Diagnosis for industrial processes: Final report

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1 Scientific project results

With the growing complexity of today's engineering systems, the need has arisen for systematic approaches to failure diagnoses, i.e., fault detection and isolation. Due to the wide flora of diagnosis problems of fundamentally varying nature, there is probably no such thing as a universal solution or framework for diagnosis. This means that the approach and methods used for a certain diagnosis problem must be carefully chosen and tuned for that specific purpose.

1.1 Fault isolation in object oriented control systems

The motivation for the project was that ABB Robotics had a problem with fault isolation when a robot halted due to an alarm. The object-oriented design goals encapsulation and modularity often stand in direct conflict with the need to generate concise information about a fault situation, and avoid propagating error messages. Error messages are sent by individual objects to notify, e.g., an operator that the object has detected an error condition. The individual objects or group of objects do not in general know how close they are to the fault source, or if the fault has already been adequately reported, and hence whether it should log an error message or not. The number of error messages or alarms in a fault scenario need not be especially large to cause problems for an unexperienced operator, the number typically ranges from 3 to 20 in our use case. The strength of the proposed approach does not lie in the amount of handled error messages in each fault scenario, but in the wide range of potential fault scenarios handled by a general method.

We advocate a two tier design with structural model fault isolation as a first phase and a second phase of behavioural model fault isolation that is used only if needed.

- We have used a *structural model* of the control system; the class diagrams and task diagrams in a UML (Unified Modelling Language) model of the control system; to find a cause-effect relation between the generated error messages in a fault scenario, and then to choose the most significant error message(s) according to this relation.

- Using a *behavioural model* of the system, in the form of UML state charts, we propose an approach to fault isolation based on *model checking* to locate strong root candidates (if they exist!). The property of being a strong root candidate is then expressed in the temporal logic CTL (normally used for verification), and we use an existing model checker to single out the strong root candidates.

  The number of global system states typically increases exponentially with the number of subsystems. To avoid the so-called state-space explosion we propose an *abstraction* mechanisms for our particular problem [C1, C2, C3].

  We have developed a prototype tool, *StateTracer*, that takes a description of a system as input and produces a fault isolation table as output along with visualisations of all merged objects. The system description is given in UML.

Our method can also be used at design time. At the design level, we want to find out, at design-time, if the error log design is sufficient, that is, if enough error messages are produced to be able to isolate all faults or if some error messages are obsolete.

1.2 Statistical methods

We have used different statistical detection methods to deal with uncertainty.

- Given a set of data, we want to determine if a new data point is generated by the same distribution. In [C4,C5] the parity space approach to fault detection is compared to PCA. It is assumed that there are additive faults on input and output signals and stochastic disturbances that cannot be measured directly. The methods are illustrated on a simulation model of an F-16 aircraft where six different faults are considered.

- David Törnqvist has studied the problem of detecting faults in an environment where the measurements are affected by additive noise [T1]. To do this, a residual sensitive to faults is derived and statistical methods are used to distinguish faults from noise. Standard methods for fault detection compare a batch of data with a model of the system using the *generalised likelihood ratio*. Careful treatment of the initial state of the model is quite important, in particular for short batch sizes. One method to handle this is the parity-space method which solves the problem by removing the influence of the initial state using a projection.

- The case where prior knowledge about the initial state is available is treated. This can be obtained for example from a *Kalman filter*.

Combining the prior estimate with a minimum variance estimate from the data batch results in a smoothed estimate. The influence of the estimated initial state is then removed. It is also shown that removing the influence of the initial state by an estimate from the data batch will result in the parity-space method. To model slowly changing faults, an efficient parameterisation using Chebyshev polynomials is given.[C6,C8,C9,T1]

- The methods described above have been applied to an *Inertial Measurement Unit*, IMU as described in [T1]. The model for an IMU is nonlinear, but has been locally linearised to fit the linear framework used above. Another possibility is to use non-linear estimation methods such as particle filters. This technique can also be used when doing simultaneous localisation and mapping (SLAM).

  Parallelling the evolution of PF applications to high dimensional state vectors, the aim of this contribution is to extend the fastSLAM algorithm to be able to cope with high dimensional state vectors as well. The derived algorithm is applied to experimental data from an autonomous aerial vehicle using the Rmax helicopter platform. The main navigation sensor unit, consists of three accelerometers, three gyros, pressure sensors, and a camera. GPS is used for evaluation. Our recent publications in this area are [C10,C11].

- In visual SLAM applications, the map consists of landmarks that are tracked with a camera sensor. The landmarks must be reidentified in each image, known as the correspondance problem. Image processing algorithms are used for this task, these algorithms sometimes get tricked by similar objects leading to a misclassifications. The statistical fault detection methods derived in [T1] has also been extended to detect these misclassifications or spurious features. This accomplished by grouping several features and fuse the camera images with data from the IMU. Results have been presented in [T2,C12].

2 Degrees

- David Törnqvist, Lic.thesis, *Statistical Fault Detection with Applications to IMU Disturbances.* Thesis no. 1258, 2006.

- David Törnqvist, PhD Thesis, *Estimation and Detection with Applications to Navigation*, No. 1216, 2008.

3 Persons supported by the CENIIT grant

The following persons were partly supported by the CENIIT grant:

- Inger Klein (project leader)
- David Törnqvist (PhD student)
- Anna Hagenblad (PhD student)

4 Cooperation with industry

The activities in the project has been carried out in cooperation with ABB Robotics and ABB Corporate Research through VINNOVAS'S center of Excellance ISIS (Information Systems for Industrial Control and Supervision). The ISIS project *Fault isolation in object oriented control systems* is a cooperation between the PhD student Dan Lawesson and his supervisor Ulf Nilsson (see the former CENIIT project *Industriell Användning av Formella Metoder* and Inger Klein. The motivation for the project was that ABB Robotics had a problem with fault isolation when a robot halted due to an alarm. Formerly two PhD students where active in the project: Magnus Larsson at the Division of Automatic Control and Dan Lawesson at the Department of Computer Science. Magnus Larsson defended his PhD thesis in december 1999, and is now working at ABB Robotics where one of his tasks is to implement the first version of the fault isolation scheme developed here.

There are close connections to the EU-project called MATRIS (Markerless real-time Tracking for Augmented Reality Image Synthesis). Partners in the MATRIS project are Fraunhofer IGD, Germany, BBC R&D, UK, Christian-Albrechts-University, Kiel, Germany, Xsens Technologies, Netherlands And Linköping University.

There are also close connections with the strategic research centre MOVI-II (Modelling, Visualisation and Information Integration) funded by SSF.

5 Cooperation with other CENIIT projects

There has been a close cooperation with the former CENIIT project *Industriell Användning av Formella Metoder.*

6 List of publications

Theses

[T1] David Törnqvist. *Statistical Fault Detection with Applications to IMU Disturbances*. Licentiate Thesis no. 1258, Jun 2006.

[T2] David Törnqvist. *Estimation and Detection with Applications to Navigation*, Linköping Studies in Science and Technology, No. 1216, 2008.

Conference papers

[C1] Dan Lawesson, Ulf Nilsson and Inger Klein, Model Checking Based Fault Isolation Using Automatic Abstraction. In *14th Intl Workshop of Principles of Diagnosis (DX 2003)*, Washington DC. 2003.

[C2] Dan Lawesson, Ulf Nilsson and Inger Klein, Fault Isolation Using Automatic Abstraction To Avoid State Space Explosion. In *Workshop on Model Checking and Artificial Intelligence (MoChArt-2003)*, Acapulco. 2003.

[C3] Dan Lawesson, Ulf Nilsson and Inger Klein, Fault Isolation in Discrete Event Systems by Observational Abstraction. In /em Proc of 42nd IEEE Conf on Decision and Control (CDC), Maui Hawaii. 2003.

[C4] Anna Hagenblad, Fredrik Gustafsson and Inger Klein, A comparison of two methods for stochastic fault detection: the parity space approach and principal component analysis, 2003, Proceedings of SYSID.

[C5] Anna Hagenblad, Fredrik Gustafsson and Inger Klein, A comparison of two methods for stochastic fault detection: the parity space approach and principal component analysis, 2004, Proceedings of Reglermöte 2004.

[C6] David Törnqvist, Fredrik Gustafsson and Inger Klein. *GLR Tests for Fault Detection over Sliding Data Windows*, 2005, Proceedings of the 16th IFAC World Congress.

[C7] Dan Lawesson, Ulf Nilsson and Inger Klein, An Approach to Post Mortem Diagnosability Analysis for Interacting Finite State Systems. In *Workshop on Model Checking and Artificial Intelligence (MoChArt-2005)*, San Fransisco. 2005.

[C8] David Törnqvist and Fredrik Gustafsson. Initial State Estimation for Fault Detection over Sliding Windows, Proceedings of Reglermöte 2006.

[C9] David Törnqvist and Fredrik Gustafsson. Eliminating the Initial State for the Generalized Likelihood Ratio Test, Proc. 6th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, 2006, Beijing, P.R. China.

[C10] Thomas Schön, David Törnqvist and Fredrik Gustafsson. Fast particle filters for multi-rate sensors, Proc. 15th European Signal Processing Conference (EUSIPCO 2007), 2007.

[C11] Thomas Schön, Rickard Karlsson, David Törnqvist and Fredrik Gustafsson. A Framework for Simultaneous Localization and Mapping Utilizing Model Structure, The 10th International Conference on Information Fusion, 2007.

[C12] David Törnqvist, Thomas Schön and Fredrik Gustafsson. Detecting Spurious Features using Parity Space, International Conference on Control, Automation, Robotics and Vision, 2008.