CONTROL DESIGN OF HYDRAULIC ACTUATORS IN AGRICULTURAL TRACTOR USING RAPID CONTROL PROTOTYPING

Timo Oksanen

Helsinki University of Technology, Automation Technology laboratory
P.O.Box 5500, FI-02015 TKK, Finland. email:timo.oksanen@tkk.fi

Abstract: In this paper control desing for agricultural tractor hitch and additional hydraulic actuators is discussed. Additional actuators are adjustable upper link, one lift rod and lower link side stabilizer arms. Hydraulic systems are modeled and unit control design for each actuator is presented. A solution to eliminate sequential movement in simultaneous action is presented. In control design and implementation process, rapid control prototyping concept is used.

Keywords: Agriculture, electro-hydraulic systems, hydraulic actuators, PID controllers, multi-input/multi-output systems, prototyping, embedded systems.

1. INTRODUCTION

A modern agricultural tractor contains a three-point rear hitch to mount implements. Some implements also have hydraulic actuators which can be operated using auxiliary hydraulic valve outputs from the tractor. The hitch and the hydraulic valves are usually functionally separated from each other, but they share the hydraulics, since the hitch is usually controlled with the same hydraulic circuit as the auxilary valves. In combined control where several cylinders are required to be moved simultaneously, usually one cylinder moves first and the others after the cylinder with the least counter pressure has moved.

Rapid control prototyping (RCP) is a concept where control algorithm development and its implementation to a real-time system is made with the same tool or toolchain. Advantages in RCP are that the algorithm can be developed with a high level tool and errors made in the implementation can be avoided. The algorithm can also be simulated with the same tool. Commonly used tools that support rapid control prototyping are MATLAB/Simulink and LabVIEW. (Hölttä, *et al.*, 2004)

In the ongoing research, the aim is to control rear hitch with accessories (adjustable upper link, one lift rod and lower link side stabilizer arms) together and to enable the combined control. The system has four degrees of freedom and each of them is hydraulically controllable. In this paper the coordinated combined control is omitted and the focus is on the servo control of each cylinder, operated simultaneously, and in implementing the controllers into an embedded controller.

2. THREE POINT HITCH

The traditional tractor three point hitch has been developed for simple implements and for easy operation about 80 years ago. The three-point hitch as a mechanical interface to mounted implements was standardized about 45 years ago and it contains only one controllable degree of freedom and it is not linear in any sense. In hitch design passive degrees of freedom are designed so that the implement mounted in the hitch behaves nicely when the tractor curves or goes over a hump. Passive degrees of freedom have been utilized as automatic hydraulic systems were unavailable at the time the three-point hitch was developed. (Srivastava, *et al.*, 2006)

An extensive analysis on traditional hitch design is studied in (Morling, 1979).

Increased level of automation in tractors and nowadays also in implements due to data bus systems (ISO 11783) makes it possible to handle more mechanical degrees of freedom. Integration of tractors and implements electronic system enables integration of control, with feedback loops and closed loop control.

With accessories of three point hitch, like hydraulically adjustable upper link, lift rods and lower link side stabilizer arms it is possible to control more degrees of freedom, i.e. to change tilt and pitch of fully-mounted implement, see Fig. 1. However, usually all hydraulic cylinders are controlled separately and it is difficult to make the required movement in the implement. With mechatronization and model based control it is possible to make handling easier. In some operations linear movements are easier for driver to handle. Needed degrees of freedom depend on the connected implement. However, using a hitch with additional degrees of freedom should not be more difficult than using a traditional hitch. The coordinated control of hitch with accessories is the research topic going on, and this paper concentrates on control of each cylinder separately, but still simulatenously. Mechatronization of three point hitch has been discussed in (Lang and Harms, 2002). Depth control of subsoiler implement using three point hitch is presented in (Anthonis, *et al.*, 2004).

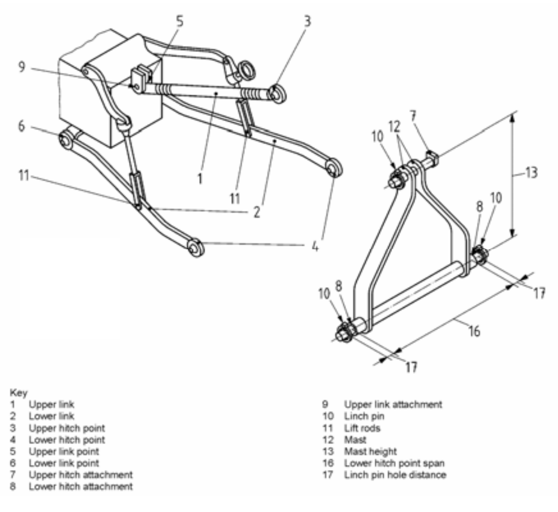

Fig. 1. Components of three-point-linkage (ISO 730).

3. RAPID CONTROL PROTOTYPING

Rapid control prototyping is a concept which covers the whole control engineering procedure. The steps can be divided into modeling the system, making system analysis, using theoretical and experimental methods to design control system, testing the control strategy and optimizing some parameters by simulation. After analysis, design and simulation of the control algorithms, the control system can be deployed easily into embedded system, usually with automatic code generation and linked compiler. After deployment the behaviour can be verified and analyzed, and parameters can be retuned.

Though this concept is named prototyping, it is suitable for developing products as well, if hardware cost-efficiency is acceptable. If the hardware for the product is different from RCP target, more optimization is needed.

Common tools that support rapid control prototyping are MATLAB/Simulink (MathWorks) and LabVIEW (National Instruments).

MATLAB & Simulink is maybe the most advanced tool with additional toolboxes to analyze and design control algoritms, and for many years Simulink has offered the code generation function, it generates C/C++ code. In Simulink there are also some advanced code generation toolchains for certain hardware. These supported hardwares are standard PC (x86) with certain I/O cards (Simulink installs its own real-time kernel), one 16-bit microcontroller (Infineon C16x), one 32-bit microcontroller (Freescale MPC5xx) and two DSP's (Texas Instruments C2000 and C6000). The advantage of a PC is that it can be custom built using supported I/O cards to add both analog, digital and bus signals as well as network, but the disadvantage is that PC's are not so rugged and the hardware is limited only to those which are supported. For the MATLAB family there are also some third-party extensions available to develop embedded control systems, like dSPACE and MICROGen, which offer boxed hardware for building embedded system more easily.

National Instruments LabVIEW has roots in building easy to use measurement systems for research and product development purposes. In LabVIEW the user interface and functionality below are combined so that the development process of visual and functional level goes hand in hand. Even if LabVIEW does not have roots in control engineering, there are packages that extend its capabilities to support control design and also modeling. In the latest versions there is also support to deploy the developed algorithm into an embedded system, but unfortunately in practice it is only applicable to National Instruments own hardware.

In the work presented in this paper, MATLAB/Simulink was used together with Phytec MPC555 evaluation board, and Freescale CodeWarrior was used as a compiler. In the selection of the tools, proven functionality of the toolchain was the most important criterion. The MPC555 controller has a floating point unit, and this makes development of algorithms more carefree.

4. MODELING THE HITCH ACTUATORS

The hitch with accessories discussed in this paper has five degrees of freedom: lifting the lower links, adjustable length of upper link, adjustable length of right lift rod and two adjustable lower link side stabilizer arms. All these are controlled with hydraulics. In the combined control presented later in this paper, a rear mounted landscape blade is connected to the three-point linkage, and in fully-mounted case the right side lower link stabilizer arm is not used, as the degree of freedom in mounted case is four.

The lifting of the lower links is part of the tractor's system, and there is an internal commercial position controller, that we couldn't and were not allowed to override, so this controller had to be used inside the control system. In the other four degrees of freedom, a positional sensor (analog output) inside hydraulic cylinder was used together with proportional hydraulic valves. Both the setpoint of hitch height and the proportional valve openings were commanded via CAN-bus. ISO 11783 offers an open interface for this commanding.

Valtra T190 tractor was used in the tests presented in this paper and the hydraulic actuators with internal position sensors were supplied by LH-Lift company. Prior to identification, all the actuator positions were scaled and offset to vary between 0 and 1. Similarly the range of valve opening is scaled to range between -1 and 1.

4.1 Modeling the hitch

The electronically controlled hitch has its own controller inside the tractor. It was noticed that it is not so simple to override the controller and to command directly the proportional valve used in the system. Therefore it was decided to use internal controller even if it was known that the best performance could not be achieved.

The dynamics of the hitch and controller (as a black box) were determined by recording step responses. A typical step response is presented in Fig. 2. Lifting speed of the hitch is limited by the hydraulic power system, the pump, and this can be seen in the steps upwards.

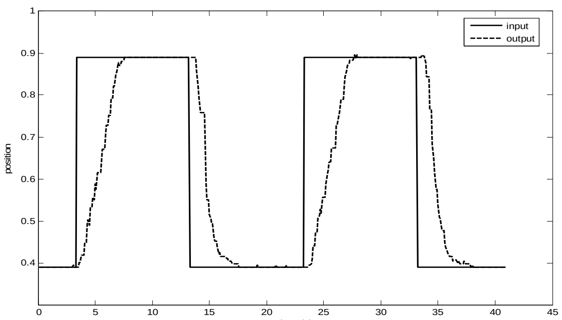

Fig. 2. Step response of hitch.

Identification of hitch dynamics was made for upward and downward movement separately. For downwards dynamics, the dynamics is first-order lag plus delay and for dynamics upwards the model is rate-limited-input plus first-order lag plus delay. To make identification of linear model, the data was reordered and offsetted to make "ladders". Using System Identification toolbox in MATLAB, the models are determined to be

$$P_{hitch}^{up}(s) = \frac{1}{1+0.289s} e^{-0.252s} \tag{1}$$

$$P_{hitch}^{down}(s) = \frac{1}{1+0.726s} e^{-0.780s} \tag{2}$$

For both models the fit (percentage of output variations explained) is over 97 percent.

The controller of the hitch is working quite well in transients upwards, but in downwards improvements could be achieved. Besides, it was noticed that using the controller of the hitch leaves a steady-state error, about 3 percent of the movement and this can be considered as hysteresis as the sign of error in steady-state depends on the movement direction.

4.2 Modeling the other hydraulic actuators

For the other four degrees of freedom the behavior should have the common structure as only the cylinder sizes and pipe lengths vary. As the positional sensor is considered as output and proportional valve opening as input, the process is integrating, and thus integrating process model should be used. Based on first experiments, the model structure was identified as FOLIPD (first order lag plus integral plus delay, eq. (3)).

$$P(s) = \frac{K_v}{s(1+sT_F)} e^{-sL} \tag{3}$$

In the open loop process, the delay consists of communication bus delay, valve dynamics, oil pressure and flow in the hydraulic pipes and position measurement delays.

A number of step responses was recorded for each actuator with different counter-masses. It was noticed that the gain is different for different directions of the actuator (because hydraulic cylinders are differential) and the delay of the process varies. It was also noticed that the input of the process (valve) saturates, in the other words, the velocity of cylinder is not increasing after certain value in proportional valve opening. The saturation point is about 40% of valve opening and the identification of linear model is made using steps below that. This saturation point correlates with the engine RPM as the pump of this tractor is gear-type. However the identification is made using idle RPM, but the dynamics have been determined to be similar, only the saturation point moves. The results of identification are shown in Table 1, (+) and (–) refer to different parameters in different directions. v_{max} is the velocity in the saturation point.

Table 1 Identification of process parameters

param	lift rod	upper link	stab. arms
K_v (+)	2	0.78	4.5
K_v (–)	1.6	1.15	6.5
L	0.2-0.3	0.2-0.3	0.2-0.25
T_F	0.15	0.15	0.1
v_{max} (+)	0.52	0.27	1.6
v_{max} (–)	0.68	0.36	1.85

5. SISO CONTROL DESIGN

In the control design SISO controllers are in inner loop to compensate differential cylinder gains and dynamics. The combined MIMO control is in hierarchy above that, resulting in a so called cascade control systes. In this chapter the SISO control design is presented. PID controller structure was used in form

$$C(s) = k + k_i \frac{1}{s} + k_d s\,. \tag{4}$$

Discretized integrator and derivative was used in controller environment. In derivative part the time-derivative of measurement is used instead of time-derivative of error signal. The discretized form is

$$C(z) = k(y_r - y_m) + k_i \frac{\Delta t}{z-1}(y_r - y_m) + k_d \frac{z-1}{\Delta t \cdot z}(-y_m)\,. \tag{5}$$

5.1 Improving hitch control

As it was concluded in chapter 4.1, the existing position controller in the hitch works well in upward transitions but there could be achieved improvements by adding a cascade controller.

In control design three control modes are considered: upwards, downwards and steady-state. In upwards mode the output=input, and in the other two modes PID controllers were used with different parameters. In mode selection two measures are used: derivative of measurement and error signal. If derivative is under certain margin and error signal is also under certain margin, the steady-state mode is used. Otherwise the mode is selected by error signal sign.

The downwards controller is tuned using AMIGO tuning rules (Åström and Hägglund., 2004). The parameters for downward movement using these rules are: k=0.619, k_i=0.758, k_d=0.183. For steady-state mode the controller was tuned by hand and the parameters are k=0.51, k_i=0.82, k_d=0.

In mode changes the integrator of PID controller is reset so that the output of controller is the same as the setpoint. With this trick unwanted discontinuities in process input can be avoided.

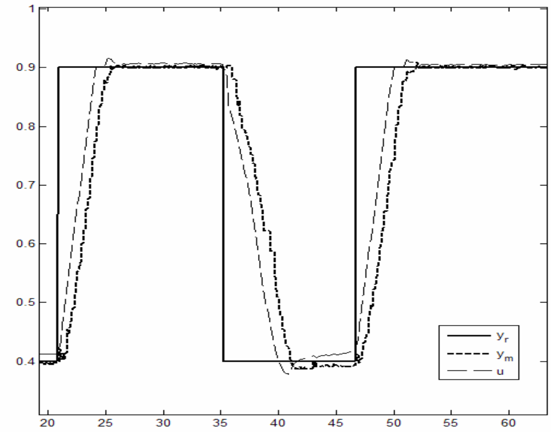

Fig. 3. Improved hitch controller

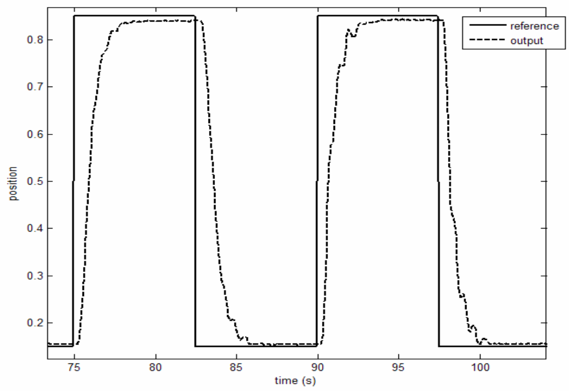

Fig. 4. Step response of controlled lift rod.

The step response of the improved controller in the real process can be seen in Fig. 3. The upwards movement is controlled purely by original controller, in steady-state phase the additional controller is removing the steady-state error, and in downwards motion the response is clearly better comparing to original system.

5.2 Control design for the other hydraulic actuators

Modeling of hydraulic system for other hydraulic actuators was presented in chapter 4.2. The identified parameters for each actuator were presented in Table 1. As only the gain of actuators is changing when changing the direction, this can be taken into consideration simply by gain scheduling the gain of controller.

At the beginning of the research AMIGO tuning rules for an integrating process with delay (Åström and Hägglund, 2004) were tried as the AMIGO tuning rules for non-integrating process were found out well working. It was noticed that AMIGO tuning rules are not giving satisfactory responses, actually the rules were not working at all. Probably the reason was that the rules work only for a certain range of process parameters. Finally the PID controllers were tuned using rules presented in (Eriksson and Oksanen, 2007). These rules are developed by using multiobjective optimization and they optimize not only the performance but also the robustness for disturbances and robustness for increased delay. As it was seen by modeling, the delay varies a little bit in this hydraulic system and using these rules guarantees the stability even if the delay increases by 100 %. So the lower limit of identified delay is to be used in tuning rules. An example of controlled process (right lift rod) response is presented in Fig. 4.

6. COMBINED CONTROL

In the control design SISO controllers are in the inner loop to compensate delay, lag and the direction-dependent gains. But the problem that fully-isolated SISO controllers have in hydraulic system is that the common oil tends to go there where the resistance is smallest. In the case process there are five actuators that are considered separate from each other in text above.

But when a fully-mounted implement is attached into three-point linkage, the actuators are not any more separated. The rear mounted landscape blade (Vama 3000 R3) is used here as an case implement. The blade can be classified into mid-light-weight implement as it weights 1000 kg.

As it can be predicted the hydraulic system, with separate unit controllers and limited pump delivery, acts so that first one cylinder moves, then another and so on. The responses of all actuators with simulatenous step input can is shown in Fig. 5. It depends on direction which actuator has least counter pressure but the sequential behavior is clear.

6.1 Avoiding sequential movements

Multi-input-multi-output process modeling is a way to model cross-interactions. But in this application the cross-interactions depend on implement and are strongly non-linear and requires extensive tests. In this application the actuators and valves themselves are SISO, only the hydraulic power system is shared and the mounted implement connects the actuators together. The implement forces can be considered as disturbances, and the hydraulic power system may be taken into consideration without modeling the process as MIMO and designing MIMO controller.

The key is that sum of the hydraulic fluid flows to actuators is limited. The available flow from the pump could be calculated analytically if the cylinder sizes, counter forces, pressure losses in pipes were known. However this same information can be found in the Table 1. The saturated velocity in each actuator in each direction represents the available speed with full control, so this can be achieved if 100 % of hydraulic power is directed only to this actuator.

The idea to avoid sequential movements is that the reference signals to unit controllers have to be filtered, so that each unit controller can get enough hydraulic power. The complete control architecture with rate limiter is presented in Fig. 6, unit controllers are marked with C_i. Four parallel unit controllers act independently.

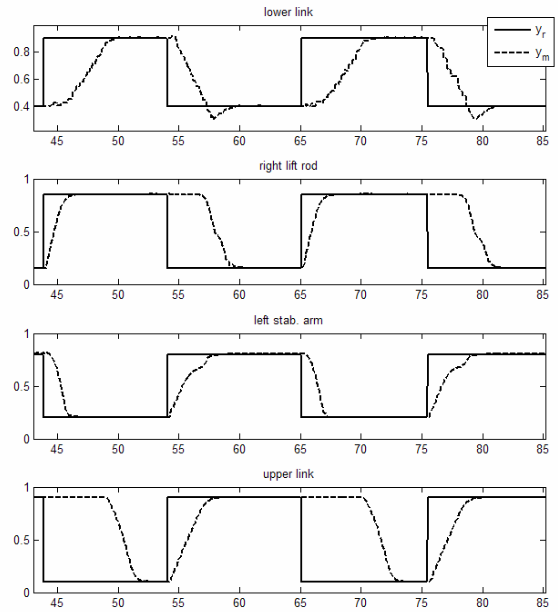

Fig. 5. Step responses with separate unit controllers.

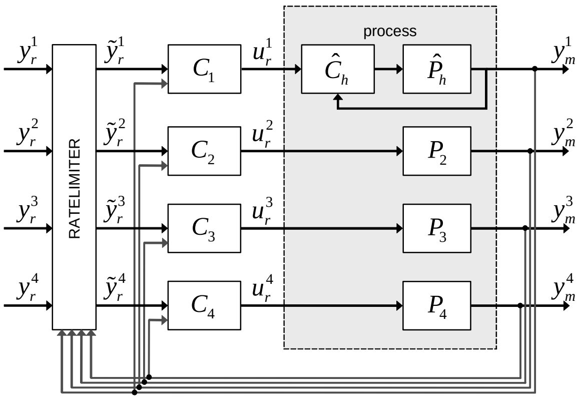

Fig. 6. Block diagram of the control architecture

In the rate-limiter algorithm, first the error signal in each actuator is calculated and normalized using saturated velocity of direction corresponding to error sign and these normalized values are sum up. If the sum E is below or equal to 1, the hydraulic system can provide enough power to unit controllers and no limitation is needed. If $E > 1$, the rate limit to change reference signal to unit controllers is set by scaling down the error signal.

$$E = \sum_i \left| \frac{y_r^i - y_m^i}{v_{(+)\text{ or }(-)}^i} \right| \tag{6}$$

$$\left({dy_r^i}/{dt} \right)_{\max} = \begin{cases} y_r^i - y_m^i, \text{ if } E \le 1 \\ \dfrac{y_r^i - y_m^i}{E}, \text{ if } E > 1 \end{cases} \tag{7}$$

6.2 Experiments

The method described above to avoid sequential movements by rate-limiting reference signals going to unit controllers was implemented to control system. The behaviour without any limitation with step inputs was shown in Fig. 5. The result with rate-limiter is shown in Fig. 7, solid line is the original reference, dashed line is rate-limited reference and bold dashed line is response. It can be seen clearly all actuators are moving simultaneously, only the lower link lowering and upper link decreasing are not following reference as well as others, but still moving all the time.

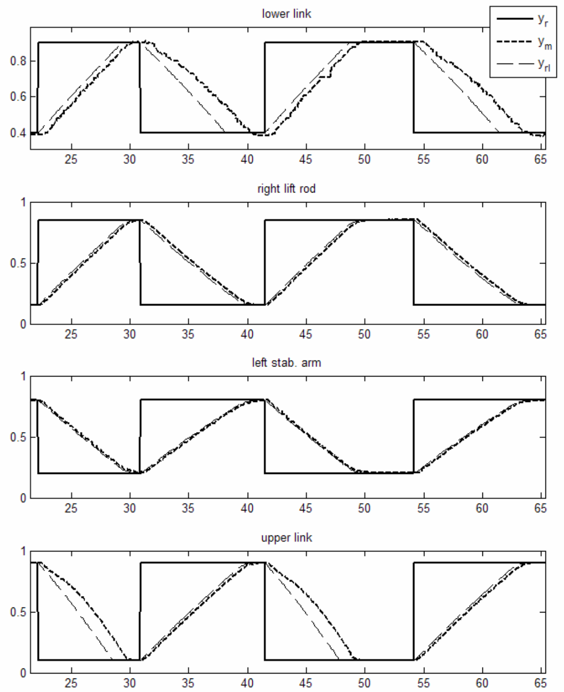

Fig. 7. Combined step response with rate-limiter.

7. CONCLUSION

In this paper a control design procedure for a three point hitch with accessories was presented. The controller was implemented to a digital controller and a rapid control prototyping compatible toolset was used.

The benefits of rapid control prototyping concept are clear: the whole process is made with the same engineering tools. This allows combining modeling, simulation, design and deployment.

It was found out that one existing position controller is not working as well as it should and it was improved using cascade control system with three modes. For the other four actuators (hydraulic valve + differential hydraulic cylinder) the controller was developed by considering the process integrating and using a PID controller. Recently published tuning rules for PID controllers for integrating process were utilized in design of unit controllers for each actuator. The tuning rules have been optimized not only for performance but also to guarantee stability under certain disturbances and delay variance and therefore the rules are perfect for this kind of process where counterforces are considered disturbances and it was found that the delay in CAN-bus connected hydraulic control system varies.

A solution for typical hydraulical system control problem with several actuators working simultaneously was presented. By limiting the rate change of reference signals to unit controllers functionality of unit controllers was ensured.

In the future research an upper level coordinated control for fully-mounted implement will be made in order to improve usability of hitch with accessories. This upper level control system will utilize unit controllers and rate limiting system presented in this paper.

ACKNOWLEDGEMENTS

This work has been financed by Tekes (National Technology Agency of Finland), and Finnish companies: Valtra, Vansco Electronics, Junkkari, LH Lift, Potila, ProAgria, Tume-Agri, Vama-Product and Vieskan Metalli.

REFERENCES

Anthonis, J., A.M. Mouazen, W. Saeys and H. Ramon. (2004). An Automatic Depth Control System for on-line Measurement of Spatial Variation in Soil Compaction: Part 3. Design of Depth Control System, *Biosystems Engineering*, **89**(1), pp. 59-67.

Eriksson, L. and T. Oksanen. (2007). PID Controller Tuning for Integrating Processes: Analysis and New Design Approach. In: *Proceedings of Fourth International Symposium on Mechatronics and its Applications*.

Hölttä, V., L. Palmroth and L. Eriksson. (2004). *Rapid Control Prototyping Tutorial with Application Examples.* Sim-Serv. Electronic publication, http://www.sim-serv.com.

ISO 11783. (1995-2006). *Tractors and machinery for agriculture and forestry – Serial control and communications data network*. Parts 1-9. International standard.

ISO 730-1 (1994). *Agricultural wheeled tractors – Rear-mounted three-point linkage*. International standard.

Lang, T. and H.-H. Harms. (2002). A new Concept for the Three-Point-Hitch as a Mechatronic System. In: *Proceedings of Automation Technology for Off-road Equipment.*

Morling, R.W. (1979). Agricultural Tractor Hitches Analysis of Design Requirements. *ASAE Distinguished Lecture* **5**, pp. 1-28. New Orleans, USA.

Srivastava, A.K., C.E. Goering, R.P. Rohrbach and D.R. Buckmaster. (2006). *Engineering Principles of Agricultural Machines*, 2nd ed., Ch. 7. ASABE, St. Joseph, Michigan.

Åström, K. J. and T. Hägglund. (2004). Revisiting the Ziegler-Nichols step response method for PID control. *Journal of Process Control*, **14**, 635-650.