FAULT DIAGNOSTICS IN AGRICULTURAL MACHINES

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ABSTRACT

Fault diagnostics in industrial applications has become very popular research topic. In agriculture the time window to complete tasks may be very short. Timing the field operations is critical when machine and human resources are limited. Different kind of dynamic model based fault detection and diagnosis methods have been studied throughout the process automation context.

Here fault diagnostics has been studied with three agricultural implements, two drills and one sprayer. In the first drill, scalar statistical analysis and classification of temporal feature patterns can be applied to analysis of possible faults in the analog measurements. In the second drill fault diagnostics was developed for electrical actuators. The nominal model of actuator was identified with test procedure, and the faults are detected by comparing the measured behavior to the nominal model. In the sprayer the pump is the most critical component with many different failure modes. Frequency domain analysis and fuzzy classifier were utilized to detect faults. Different faults were induced to the pump and the diagnostics were developed based on the collected data.

Remote diagnostics is needed if the failures are hard to detect automatically. For example some actuators change their behavior slowly due to wearing and it may be difficult to know when the fatal failure will appear. By implementing remote diagnostics the manufacturer can centrally collect fault diagnostics data and use statistical methods for improving and fine tuning preventive maintenance programs. Here the remote diagnostics system was developed to one implement, hydraulic actuator condition monitoring in one drill. The remote diagnostics features were implemented in the Task Controller of an ISOBUS compatible machine control system.

In all cases the self diagnostics methods were implemented as software components to the implement controller software. A good development procedure and tools for fault diagnostics is presented also in the paper.

KEYWORDS. fault diagnostics, condition monitoring, machines, software components, sensors, mechatronics, seed drills, sprayers, remote diagnosis, services

INTRODUCTION

The general development of engineering and automation has offered new possibilities for agriculture area. New requirements for automation systems in agricultural machines are set and especially reliability of systems has become more important research area. Because fault diagnostic is an important part of reliability of automation systems in agricultural implements a research and a development studies were needed in that area too. Auernhammer (2003) has considered new intelligent technologies in agriculture and role of mechatronics, the combination of mechanics and electronics together with hydraulics makes intelligent components available which can be connected using electronic communication. Also Sigrimis et al. (2000) have

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discussed widely the incoming information society in their paper. According to them concurrent engineering in biology, mechanics, electronics and other areas gives possibilities to create information and communications services and applications for example to agriculture, and it is an unique challenge for Agro-Engineering. ICT technologies of GroupWare, simulation tools, design tools, and in field implementations are the enabling technologies to help the task.

In the AGRIX project (Automation system for agricultural implements) an ISO 11783 compatible prototype system was developed. The system consists of one tractor and four different implements. A generic, configurable, open and smart implement controller was the main goal in the project. Fault diagnostics was developed for one pneumatic combined seed drill, one no-tillage drill and one sprayer. References see e.g. Öhman et al. (2004), Öhman et al. (2005), Oksanen et al. (2004), Oksanen et al. (2005) and Oksanen et al. (2005).

Fault diagnostics has become very popular research topic in industrial applications. Fault diagnostics is desired in modern process control, because the processes are commonly linked to each other and if some part of a process fails the whole process is affected and economic losses may be remarkable.

In agriculture the field operations are mostly time critical. Timing the field operations is critical when machine and human resources are limited. It is important to have the machines in proper working condition when they are needed on the field. The failure probability must be low and if the failure happens the down time must be short. Therefore the fault diagnostics function is profitable also in agricultural machines.

Fault diagnostics can be considered as an added value for product. Product life cycle approach is common when developing and marketing new products today. Life cycle management is a business decision-making approach that considers benefits, costs and risks over the full cycle of a product or service. This approach is also known as extended product. Remote diagnosis and telemaintenance are typical examples of such services.

Fault diagnostics can be divided into model based methods, data based methods and knowledge based methods. However there are many different ways to categorize methods of fault diagnostics.

Scheduled maintenance is the usual way to maintain implements. This is done off season. It is quite difficult to develop so accurate fault diagnostics and remote diagnostics so that farmers could change to condition based maintenance procedures. Condition based maintenance is nevertheless one objective of fault diagnostics. Unscheduled maintenance is what everyone wants to avoid because then the failure has already taken place.

METHODS AND TOOLS

Fault diagnostic methods

Different kind of dynamic model based fault detection and diagnosis methods have been studied throughout the process automation context, see e.g. Patton et al. (2000) The application of these methods in working machine context is difficult, because the monitored subsystems are usually too simple SISO systems in order to utilize real logical redundancy on the basis of MIMO dynamical models. In the same way another main approach in fault diagnosis, based on multivariate statistics, see e.g. Jong-Min et al (2004), PCA, PLS etc. seems to be too much for this application.

Methods applied in this paper

Methods used in the AGRIX project vary from model based to time signal processing frequency transforms and fuzzy logic. Also statistical data based methods are studied. Different methods used were determined after an extensive test-program done to each implement. Methods used here are based e.g. Hammouri et al. (2004), Lee et al. (2004), Manabu et al. (2004), Oakland (2003) and Venkatasubramanian (2003). Results are presented in Miettinen (2005).

For example quite simple scalar statistical analysis and classification of temporal feature patterns can be applied on analysis of possible failures. The most important measurement on which one could apply model based dynamical methods is the behavior of oil pressure in main line measured during hydraulic valve control. The behavior of oil pressure is very context dependent but it surely contains information about certain faults. In the position control of hydraulic cylinders the hits on the limits can probably be detected from the oil pressure measurement. These will be studied. Systematic and simple procedures for remote fault diagnosis and maintenance will be developed and tested. The methods should be reliable and there should not be wrong alarms nor undetected faults.

Traditional development tools

High-level graphical programming tools are widely used in industrial automation. Most embedded systems on the other hand are still programmed with assembler or C languages because of the platform limitations. However, the computational and memory limitations are becoming less important with every new generation of micro-controllers. The control functions of traditional agricultural machines have been quite simple and low-level languages have been adequate for programming these systems. But the machines are getting bigger and more complex. Large machines require more automation to keep the operator strain at an acceptable level. Emerging production methods, such as precision farming, require positioning systems and feedback control. Automation technology can also be used to produce more accurate farm records. To reach their full potential, separate control systems need to be connected. Creating distributed real-time embedded control systems with low-level languages is slow, error-prone and prohibitively expensive, especially if the production series are small. Platform limitations have also prohibited the wide use of intelligent fault detection algorithms. Also, the more complex the machine is the more it can benefit from a fault diagnostics system.

Higher level development tools

Higher level development tools provide graphical programming framework for building control systems and other periodically executable software components with same functionalities that traditional programming tools provide. Code reusability with graphical development tools is easier than with traditional code. In the AGRIX project RTI's Constellation software development system was chosen for building control systems, RTI (2003). Constellation allows that components for processing continuous signals are executed at the specified frequency. The control systems can also be reconfigured on the fly by activating and deactivating components. This kind of mode change is needed e.g. to transition from manual to automatic control. In addition, Constellation provides a framework for processing discrete events. UML-style state machines can be used for event processing. State transitions can be triggered by events or changes in continuous signals. Because time can be handled as a continuous signal, implementing time-dependent state transitions is very easy. Constellation encourages component reuse. The components are loosely coupled by well defined interfaces. Because components are connected using interfaces, it is possible to compose fundamentally different control systems from the same set of components. Creating new interfaces and adding them to new components is easy. New components can be created by combining existing components, drawing state machines or by writing primitive components with C++. Because Constellation is based on C++ programming language, it creates relatively efficient and fast code. Constellation runs in Windows and Linux operating systems. It can also create executables for VxWorks operating system and supports various processor architectures.

MATLAB is a software package for mathematical computing. Several MATLAB extensions, called toolboxes, offer computing tools for special application and method areas. MATLAB/Simulink is a tool with graphical user interface for modeling, simulating and analyzing dynamic systems. Simulink is mainly used to simulate and analyze dynamic systems, both linear and nonlinear, in continuous and discrete time and hybrid of those. Simulink is widely used in control engineering. Constellation has wrappers for Simulink models so that they can be used as easily as C++ components. Most controllers, filters and fault diagnostics were created with Simulink.

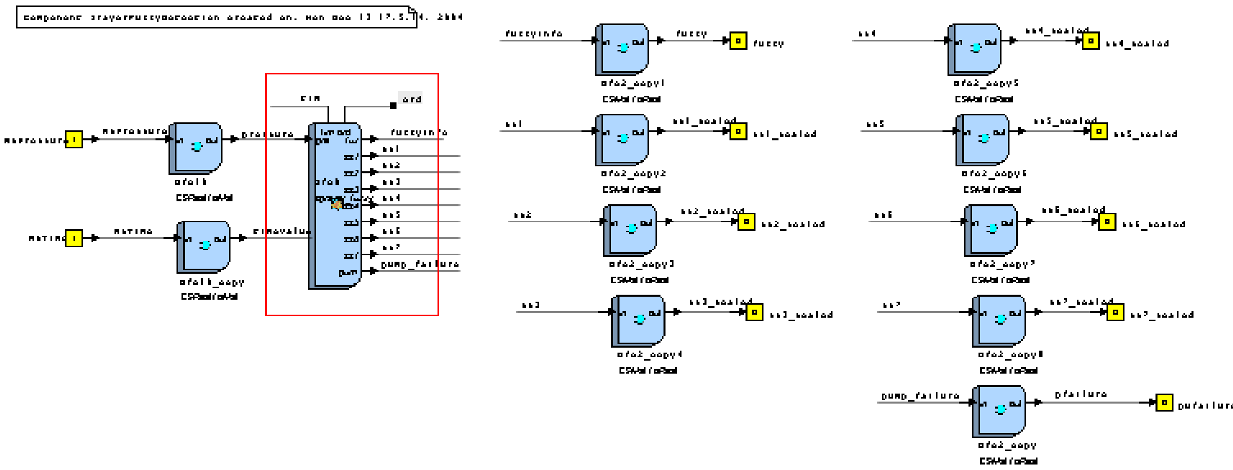

Figure 1 Simulink model inside Constellation

In Figure 1 Simulink model has been imported as a Constellation component. Simulink model inside this Constellation Composite Component is shown in Figure 4.

MACHINES

In the AGRIX project (Automation system for agricultural implements) an ISO 11783 compatible prototype system was developed. The system consists of one tractor and four different implements. A generic, configurable, open and smart implement controller was the main goal in the project. Fault diagnostics was developed for three of our case implements, one pneumatic combined seed drill, one no-tillage drill and one sprayer.

The system architecture of the AGRIX system is based on ISO 11783 (ISOBUS) network. In the project, commercial Virtual Terminal was used, and also a commercial tractor was equipped with ISOBUS adapter. The developed parts are the implement controller (same platform for all implements), compatible Task Controller and the adapter to connect GPS to the network. For research purposes the system contains also a separate logging system.

Figure 2 The implements used: Tume Airmaster™, Junkkari ™ sprayer, and Junkkari Superseed™.

The hitch connected Junkkari sprayer has PTO powered pump and its boom is divided into five sections. The pump is a fixed volume pump i.e. the liquid flow is proportional to pump's rotation speed. The coarse regulation is done by manual pressure relief valve next to the pump. The continuous control is done by an electrically controlled pressure relief valve just after the coarse regulator. Coarse regulator was tuned to keep the pressure at 7 bars. The pressure sensor and flow meter are located after the valves and that information are used in control system. The section valves are located after those, parallel. The flow goes through selection valves either to sections or back to the tank through tunable choke. In discussions with the sprayer manufacturer it turned out that pump faults are the most common faults in the sprayer.

In the pneumatic combine fertilizer and seed drill (Tume Airmaster, Figure 2) coulters are located at the rear, containers in the middle and leveling board at the front. This drill has seven hydraulic functions which can be controlled separately using magnetic valves in this prototype. A pressure sensor was installed to the pressure line; this information was considered to have rich information content about the state of machine. For research purposes several limit switches were installed to hydraulic functions, in order to gather sufficient information for the off-line fault diagnostics development phase.

The no-tillage drill (Junkkari Superseed, Figure 2) has hydraulic functions, which are directly connected to tractor's ISOBUS valves. The implement controller controls the valves through the ISOBUS network.. The used ISOBUS valves are able to transmit the estimated flow, and this was meant to be used in diagnostics. In both drills, electrical linear actuators were used to control feeder device application rates, and these electrical actuators were considered vulnerable.

RESULTS

Extensive testing of the implements was carried out to recognize normal and abnormal operation of the selected subsystems. Sensors that could help detect failures were added, but main idea was to see if faults could be detected with the sensors already in place. After normal and abnormal operation modes were measured the best way to identify the failure were chosen and the diagnostic component was developed. Varying fault diagnostic components were implemented with Simulink and tested in real machines. Common failures were caused on purpose to test operation of the components in real conditions. MTT Agrifood Research Finland has tested the system with diagnostic components for one season.

The sprayer

Pressure sensor was situated in the main water line to measure liquid pressure. Liquid pressure was studied in normal and faulty situations of pump operation using different sprayer pressures. First assumption was that cavitation of the pump would increase the standard deviation of the pressure which was confirmed experimentally. It was established that different pump failures such as forcing valve or suction valve failures and cavitation produced high standard deviation to the measured pressure. To differentiate between these failures the frequency domain was used instead of the time domain. Power spectrum was produced and different failures were successfully detected with fuzzy logic rules that where devised from normal operation. Normal and failure functionality analysis was done by deliberately causing usual pump failures and measuring the failure conditions. In Figure 3 it is possible to see that cavitation causes abnormal frequencies in the power spectrum.

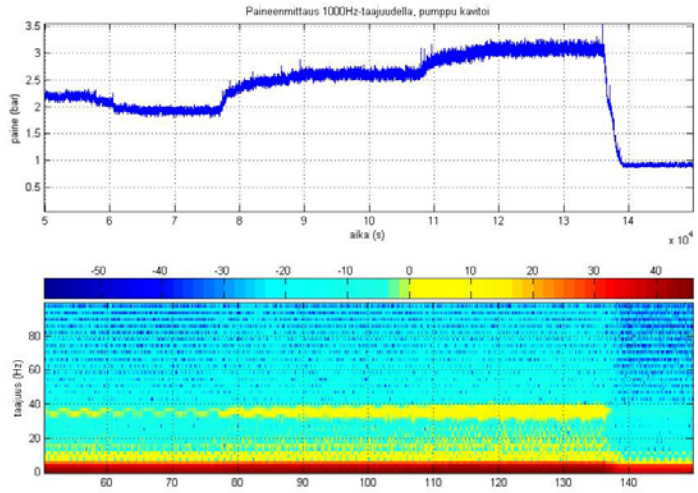

Figure 3 Power spectrum of pressure measurement when the pump is cavitating.

The structure of the fault detector is shown in Figure 4. The power spectrum is calculated in real time from collected measurement data. The calculated power spectrum is fed into the fuzzy logic classifier. Fuzzy rules calculate fuzzed value which is unfuzzified and fed it into the fault isolator component which decides whether the implement is operating normally or has a failure.

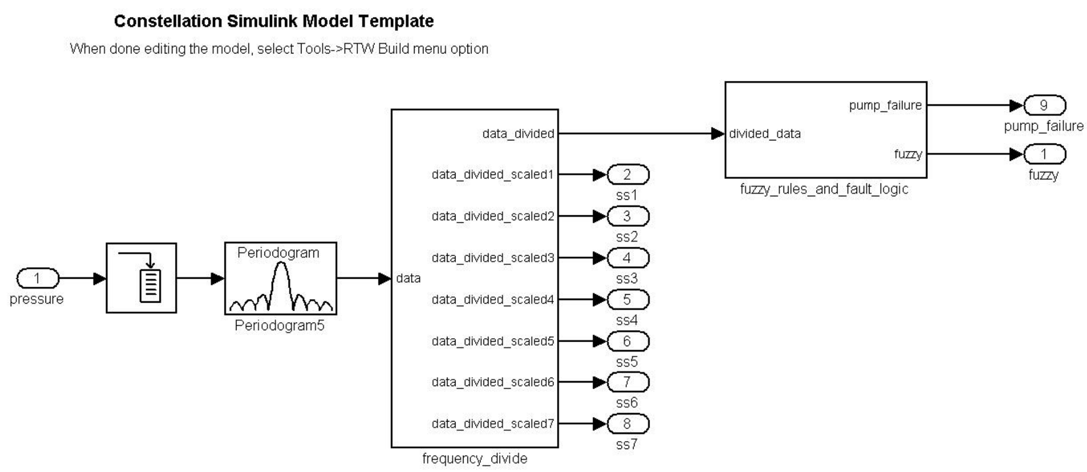

Figure 4 Simulink model of Sprayer Fault Diagnostics.

Failure messages are displayed to the user on the Virtual Terminal (ISOBUS) and are saved to Task Controller task file.

<u>Hydraulics of the drill</u>

12 limit sensors and one oil pressure sensor were installed. The idea was to use only the oil pressure measurement in the pump line together with controlled on/off valves in the drill to detect behavior of the hydraulic cylinders. The limit sensors were installed only for the data analysis purposes, in order to have numeric data when actions really happened. In the developed diagnostics system component the limit sensor data is not necessary, but it can be used to monitor oil pressure sensor and vice versa.

SPC (Statistical Process Control) was used to detect failures in hydraulic actuators. Variation of individual hydraulic cylinders where calculated and alarm limits and failure borders where established during normal use of the drill hydraulics.

Three independent failure detectors were developed. The main detector calculates individual operation times of the actuators from oil pressure sensor information. Limit sensor detector was first developed to confirm detected behavior of the hydraulic valves from the pressure sensor detector. If both pressure sensor and limit sensors are used in the machine then all cumulated information can be used to detect sensor failures. The third failure model detects sensor failures by comparing statistical values calculated by the two previous detectors.

Variation of one such hydraulic controller in use is shown in Figure 5. Alarm borders are shown in red.

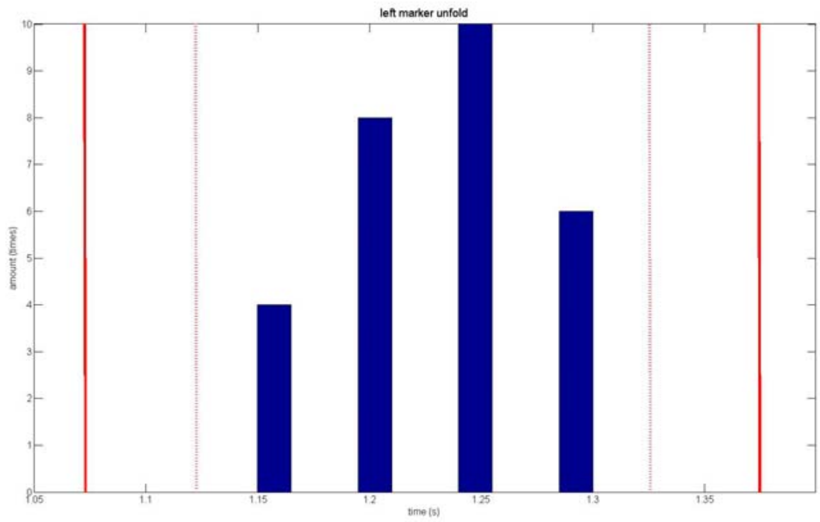

Figure 5 Example of Statistical process values for controlling state

Using the flow estimates from the ISOBUS valves to improve the fault detection was also attempted. However this was not successful because the flow estimates from the ISOBUS-valves used in the project were too inaccurate.

<u>Electrical actuators in the drill</u>

Linear actuator fault detection component used measured current consumption. Basically it monitors if actuator gets stuck (jammed), potentiometer is broken or the motor doesn’t get any power. Secondary goal was to monitor individual actuators over time. Linear actuators are monitored by their power consumption and operational speed.

Linear actuators were first tested for power consumption versus resisting force. Results of one such test is shown in Figure 6. Then linear actuator speed versus resisting force was tested. Results are shown in Figure 7.

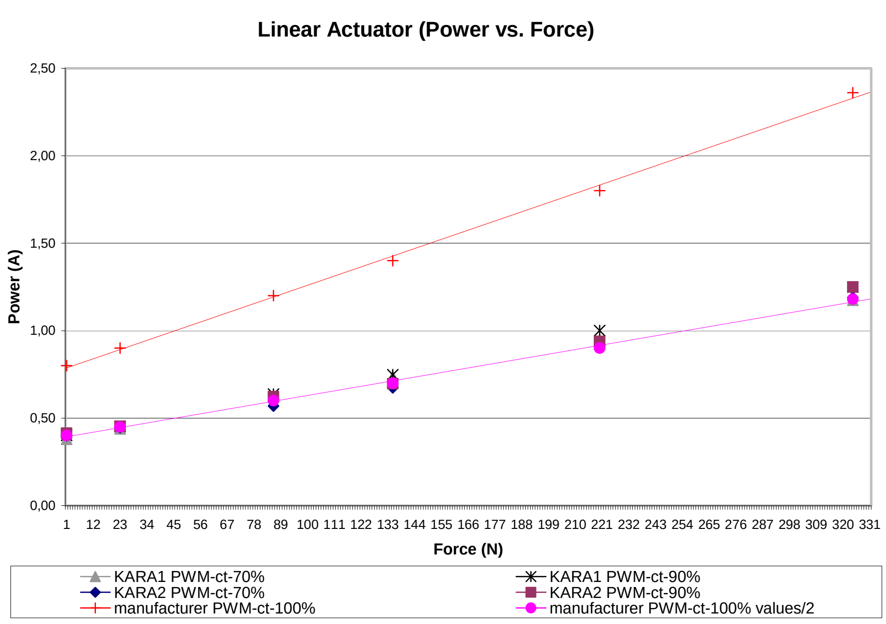

Figure 6 Power consumption versus force

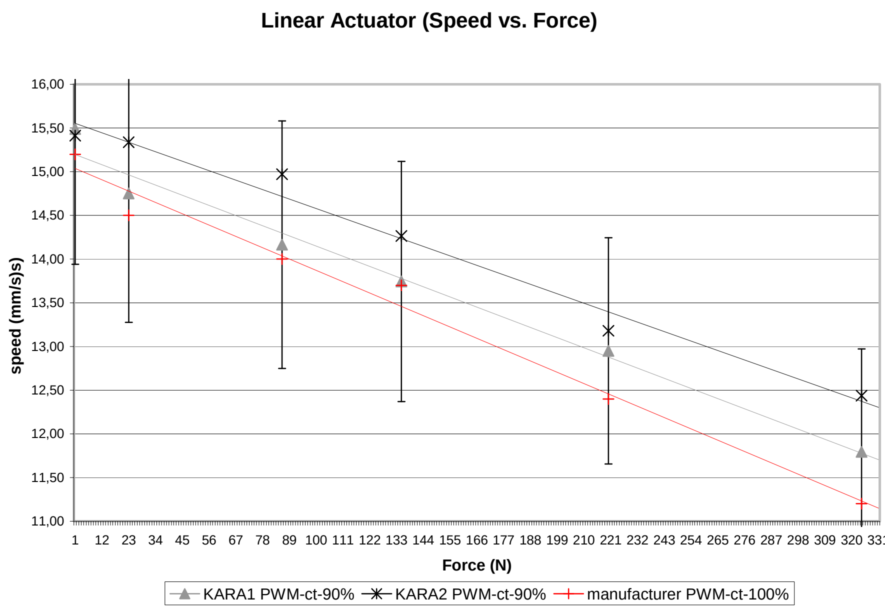

Figure 7 Speed versus force

By combining those two models in force, the power consumption versus actuator speed was defined. Linear actuator fault detector checked power consumption versus speed at run time and compares it to defined value. Calculation is constricted to movement that lasts over two seconds so that start friction doesn't affect measured values too much. This model can follow changes in power consumption and speed. Fault detector has also parts that monitors common failures such as actuator is not moving or responding. These failures could be caused by potentiometer or electric wire failure. Linear actuator component displays failures to the user on the Virtual Terminal (ISOBUS).

Structure of actuator fault detector is shown in Figure 8. Simulink model contains StateFlow-component (mean_calculation) which monitors actuator functions and calculates key ratios, on the left. Errors are reported to the user. Key ratios are then fed into power consumption model which give as model defined speed. The calculated speed is then compared to model speed.

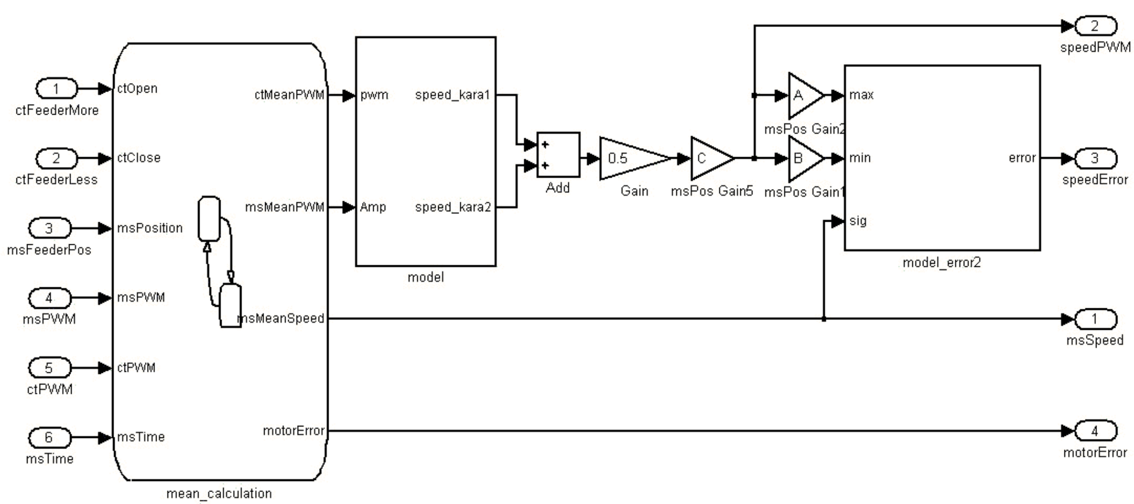

Figure 8 Linear actuator fault detection component

<u>Telemaintenance</u>

Remote diagnosis and telemaintenance was also one of the studied problems in farming implements. All realized fault diagnostic components calculate selected key ratios to be sent to the fictional maintenance service provider. Remote diagnostics were implemented as non-real time because continuous connection was not seen as a real option at the moment. This was also a good way to develop component operation over time. Remote diagnosis was built so that it used basics of ISO 11783 standard, ISO (2004). Diagnosis information is asked from implement by Task

Controller which stores fault detection component data and can send it to the service provider through farm management information system (FMIS) or directly over GPRS connection. Both of these ways where tested in the thesis. Task Controller used was also developed in the AGRIX project. Fault diagnostics was not yet defined in the ISO 11783 standard during AGRIX project. Work done shows that remote diagnostics information can be easily mediated through Task Controller. No additional GPRS component was needed because modern mobile phones have built in GPRS and Bluetooth. Bluetooth and GPRS were used to connect Task Controller to service provider.

CONCLUSION

The commonly known fault diagnostics methods were used in machine control system to detect system failures and the sources for them. The methods were tested with three different implements, one sprayer and two different kinds of combine drills. In sprayer it was concentrated on the pump faults, in one drill for hydraulical actuators and on the other drill for electrical linear actuator. In all cases first the normal operation properties were analyzed and if possible also the failure state properties. The signals were recorded and data based online fault diagnostics system were developed using data and simulation. Finally the diagnostics system was tested with all the machines in field tests.

Technically it is possible to develop fault diagnostic functionality for implement controllers, but it needs time and proper analysis of machine functionality, both in normal and fault states. If the machine behaves differently in different conditions it has to be modeled and the conditional state has to de detected directly or indirectly. A good way to do the analysis is to first plan a set of tests which will produce a rich set of data in normal condition, then cause the faults and do the same. The data should be recorded from all sensors available in machine and also store additional test information. The data should be analyzed using proper tools. And finally the automatic diagnostics system can be developed straight-forwardly based on analysis.

It depends on the machine, the amount of machines produced, and customer needs that how profitable it is to develop fault diagnostics. The generality for fault diagnostics is hard to find if the machines vary from each other. The generality can be found from the components of machine. For example the electrical linear actuator could contain internal fault diagnosis and intelligent protection against external malfunctions. However the proper tools can speed up the development process.

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