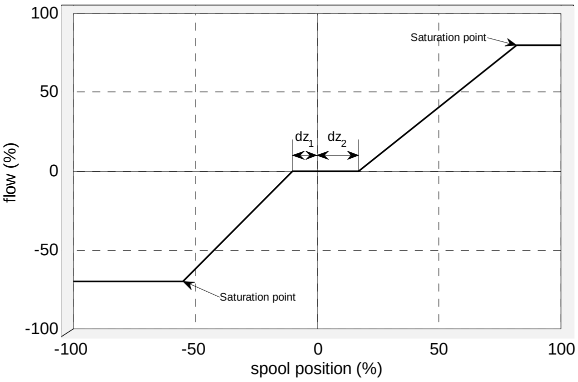

Figure 2. A rough approximation of hydraulic valve behaviour with constant load and pressure.

For each process to be commanded through ISO 11783 interface, the dynamics is involved. The dynamical response cannot be assumed to be constant for any interface, as the resistance to move the tractor, to lift the hitch, to rotate the PTO shaft, or to push the hydraulic oil varies when the tractor carries out the operation. Therefore a simple dynamic model should be used for identification.

In Eriksson and Oksanen (2009) and Oksanen (2007) the following model was used to the dynamics and gain of an auxiliary valve and a hydraulic cylinder, a transfer function from the valve command to the position of the cylinder.

$$P(s) = \frac{K_v}{s\left(1+sT_F\right)} e^{-sL}, \qquad (1)$$

where L is the constant delay, T_F is the first order lag time constant, and K_v is the gain. In Oksanen (2007) the identified parameter values were in the range L: 0.2-0.3, T_F: 0.1-0.15. In the research, the saturation of the actuator was reached on 40% opening of the valve.

Oksanen (2007) had also modeled hitch level control behavior in one tractor to follow a model

$$P_{hitch}(s) = \frac{1}{1+sT_F} e^{-sL}, \qquad (2)$$

which is following the same structure as (1), but without an integrator. In the research both upwards and downwards movement were reported following the model well, but the parameters differed from each other remarkably – in downwards movement the parameters were roughly three times larger.

4. METHODS

On the point of view of control engineering, the most challenging case is a case of an auxiliary hydraulic valve in any tractor, and a hydraulic cylinder on the implement side with user defined couplings – as concluded above. Later on, the focus is in this case.

4.1 Gain scheduling and requested parameters

The easiest way to handle the control of a plug-and-play system is to deliver a model of each subsystem to the controller side and form the complete model in the implement. Still, ISO 11783 does not support asking these kinds of parameters when speaking proportional interfaces, hitch level and auxiliary valve opening.

The practical problem related to a hitch is that the configuration may be changed by the user, to increase lift capacity by moving a fastening point of the lift rod and lower links, or by adjusting the length of a lift rod. Also, in case of auxiliary hydraulic valves, the position of a spool is not corresponding to the flow and the only way to improve the interface would require measuring the actual flow.

4.2 Adaptive control

Zhang et al. (2001) presents a method of an adaptive control system with a learning algorithm used to solve system the dead zone and the nonlinear gain. In their system, a type of PI controller is used to compensate flow and load variations and CMAC neural network controller is used to calibrate proper gains.

In ISO 11783, if the subsystem parameters beyond the command interface are unknown, which is the case in the first plug-in, it is hard to realize any automatic control. The lag, the delay and the gain of the process can be assumed to be in certain range, but as a user may connect the hydraulic quick couplings in any way, the enabled controller may lead to an unstable system and be dangerous. Therefore, a fully adaptive controller itself is not a safe solution for this purpose.

4.3 Identification through initial response tests

If nothing is known about the tractor hydraulic system; and for safety reasons it may not be trusted that a user has coupled the hydraulic connectors to the right valves, an adaptive control with online identification is a risky business.

With initial response tests, an implement may once learn a rough model of a tractor and use the estimated parameters in the control law. The model of a tractor should be simple enough, to be compatible with any tractor. This automated procedure should match with a safe tuning procedure of a mechatronical system, as it would be done by human. The automated control may not be enabled before the response tests are carried out.

5. RESULTS

The following procedure is proposed to control a hydraulic cylinder using ISO 11783 hydraulic valves. The proposed method makes the identification of the process using the test procedure. The procedure is driven by a human that can check the correct behavior and stop the procedure, if one detects a safety risk or a danger during the procedure. The proposed method contains steps that are done one by one.

The procedure should be done every time the implement detects a new tractor, and every time the system is reconnected. If the procedure is not done, an automatic cylinder position control is disabled.

Let’s assume that the cylinder is installed on the implement to lift something, and the sensor is installed so that moving cylinder up increases the value. Let’s assume also that during the test procedure the cylinder may be moved in range 10%-90%.

5.1 Step 1: Check of proper connections

In the first step, the system should ask a driver to move the cylinder up/down using push buttons in the virtual terminal. The valve is commanded to open to a defined value, which should be tunable for a user. When the user presses “up” button, the user should invert the valve by either setting the invert parameter or by changing the quick couplings of hydraulic pipes. The implement also detects the wrong movement using its position sensor, and shall prevent transition to the next stage until the right movement is detected in both ways.

5.2 Step 2: Ramp response

The implement controller should ask a user to drive the cylinder to as down using manual push buttons. After that the system should ask the user to press “test up” button, which enables the implement to start ramp input function with a low rate. The user may stop the movement by taking finger out of the button. From the successful ramp response, the system can detect a value of the positive dead zone. The same is repeated another way using “test down” button to detect the negative dead zone.

5.3 Step 3: Step response for gain and saturation

The next step is to identify the gains, in both directions and the saturation. In this test, the implement ECU controls the gain of the step, but driver is responsible for starting and interrupting the step input; the system shall stop the step in case of no interrupt. The test is started using small inputs and increased by small steps. Every other movement is up/down. The number of steps depends on the implement to be controlled, but the increment of 10 percentage units is suggested, starting from dead zone +5 percentage units.

From each valid response (not interrupted) the average speed of last half of movement is computed. In movement up the time from 50%-90% is recorded, for instance. The gain K_v is counted by dividing average speed by input step level.

The procedure is repeated until the K_v starts to drop or the average speed is not increasing any more. Thus the saturation point is identified and the process gain can be counted as an average of the recorded K_v below this point.

An example of a test response is shown in Figure 3. Step starts from 10% in both directions and is increased by 10% in each step. For illustration purposes, the procedure is repeated to full 100%. The saturation point can be detected easily from steady-state speed vs. input step diagram, see Figure 4. In the example, the saturation is detected at input 0.4 in positive movement and at -0.3 in negative.

The data in the graphs below is from real process experiments. The process contains a tractor with fixed displacement hydraulic pump, a CAN bus controlled hydraulic valve, a hydraulic cylinder in tractor rear hitch upper link and a hitch mounted landscape blade. In the experiment, the upper link was controlled in and out. (Oksanen 2007)

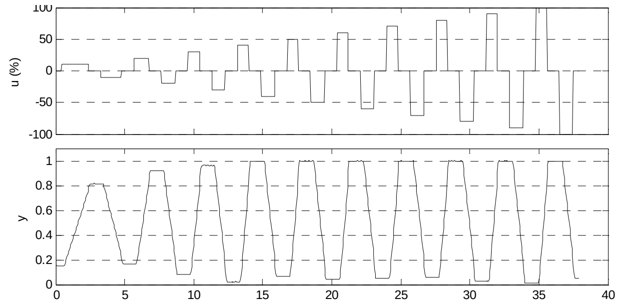

Figure 3. Step input function (top) and cylinder position response (bottom)

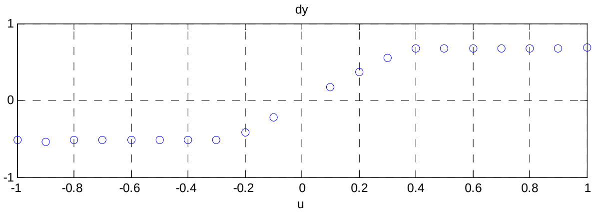

Figure 4. Steady-state speed vs. input step.

5.4 Step 4: Step response for lag and delay

Finally, the user is asked to repeat the same actions as earlier, three times in both directions. In this test, the step size of 50% from the dead zone to the saturation point is used, in both directions separately. From the step responses, in the time domain, the delay can be detected from a time derivative of the measurement. To estimate the lag, a line is fitted to steady-state movement (the gain is already known) and checking the cross point of that line and time axis. The lag is counted by subtracting the delay from the cross point, as illustrated in Figure 5. Averaging over three responses is required to eliminate time delay variations within the system, by requiring that all three values should be within certain range (e.g. maximum deviation allowed 300ms).

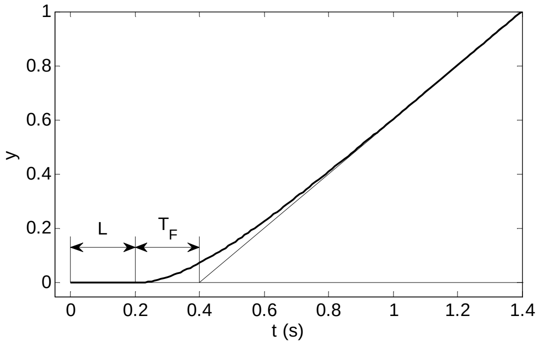

Figure 5. Delay L and lag T_F identified from step response (bold line) in integrating process. Solid line is fitted to steady-state phase and drawn projected backwards.

An example of this step is shown in Figure 6, where steady-state *dy*/*dt* is estimated to be 0.67, L is 0.35 and T_F is 0.05.

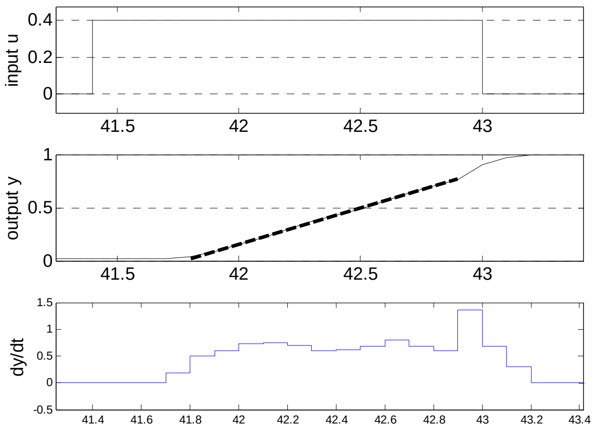

Figure 6. Step input function (top) and cylinder position response with fitted steady-state line (bottom) and time derivative.

5.5. Control law

After the proposed test procedure, the following parameters are known for the hydraulic valve-hydraulic cylinder system (1): positive gain, negative gain, positive dead zone, negative dead zone, positive saturation, negative saturation, positive delay, negative delay, positive lag, negative lag. For the delay and the lag, a single value describing both ways of movements may be used.

In the controller, the dead zone should be compensated by introducing nonlinear function to the output of a linear controller. The saturation should be taken into account to prevent windup, e.g. in PID controller anti-windup methods utilize this parameter.

PID-controller may be used as a linear controller. For instance, for the system described by (1), Eriksson and Oksanen (2009) have proposed tuning rules, that take into account robustness for disturbances (gain change) and for jitter (delay variation).

The proposed tuning rules are

$$k = \frac{10^{f(L,T_F)}}{K_v L},\; k_i = 0,\; k_d = \frac{T_F^{\,g(L,T_F)}}{K_v} 10^{h(L)}, \qquad (3)$$

where

$$\begin{aligned} f(L,T_F) &= 0.0027(T_F/L)^2 - 0.0794 T_F/L - 0.34, \\ g(L,T_F) &= 0.02 + \left(0.51 - 0.076\log_{10}(T_F)\right) L^{0.15}, \qquad (4) \\ h(L) &= 0.97 - 1.48 L^{0.15}. \end{aligned}$$

(Eriksson and Oksanen 2009).

The procedure is not limited to a PID controller and to the presented tuning rules, but it is emphasized to take care that the control law is capable of handling a large scale of parameter variation. Mathematical analysis or simulation should be utilized to verify the stability.

6. CONCLUSIONS

Control over the ISO 11783 network was found to be challenging. Some resources, like cruise control or PTO speed were considered pretty simple, on the point of view of control, while the others require more effort. Cylinder position control with ISO 11783 auxiliary hydraulic valves was considered the most challenging control problem in a plug-and-play system.

ISO 11783 does not support requesting physical parameters corresponding to the limits of proportional control, and therefore this control schema is not valid, unless these messages are added to the standard and additionally required in each Class 3 tractor to be supported mandatory.

The proposed solution to realize closed loop control over a network by an implement is to realize a *human driven identification procedure*. In the identification procedure, rough estimates for positive and negative gain, a dead zone, lag and delay are automatically computed. In the human driven procedure, the safety of operation during the procedure can be guaranteed.

The proposed method is not capable of handling varying parameters during the operation, the temperature of hydraulic oil and engine RPM for instance. Also the model to describe the nonlinearity of a hydraulic valve is rough, and two-stage piecewise linear function may be required if a precise position control is the goal.

The other problem related to the proposed method is to realize the requirement of “has to be redone every time the system is reconnected”. In practice, an implement does now know automatically if a user has changed the length of lift rods, or changed the hydraulic pipe quick couplings vice versa.

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