

# USE OF FAULT TOLERANT CONTROL SYSTEMS IN AGRICULTURE MACHINERY

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**Abstract:** *The active fault-tolerant control approach relies heavily on the occurred faults. Higher performances and more rigorous security requirements have invoked an ever increasing demand to develop real time fault detection and isolation system. The problem of fault diagnosis using analytical redundancy (model-based) methods has received increasing attention during recent years due to the rapid growth in available computer power. The main objective is to design and maintenance a fault-tolerant control system which guarantees a high overall system reliability and dependability both in nominal operation and in the presence of faults. Such an objective is achieved by a control performance index, which is proposed based on system reliability analysis. The methods involve generation and evaluation of signals that are accentuated by faults that have actually occurred. The procedures for generating such signals, called residuals, are based on two main distinct approaches. Direct approach consists in the elimination of all the unknown variable, keeping input-output relations involving only observable variables. Indirect approach estimates states, outputs or parameters in order to generate discrepancy signals obtained by the difference between the actual variables and their estimates.*

**Keywords:** FAULT-TOLERANT CONTROL, MAINTENANCE, RESIDUAL SIGNALS

## 1. Introduction

Unmanned, supervised, small machines in semi-public agricultural or horticultural areas will be common in the foreseeable future. Highly automated and autonomous machines save labour costs, remove people from performance of risky operations, and reduce negative environmental impacts. The considerable complexity of semi-natural outdoor environments found in agriculture and horticulture and of the mobile robot itself, result in substantial challenges to achieving reliability and safety under unmanned and/or unattended operation.

They are many problems to solve<sup>1</sup>:

- specifications and identifications of descriptions of reliable and safe behaviours and strategies under outdoor unmanned conditions, that meet legislative as well as task-determined requirements,
- developing sensor-based perception system for relevant description of the machine's behaviour as well as its environment interaction,
- developing internal generic robot fault handling and decision support routines, prepre to on-line failure detection,
- adding hardware and software components to the existing field robot,
- upgrading user sensor interface and usability prognoses oriented procedures,
- implementing and test the improved robot,
- conducting due to an economic and technology assessment.

## 2. Path and movement development planing

Looking towards the future to a point in time when humans are removed from field machinery, there are several emerging technologies that will be essential for autonomous operation. Global Navigation Satellite Systems (GNSS) and Geographical Information Systems (GIS) are aiding the progression of agricultural machines from the simple, mechanical machines of yesterday to the intelligent, autonomous vehicles of the future.

The accuracy of differential global position systems (DGPS)<sup>2</sup> degrade with increasing distance to the reference station. For DGPS systems, an inter-receiver distance of a few hundred kilometres will yield a sub-meter level accuracy, whereas for Real Time Kinetic (RTK) systems a centimetre level accuracy is obtained for distances of less than 10 km. To service larger areas without compromising on the accuracy, several reference stations have to be deployed.

Instead of increasing the number of real reference stations, Virtual Reference Stations (VRS) are created from the observations of the closest reference stations. The locations of the VRS can be selected freely but should not exceed a few kilometres from the rover stations. Typically one VRS is computed for a local area and working day.

The observations from the real reference stations are used to generate models of the distance dependent biases. Individual corrections for the network of VRS are predicted from the model parameters and the user's position. This kind of network applied to DGPS and RTK systems is known as wide-area DGPS (WADGPS) and network RTK respectively. An example of a commercially available network RTK is Trimble's VRS that provides high-accuracy RTK positioning for wider areas. A typical VRS network set up consists of GNSS hardware, communications interfacing and, modelling and networking software. Most of the existing network RTK systems have been installed in the densely populated areas of central Europe.

With the introduction of microcontrollers to agricultural field machinery it was not long until equipment designers realized the need to share and manage information between controllers. Following the lead of the truck, bus and automotive industries, equipment designers began looking for bus configurations and data structures to support continuing machinery development. Quickly, most designers realized the need for standardization to facilitate interoperability and interchange ability the industry came to grips with for hitching<sup>3</sup> and hydraulic systems<sup>4</sup>.

ISOBus is a distributed network protocol specification (developed under ISO 11783) for equipment which utilize CAN technology for electronic communication in the agricultural industry. Development of this ISO protocol began in the early 1990s when a working group was formed to develop an interim connector standard (ISO 11786). In 1992, ISO 11783 was formed to continue development of the communications protocol standard. Initially, much of the ISOBus standard was based on protocols developed by the automotive industry (SAE J1939); however, revisions have been made to support applications in the agricultural and forestry equipment industries. The main goal of ISO 11783 was to standardize electronic communications between tractor components, implement components and the tractor and implement<sup>5</sup>.

FlexRay is a distributed network protocol that has been developed to improve on existing CAN technology. These protocols are typically developed by the automotive industry, but are soon integrated into agricultural vehicles as was seen with the CAN protocol under ISO standard 11783. One of the problems associated with existing CAN protocols is that in some cases,

manufacturers are coming to a point where bus capacity will be exceeded. FlexRay offers the ability for data to be transferred at higher frequencies (10Mbps) compared to existing CAN protocols (250kbps) typically used today<sup>6</sup>. Another important aspect of FlexRay is that it utilizes a time-triggered protocol that allows data to be transmitted and received at predetermined time frames which helps to eliminate errors that can occur when multiple messages are sent out on the bus. Additionally, the FlexRay protocol is capable of operating as a multi-drop bus, star network, or hybrid (using both multi-drop and star) network. This allows the protocol to be adapted easily into existing bus protocols while also providing increased reliability where desired with the star network. As automotive and agricultural vehicles develop in the future, FlexRay will certainly be the next network protocol used to ensure efficient and reliable data communication.

The need to reconcile data is being driven by map-based application. "Prescription maps" direct where and how inputs will be applied to crop production systems. Data regarding input metering and placement is further complicated by the nature of field equipment apply inputs. Production managers and suppliers have multifaceted data transfer needs that range from moving prescription maps from the farm office to field equipment and then returning plans field operations verification files along sensor data for summarizing crop health and performance to the field office.

One attempt at coordinating data transfer has been proposed and adopted by Macy<sup>7</sup> and is termed the Field Operations Data Model (FODM). FODM was created as a framework to document field operations, and more recently has been expanded to support business functions. FODM is based on three components: description of field operation, framework and a general machine model. Field operations are described using one of four models; whole-field, product-centric, operations-centric or precision ag. The FODM framework is object-based which includes resources (people, machines, products, and domains) and operation regions (space and time). Data logged to summarize field operations can either be infrequently changing data (ICD) or frequently changing data (FCD). The general machine model (GMM) provides a description of the physical features of field machines including components, sensors and product storage or containers.

### 2.1. Problems of Robot Control Architectures

Most of the initial work done on control architectures of mobile robots was carried out in the aerospace and artificial intelligence research laboratories to accomplish military missions and space explorations. Unlike industrial robots, where the environment is controlled and structured, the work environment of robots is relatively unstructured, unpredictable and dynamic. An intelligent, robust and fault tolerant control architecture is essential to ensure safe and desired operation of the robot. A behaviour based (BB) control approach provides an autonomous mobile robot, the intelligence to handle complex world problems using simple behaviours. Complex behaviours of a robot emerge from simple behaviors<sup>8</sup>, behaviour being defined as response to a stimulus<sup>9</sup>. BB control structure can be either reactive or deliberative in nature. Reactive behaviours are part of reactive control architectures where the behaviour responds to stimuli and develops control actions. Deliberative behaviours on the other hand are pre-defined control steps which are executed to accomplish a given task. Associating these behaviours to actual actions of an agricultural robot is crucial to understand the capabilities of a robot. The importance of decomposition of agricultural tasks into robotic behaviours was illustrated by Blackmore<sup>10</sup>. For the robot to tackle unknown environments and attain assigned goals both reactive and deliberative behaviours are important<sup>11</sup> and thus a robust fault tolerant intelligence is achievable with a combination of reactive and deliberative behaviours.

From this point of view, the issues of reliability and safety systems are issues of the utmost importance.

### 2.2. Safety assessment and definition

The safety assessment of the machine had the aim to determine the compliance to legal standards and to draw attention to the most probable operational risks. For highlighting and ranking of risks a failure modes and effects analysis (FMEA) was conducted<sup>12</sup>.

#### Relevant standards

The tractor basis is modified to an extent where it cannot be regarded as a tractor despite the following definition in Directive 2003/37/EC for tractors:

'Tractor means any motorized, wheeled or tracked agricultural or forestry tractor having at least two axles and a maximum design speed of not less than 6 km/h, the main function of which lies in its tractive power and which has been especially designed to pull, push, carry and actuate certain interchangeable equipment designed to perform agricultural or forestry work, or to tow agricultural or forestry trailers; it may be adapted to carry a load in the context of agricultural or forestry work and/or may be equipped with passenger seats.'

Consequently this autonomous machine can be regarded as a 'machine' and the risk evaluation should be carried out with respect to the essential health and safety requirements of directive 98/37/EC for machinery<sup>13</sup>.

Requirements for safety and reliability for an automatically controlled machine are specified by the directive of machinery which in clause 1.2.1 states: Control systems must be designed and constructed so that they are safe and reliable in a way that will prevent a dangerous situation arising. Above all they must be designed and constructed in such a way that:

- they can withstand the rigors of normal use and external factors,
- errors in logic do not lead to dangerous situations,
- acceptance for the reliability of control systems may be based on the principles of redundancy,
- self-monitoring given in the European standard EN 954--1 which now will be replaced by EN ISO 13849 -1 – Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design and Part 2: Validation.

Acceptable solutions for electro-hydraulic control systems are shown in BIA report 6/97 – Categories for Safety-related Control Systems in Accordance with EN 954-1.

The implements mounted on the machine to perform a particular operation (spraying, weeding, etc.) are conventionally constructed and safeguarded for the use of a manned tractor. The implement manufacturer did not foresee that an automatic machine without a driver would operate and control the implement. Consequently a new supplementary risk assessment has to be made for every attached implement to be used by the automatic machine. A supplementary risk assessment for the implements was not undertaken as a part of the risk evaluation. The focus was on the automatic main machine.

The risk evaluation performed by the machine safety consultant can be summarized<sup>13</sup>:

- The automatic machine is an interesting new aspect in outdoor mechanization.
- The functionality and the design of the machine shows that it is possible to work without an onboard driver.
- The outdoor operations should be reduced to applications under semi-public conditions to more easily comply with legal requirements.
- The evaluation of the safety shows that documentation and design of the control system does not meet the requirements for safety for a machine. The control system must be

redesigned and rebuilt to meet performance level PL 'd' of EN ISO 13849.

- The emergency stop system (safety circuit) has to be re-evaluated before it can be regarded as acceptable to let the machine work without surveillance.

To reduce the identified risks for autonomous outdoor operations the following problems must consider:

- fulfilling the legal requirements an emergency safety circuit was installed to backup faults in the control system and to protect the environment as well as the machine itself;
- the outdoor operations have to be reduced to applications under semi-public conditions to comply more easily to legal requirements as well as to achieve a reasonable economic viability;
- a perception system is needed to detect obstacles and to improve the localisation system for navigation purposes;
- additional hardware and software monitoring is necessary to optimise the systems behaviour;
- some safety risks had to be excluded at this stage of the project (e.g. the possibility of free public access to the area, the presence children) or tried to be met by defining rules for the operator behaviour;
- it was identified that due to its complexity the most difficult and challenging task is to increase the reliability and fault tolerant behaviour of the installed computer control system.

### 3. Fault-tolerant control (FTC)

In the task of fault detection a series of measures are used (Fig. 1). Generally speaking, FTC systems can be categorized into two main groups: active (ATFC) and passive (PFTC)<sup>14</sup>. The active FTC techniques (Fig. 2) involve adapting the control law by using the information given by the fault detection and isolation (FDI) block<sup>15</sup>. With this information, some automatic controller adjustments are performed after the fault trying to guarantee that the control objectives are reconfiguration mechanism.

Two main potential advantages of active FTC are as follows:

- the ability to use information from the fault provided by an online fault diagnosis system and controller reconfiguration;
- the possibility to achieve the optimal performance with the available configuration. However, the price to pay for these nice features is that the overall system becomes more complicated and costly<sup>16</sup>.

To design fault tolerant control systems (FTCS)<sup>17</sup>, one of the important issues to consider is whether to recover the original system performance/functionality completely or to accept some degree of performance degradation after occurrence of a fault.

In a control system, there are two aspects of performance: dynamic and steady-state. In FTCS, both types should be considered as well. To represent the degradation in dynamic performance, one could use a performance-degraded reference model with a model-following control principle. In general, at least two different models: one for normal and one or more for impaired systems need to be used.

Let's consider a system that is described by the following linear stochastic differential equation under the normal operation:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{w}(t) \\ \mathbf{y}(t) &= \mathbf{C}_r\mathbf{x}(t) \\ \mathbf{z}(t) &= \mathbf{C}\mathbf{x}(t) + \mathbf{v}(t) \end{aligned} \tag{1}$$

To model actuator faults, control effectiveness factors are used<sup>18, 19</sup>. The dynamic part of the system in the presence of actuator faults can be represented as:

$$\mathbf{x}_{k+1} = \mathbf{F}\mathbf{x}_k + \mathbf{G}^f\mathbf{u}_k + \mathbf{w}_k^x \tag{2}$$

where the post-fault input matrix  $\mathbf{G}^f$  relates to the nominal input matrix  $\mathbf{G}$  and the control effectiveness factors  $\gamma_k^i, i = 1, \dots, l$ , in the following manner:

$$\mathbf{G}^f = \mathbf{G}(\mathbf{I} - \mathbf{\Gamma}_k), \quad \mathbf{\Gamma}_k = \begin{bmatrix} \gamma_k^1 & 0 & \dots & 0 \\ 0 & \gamma_k^2 & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \dots & \gamma_k^l \end{bmatrix} \tag{3}$$

where  $\gamma_k^i = 0, i = 1, \dots, l$ , indicates that the  $i$ -th actuator is healthy, and  $\gamma_k^i = 1$  corresponds to a total failure of the  $i$ -th actuator, and  $0 < \gamma_k^i < 1$  represents partial loss of the control effectiveness in the  $i$ -th actuator.

The corresponding transfer function matrix of the desired reference model is then:

$$\mathbf{T}_d(s) = \mathbf{C}_d(\mathbf{I}s - \mathbf{A}_d)^{-1}\mathbf{B}_d. \tag{4}$$

Let's assume that the eigenvalues of the closed-loop system are represented as:

$$\mathbf{\Lambda}_f = \text{diag}[\lambda_1, \lambda_2, \dots, \lambda_n]. \tag{5}$$

Suppose that the eigenvalues of the degraded reference model are represented as:

$$\mathbf{\Lambda}_f = \mathbf{\Psi}^{-1}\mathbf{\Lambda}_d \tag{6}$$

where:

$$\mathbf{\Psi} = \text{diag}[\alpha_1, \alpha_2, \dots, \alpha_n], \quad \alpha_j \geq 1, \quad \forall j = 1, \dots, n. \tag{7}$$

This matrix is known as the mode degradation matrix. Each element in this matrix represents the expansion factor of the corresponding mode from the desired reference model.

The transfer function matrix of the reference model for the degraded system then becomes

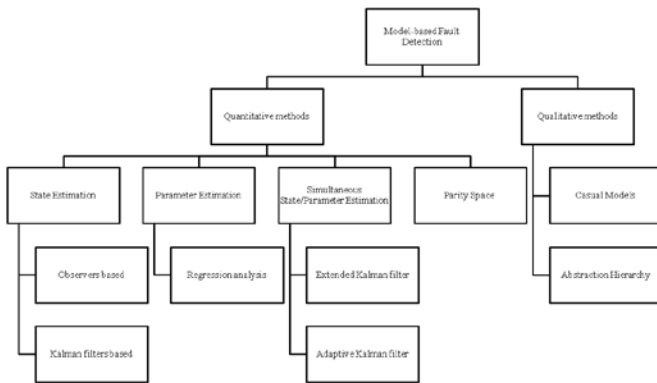


Fig. 1 The taxonomy of model-based fault detection methods

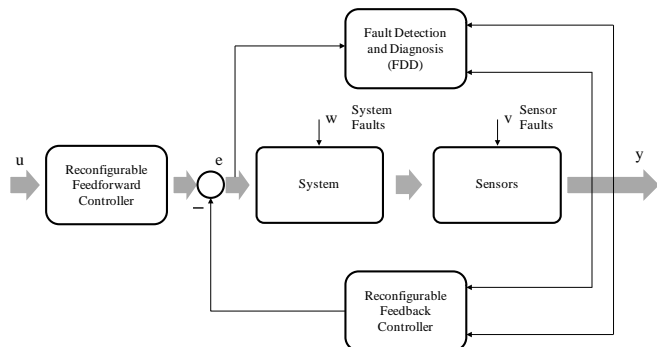


Fig. 2 Active Fault tolerant system diagram

$$\begin{aligned}
 T_f(s) &= C_d(Is\Psi - A_d)^{-1}B_d = \\
 &= C_d(Is - \Psi^{-1}A_d)^{-1}\Psi^{-1}B_d = \\
 &= C_f(Is - A_f)^{-1}B_f
 \end{aligned} \quad (8)$$

Hence, the degraded reference model can be represented as

$$\begin{aligned}
 \dot{\mathbf{x}} &= A_f\mathbf{x} + B_f\mathbf{u} \\
 \mathbf{y} &= C_f\mathbf{x}
 \end{aligned} \quad (9)$$

where  $A_f = \Psi^{-1}A_d$ ,  $B_f = \Psi^{-1}B_d$ ,  $C_f = C_d$ .

Generally speaking, the comparison the dynamics of original system with the degraded system is the key problem of fault tolerant systems.

Significant work will be properly identify of the model takes into account the development of damage

#### 4. Conclusions

In this paper, a new approach to design a FTC has been proposed. The advantage of the approach is that it allows the controller design to be defined by a set of admissible faults. When the fault is in this admissible interval, the nonlinear system can be recovered with the performance desired.

A state feedback control can stabilize the faulty plant with acceptable performance degradation.

As a further research, the computation of fault estimation will be proposed including the effect of model uncertainties. Also, the influence of delay introduced by FDI module will be analysed.

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