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- **Topic:** Dependable Robots (Fault Detection, Diagnosis and Prediction)
- **Author:** Salman Omar Sohail
- **Date:** 18 Dec 2019

1 Abstract

Humanity has entered the era of cyber-physical-systems in which automation is at the heart of it all. The enormous scale and complexity of automation towards which humanity is converging mandates dependable systems where dependability itself largely relies on a faultless system. However, faultless systems do not exist in reality due to which methodologies have been developed to cope with these faults. Methodologies such as fault detection, fault diagnosis, fault recovery, fault prediction and fault tolerance. Each of these methodologies are ordinarily used in conjunction with each other for removing faults and making sure they don’t come back. Fault detection, diagnostic and recovery methods are core methodologies while fault tolerance and fault prediction can be considered as highly beneficial add ons. The approaches employed by all the methodologies are one of three (or a hybrid) model-based, knowledge-based and/or data-driven based approach. This scientific report reviews the methodologies of fault detection, diagnosis and prediction. Aspects relating to what has been done in the field and what is being done has been investigated.

2 Introduction

Dependability within a robot is a core aspect that is required for its use in the real world. Dependability can be defined as a system that is safe, reliable, dependable, secure and maintainable. The advent of industry 4.0 has boosted the integration of robots within the industry in all types of environments. The robots which are being integrated into the industry are required to perform a variety of tasks which range from simple pick and place tasks to autonomously mapping and recording data from an irradiated building. The increased use of robots makes the need for dependable systems all the more important.

The robots developed are typically prone to faults which threatens their dependability and when their dependability is threatened, so is the work they perform and the humans around them. Ensuring dependability is very critical and this is achieved by a faultless system. Faults that are external in nature, cannot be dealt directly, however, internal faults (sensors, actuators, controllers etc.) within a robotic systems can be dealt with. The general model used to achieve this is a five step procedure:

1. Fault Detection
2. Fault Diagnosis
3. Fault Prediction
4. Fault Recovery
5. Fault Tolerance

Fault detection simply detects the fault and its location, ordinarily in real time. Fault diagnosis determines the type of the fault and analyzes it. Fault prediction uses prior data to provide an estimate of where the next fault is likely to occur. Fault recovery is the process of recovering from the fault. Fault tolerance is the ability of a system to grow immune to the faults. The application of these domains allows for a more dependable robots, robots that are tolerant to faults. The epitome for a faultless dependable robot is the one that can quickly, effectively and successfully deal with any type of fault autonomously.

The begininng of fault detection and diagnosis started when fault reduction techniques were borrowed from parent fields (especially from Mechanical Engineering) and were modified so that they could be applied in robotics. A primary example of this is the application of fault tree analysis, in which all possible faults were carefully designed and implemented. However, this technique became of less importance as modeling all possible out comes of faults required too much time and processing. Slowly but surely, application of approaches using modeling, statistics and machine learning algortihms started popping up which have produced significantly better results then the previous approaches for fault detection, diagnosis and prediction.

Research has been going on for decades in attempt to make robots less susceptible to faults. Despite the research and effort that has been put into the field of robotics, there is still a long road ahead. A large amount of time is invested for developing a robot that can pick and place an object in controlled conditions. Robotics itself is a relatively new field and is slowly gaining traction in its development and research. Research in fault detection, fault diagnosis and the other fault related fields are more important than ever before.

3 Description of the subject

Dependable Robots

»Overview

- Dependable robots have become a vital part in shaping the future of the Industry 4.0 revolution.
- They ensure safe, reliable, maintainable and secure systems (robotic systems). [2]
- The factors that hinders the dependability of a system are faults.
- Faults are the deviation from the normal behavior of a system. [11]
- Faults occur within the sensors, actuators and within the software of a system.
- Faults in a system typically happen within the design phase and run-time of a system.
- Faults when left unresolved may not only threaten the dependability of a system but the core infrastructure of the robotic system's.
- The methodologies and approaches utilized for the of treatment of faults is detecting them (fault detection), analyzing their type and repairing them (fault recovery).
- More deep approaches involve using the data from prior faults to predict future faults (fault prediction).
- Certain approaches utilize the new fault data that allows the system to adapt to the same type of the faults (fault tolerance).

Fault Detection

»Overview

- Fault detection is the first and most vital step for dependable robot systems.
- The fundamental approach of fault detection is the comparison of the normal operational state of a system with the faulty state of the system.

- Fault detection usually have three parameters against which their performance is measured. Reaction speed, robustness and fault sensitivity. [11]
- Factors that affect fault detection are noise, disturbance, false positive, missed alarms and modeling errors.
- The main objective of fault detection is to immediately detect faults in a system.
- The biggest drawback of fault detection is the missed faults or false positives.
- Once a fault is detected, a good amount of resources is dedicated for the fault diagnosis and fault recovery. So, it is imperative that the fault detection system detects the correct fault.
- Fault detection can be enhanced by preprocessing data with feature extraction techniques like principal component analysis.
- Fault detection is typically applied in the data set received from sensors.
- Advanced methods for fault detection involves fault injection, in which a fault in injected into the system either for testing or training the machine learning algorithms.

»Methodology Employed

- Faults detection is usually achieved by one of three methods being model-based method, data-driven method and knowledge base.
- Model based fault detection approaches model the system using differential equations. When these modeled systems which are typically linear and can also be linear at some cases, are processed they generate data. The generated data is compared with the measured data which allows to detect discrepancies between the two models.[11]
- Data based fault detection relies on analysis of the signal generated by the system which maybe in the form of electrical signals, vibration, heat etc. to infer if there is an anomaly from the normal behavior.
- Knowledge based fault detection relies on algorithms that goes through a data base (which may be fed or self generated) matching the fault cases with recorded cases. [8]
- In reality these methodologies in of themselves are insufficient for fault detection and parameters have to be modified and combined sometimes with other approaches to provide effective fault detection.

Fault Diagnosis

»Overview

- Fault diagnosis is the analysis of faults which have been detected by fault detection. It identifies the type and extent of a fault, isolates it and based on the type of fault the steps required for recovery.[3]
- Fault diagnosis if broken down can be described as the product of fault identification, fault isolation and fault recovery. Some literature refer to these individually, however, generally fault diagnosis covers all these domains.
- Fault detection and fault diagnosis are almost always utilized together sequentially for a complete fault identification and isolation procedure.
- The main objective of fault diagnosis is to isolate and identify the type of fault.
- The biggest drawback of fault diagnosis is the time required for processing and identifying the fault.
- For a robotic system, the resources spared are limited and cannot be entirely dedicated for fault diagnosis especially in time and situation critical tasks due to which research is being done in fault diagnosis which merges multiple approaches to enable quick real time fault diagnosis.
- Fault diagnosis can be enhanced by preprocessing data with feature extraction techniques like principal component analysis.

»Methodology Employed

- Faults diagnosis is similar to fault detection that it is usually achieved by one of three methods being model-based method, data-driven method and knowledge base.
- Model based fault diagnosis approaches model the system using differential equations. When these modeled systems which are typically linear and can also be linear at some cases, are processed they generate data. The generated data is then used to identify the type of fault. [11]
- Data based fault diagnosis relies on analysis of the signal generated by the system which maybe in the form of electrical signals, vibration, heat etc. Based on the signal, the anomaly
- Knowledge based fault detection relies on algorithms that goes through a data base (which may be fed or self generated) matching the fault cases with recorded cases. [8]

Fault Prediction

»Overview

- Fault prediction utilizes past fault data as a basis to predict future faults.
- The main objective of fault prediction is to estimate the time and location of faults.
- The biggest drawback of fault prediction is the need of large data sets.
- Methods are being research in which minimum data sets can be used to estimate faults.[10]
- Systems that are linear allow for more effective fault prediction.
- Non-linear systems require additional processing for fault prediction.
- Fault prediction can be enhanced by preprocessing data with feature extraction techniques like principal component analysis.
- Fault prediction for hardware components effectively increases and enhances their remaining life and prevents catastrophic failures.

»Methodology Employed

- There are three ways in which fault prediction can be performed similar to fault detection and fault diagnosis that is by model-based approach, data-driven approach and knowledge based approach.
- In the model-based approach, the system is modeled and based on the data, it provides an estimate of what the fault may be in the next time step ‘t’.
- In data-driven approach, statistics are used in which the occurrence of certain parameter of the data set are examined. Based on filtered relevant information, an estimate is generated for future faults.
- In knowledge based, algorithms are used to process previous fault data to provide an estimate. These algorithms are ordinarily logic languages, though object oriented language are used as well.

4 Annotated Bibliography Dependable Robots

Note

Each report has 4000+ characters exclusive of the abstract and reference and inclusive of the *summary*, *keywords*, *notes*, *contributions* and *deficits*.

4.1 Dependable Robots

Basic concepts and taxonomy of dependable and secure computing
Reference

DOI: 10.1109/TDSC.2004.2

Year: 2004

Author: A. Avizienis and J. -. Laprie and B. Randell and C. Landwehr

Abstract

This paper gives the main definitions relating to dependability, a generic concept including a special case of such attributes as reliability, availability, safety,integrity, maintainability, etc. Security brings in concerns for confidentiality,in addition to availability and integrity. Basic definitions are given first. Theyare then commented upon, and supplemented by additional definitions, whichaddress the threats to dependability and security (faults, errors, failures), theirattributes, and the means for their achievement (fault prevention, fault tolerance, fault removal, fault forecasting). The aim is to explicate a set of generalconcepts, of relevance across a wide range of situations and, therefore, helpingcommunication and cooperation among a number of scientific and technical com-munities, including ones that are concentrating on particular types of system,of system failures, or of causes of system failures.

Summary

•**Overview** This paper provides a very in depth view in Dependability of systems. It defines an agreed upon definition of dependability. It clearly explains the hierarchy and important factors that can cripple dependability which to no surprise is faults. It provides an in depth map of characterization of the sub topics of dependability. It also clarifies relating concepts. Although this

topic is mainly focused in computing systems, it can be extended to other systems as well, system if the fielf of computer and mechanical engineering. This paper splits dependability into three main areas.
Area (1) Dependability attributes whichcontributes towards the main things which are required for dependability.
Area (2) Threats are the second area which threatens dependability andare mainly composed of the faults, errors and failures.
Area (3) Meansdeals with the third area that deals with detection, diagnosis, error recovery, tolerance and prediction.

First the paper deals with faults. A detailed taxonomy of fault is also provided, which attempts to quantify all possible faults and their relations. The paper then moves forward to explain failures. It provides a very, very detailed taxonomy. It further goes on to explain the relationship between dependability and security with error. It then nicely ties all of this together with the faults, failure and their propagation. The paper then discusses the attributes of the dependability and then expounds about how to deal with thewith faults that occur. It deals with some strategies of faults which includes fault tolerance. A major part of fault tolerance is actually dealing with the errors and their sub-types, masking them and recovering from them. Next thing discussed is the fault removal and methods of employing them. Finally it deals with fault prediction and all their associated attributes. Once again it sums up the relation of all of these with dependability. The paper concludes that the importance for dependability, especially in critical components is a must and all types of attributes should be kept in mind while developing a dependable system. An important note to keep in mind is that faults are bane of dependability and are the crux of this entire paper.

•This paper is about
–This paper clearly defines the terminology and definitions pertaining to dependability and security as well as defining their relationships. It provides an in depth explanation for each of the building blocks of dependability and security, clearly defining, ordering and displaying their relationship.

•This paper is relevant because
–Consensus in the basic terminology and definitions is the foundationon which further work is made as it sets a standard.

•Previous works on this
–The previous works dealt with methods and approaches to individual issues.

•Previous works deficiencies
–The deficiency in previous work is that they are targeted and related to a very fault diagnosis.
–It does not provide a united and clear definition for the faults.

•Paper’s proposed solution
–This papers provides an in depth taxonomy and very precisely defines dependability. Not only does this paper define it and its relation but provides the requirements and conditions that need to be met to achieve dependability.

•Paper solution is good because
–This paper encompasses all relevant information required for devel-oping a dependable system whether it is hardware or software.
–It provides the appropriate direction and puts the term Dependabilityand security elegantly into perspective.

•Future direction
–Improvement on the explained methodologies.
–Expanding current methodology data base.

Keywords

Dependability, security, trust, faults, errors, failures, vulnerabilities, attacks, fault tolerance, fault removal, fault forecasting

Notes

This paper displays the dependencies of dependability and systematically showshow fault detection, diagnosis and recovery plays an important and heavy roleon the quality of dependability of a system. This paper is a very importantand crucial especially due to the agency backing it (NASA) and the peoplewho worked on it for over 24 years. This paper has heavy weight due to itscredentials alone.

The methodology they have used to or it is more correct tosay that the structure which they have used to construct each of the topics areas follows. Define the most basic definitions, then describe their sub topics.After all that is done create a visual taxonomy and display all the possible andrelevant relations. After that tie all the information with the main topic inhand.

Contributions

This paper defines the criteria for dependability and security very well. Itprovided a well structured taxonomy for all the sub components of the topic.While precisely defining them according to the classical perspective

Deficit

Currently, I do not have enough knowledge to say what is missing.

Safety-critical advanced robots: A survey
Reference

DOI: 10.1016/j.robot.2017.04.004ï

Year: 2017

Author: Jérémie Guiochet, Mathilde Machin, Hélène Waeselynck

Abstract

Developing advanced robotics applications is now facing the confidence is-sue for users, which is a main limitation for their deployment in real life. This confidence could be justified by the use of dependability techniques as it is done in other safety critical applications. However, due to specific robotic properties (such as continuous human-robot physical interaction or non deterministic deliberative layer), many techniques need to be adapted or revised. This paper reviews the main issues and research work in the field of dependable robots, making the link between the dependability and robotics concepts. It also presents main challenges for increasing robot dependability.

Summary

•**Introduction** This paper is a survey that gives an overview of the dependability of robots and the key issues that influence them. The key issue that the paper has focused on is safety. It discusses a number of other research papers, summarizing them, their solutions and their left over challenges.

•**Criteria** Firstly, the criteria for dependability is discussed and why the need of dependability and confidence within an autonomous system isrequired and why safety is the crux of the theme.

•**Architecture** Secondly, the autonomy and its foundation is discussed. Thepaper points out that the software architecture is the most vital component of a robotic system. Although, the layers of the architecture is blurred in some architectures, the paper treats each as a separate entity.
These entities being: Decisional layer, Executive layer and Control layer.

•**Discussion on Architecture Components** The paper goes on to explain these layers starting with decisional layer as the information on these are paramount for understanding the future topics that are to be discussed. In decisional layer, it receives an objective, it formulates a path to the objective using heuristics or prior knowledge and passes it on to the executive layer. The executive layer then executes the formulated plan received from the decisional layer. Functional level provides feedback and includes the information from perception parameters.

•**Classification Based on Proximity** The paper then highlights the need of a classification based on the proximity of the robot and incidentally, the authors of this paper have published another paper just on the classification of robotic, the classifications based on proximity for safety applications.

•**Hindrances** The paper goes on to discuss the new challenges that are influencing safety which are new hazards such as human injury caused by interaction which may cause cutting, crushing, clamping etc.. Another example of some new hazard is bad synchronization and faulty interface like in China Hi-tech fair 2016 in which a robot injured a person due to unwanted movement.

•**Fruits of Previous Research** According to surveys conducted in some robotic competitions the software is the major contributor for cause of failure and their frequency compared to hardware is much more high. This entails that these faults are focuses mostly on the decisional layer.

•**Robo Safety** The paper moves on to discuss the robot safety standards and how there are a range of these standards available. Some that are discussed are probability of occurrence of harm and the severity of harm, it than weighs the acceptability of the action/plan. Another type of check is the Safety Integrity Level (SIL) check. The ISO provided standard requires the system to have an emergency stop function, limit work space, protective stop etc. Many other methods are available but none of them are firmly rooted and are lacking wide spread acceptance by the safety community.

•**Resolution of Faults** The paper then reaches the crucial topic of the means to deal with the items that derail the dependability of a robots, namely"faults". It discusses in reasonable detail the big 4: Fault prevention, removal, forecasting and tolerance.

•**Best Mechanism for Fault Resolution** The paper informs us about the bestway to deal with fault is to prevent it from happening in the first place. This can be done by using certain environments and by complying with certain standards and re-checking.

•**Fault Removal** Next is Fault removal. This is done by either dynamic verification in which a the robot is plugged in an emulator and the problems are identified or by actually testing the robot in real time which is risky. The second one is static verification in which the models and parameters are checked via algorithms and verified. This ensures rigorous design.

•**Fault Forecasting** The second last one is fault forecasting which is done by two methods either by bottom up that uses probability methods or top down which uses fault tree analysis, both have several challenges respectively. The paper discusses several methods and techniques employed by various researcher.

•**Fault Tolerance** Finally Fault tolerance is discussed, It discusses how mucha robot is resistant to various dependability threats and how it deals withthe threats in the various levels of the robot architecture. Fault tolerance mainly involves checks and models for checking.

•**Challenges** Challenges presented for this paper are, The autonomous robots that are developed must be able to traverse various and previous unknown environments and uncertainties efficiently and effectively whilst maintaining the a certain degree of confidence and dependability.

•**Future Direction** Moving to the future, certain key areas are: Modeling and simulation for safety analysis, Formal methods for verification, Correct-by-construction control and planning, Identification of hazardous situations, Human–robot interaction models, Adaptive safety monitoring and Certification.

Keywords

Dependability, Safety, Collaborative autonomous robot

Notes

A brief overview of dependability factors and a quick review of how differentresearch group dealt with certain aspects of fault prevention, detection, forecastand tolerance.

Contributions

A survey of explicitly describes the link of dependability and safety of robots.

Deficit

Mention of some extra dependability issues would have been much appreciated.

Fault tolerant planning for critical robots (International Conference for Dependable Systems) Reference

DOI: 10.1109/DSN.2007.50

Year: 2007

Author: Lussier, Benjamin and Gallien, Matthieu and Guiochet, J´er´emie and Ingrand,F´elix and Killijian, Marc Olivier and Powell, David

Abstract

Autonomous robots offer alluring perspectives in numerous application domains:space rovers, satellites, medical assistants, tour guides, etc. However, a severelack of trust in their dependability greatly reduces their possible usage. Inparticular, autonomous systems make extensive use of decisional mechanismsthat are able to take complex and adaptative decisions, but are very hard tovalidate. This paper proposes a fault tolerance approach for decisional plan-ning components, which are almost mandatory in complex autonomous systems.The proposed mechanisms focus on development faults in planning models andheuristics, through the use of diversification. The paper presents an implemen-tation of these mechanisms on an existing autonomous robot architecture, andevaluates their impact on performance and reliability through the use of faultinjection.c©2007 IEEE.

Summary

•**Background** The paper starts off by illustrating the utilities, benefits and challenges faced in complex autonomous systems. One particular and critical challenge is of predicting and validating the behaviour of said autonomous system. A particular method to deal with this is residual faultdevelopment model. This paper addresses such a mechanism.

•**Dependability in Autonomous Systems** In this section the author buildsup the general knowledge pertaining to autonomy by defining them, their types, characteristics and principles. The first term defined is autonomy. It is defined in a custom matter that suits that field of robotics quite well. Then it defines robustness and fault tolerance and draws a fine line differentiating the both terms as they are often taken in the same meaning. Next, the architectures are discussed in which there are 4 major architectures:

1. Sense-plan-act style
2. Subsumption style
3. Multi agent style
4. Hierarchical style

Each of which are defined within the paper. The flaws of sense-plan-actstyle are highlighted. Subsumption style architecture is used in entertain-ment robots while multi-agent style is being increasingly used, however,for most practical robots the hierarchical architecture is used which hasusually three layers, decision layer, executive layer and functional layer.These layers are defined and some sample case of their implementation is pointed out and how the hierarchical layer is effective at diagnosing and recovering from faults. Due to difficulty of fault tolerance, the article suggests that residual development is a viable solution and is presented as so due to lack of research work on this topic.

-Deliberation and Decision This paper regards deliberation anddecision as key components in autonomy and dedicate an entire section of their paper dedicated to it. Decision as the paper defines it are basically search algorithms that optimally search for a plan to reach the most favourable path to the goal (which is actually artificial intelligence), with reasonable space and time complexity. The implementation of these decisional mechanisms depend upon heuristic search, dynamic programming, neural models etc. A key feature which is desired is that the decision is generic and independent and is able to use domain specific knowledge.

-Planning The paper then moves on to planning in which they convey the expected behaviour, the principle on which it works, required attribute, challenges, case scenarios and related work done on planning.

•**Fault Tolerant Planning** This section deals with the designing and implementation of fault planner models and heuristics. This will be dealing specifically with hierarchical architecture with a centralized planner. The proposed method is to run the planner sequentially or concurrently and using the same method for recovery block. For fault detection a watchdog time is suggested as it checks if the search is too slow, a dead lock has occurred or if there is a timing error. A set of implementation andconstraint criterion is defined as well a criterion for undesired behaviour.The paper then defines the end condition and then displays the pseudocode of the actual implementation of what has been stated.For recovery two mechanisms have been proposed.

1. The first one switches to other planners when the initial one fails and if all planners fail and un-satisfied goals remain then performs diagnosis on the planners and detectsthe issue whether it was within the planner or external and so on and so forth.
2. The second option runs the planners concurrently. When a compliant planner is found, it is run and other planners are put on hold, in event that all planners fail then a watchdog timeout occurs.

Next, the paper talks about coordination which coordinates between the error detectorsand planners. The final thing discussed is the implementation. This has been implemented within several robots and successfully so. One of the architecture this is implemented is the LAAS architecture. Sample cases and varied implementations are demonstrated.

•**Mechanism Validation** This section handles the criteria used to evaluate the proposed and implemented fault tolerant system. Firstly is theframework which depends on two factors simulation and fault injection. Secondly, is the software architecture. Thirdly, is workload. Fourthly is fault load. Fifthly, is records and measurements and then finally results.The paper then discusses the performance and efficiency based on these 5 parameters with their sample cases.

•**Conclusion** Presentation of a fault tolerant system with implementation and test case scenario. Future directions involve plan analyzer, concurrentand sequential planning policies, more experimentation

Keywords

autonomous, mechanisms, planning, systems, fault, Decisional

Notes

One of the first of its kind, fault tolerance with proper backing i.e. a number oftest cases along with implementation methods and criteria set for checking.

Contributions

Unique fault tolerance system.

Deficit

Discussion of a few test case scenarios are enough to get the idea through andrest should be added to the appendix.

A dependable perception-decision-execution cycle for autonomous robots
Reference

DOI: 10.1109/ICRA.2012.6225078

Year: 2012

Author: Stephan Gspandl ; Siegfried Podesser ; Michael Reip ; Gerald Steinbauer ; Máté Wolfram

Abstract

The tasks robots are employed to achieve are becoming increasingly complex, demanding for dependable operation, especially if robots and humans share common space. Unfortunately, for these robots non-determinism is a severe challenge. Malfunctioning hardware, inaccurate sensors, exogenous events and incomplete knowledge lead to inconsistencies in the robot's belief about the world.

Summary

- **Background** The paper starts by emphasizing the on the requirement of dependable robots as they are beginning to influence a large aspect of human technology.
- Their core framework which is the perception - decision - execution cycle are susceptible to threats mainly due to uncertainty, uncertainty of the environment specifically. Some factors are in-deterministic environment, dynamic environment, stochastic environment, incomplete knowledge etc.
- This paper deals mainly with these issues and excludes faults within the hardware and software of the robot.

- **Proposed Solution** The proposed solution is a diagnosis and repair framework which utilizes IndiGolog and history based diagnosis. This framework can discern the irregularities of the belief of the robot. Based on its diagnosis it can reason and decisively modify parameters in order to repair the belief.

- **Contribution** A robot control architecture employing high level control IndiGolog along with a way to correct the belief of a robot based on the environment.

- **Previous Research** For past literature, the paper discusses some related key works, some of which are dealing with detection of sensor failures and recovery due to change of environment and a particle filter that detects faults from noisy observation.
- The paper then discusses architecture used by fellow researchers to improve robustness especially in the case of unexpected external events. An architecture that was specifically highlighted was the Livingstone architecture which was model-based reasoning.
- It allowed high dependability without the need to handcraft a solution for each recovery process.
- A paper on execution monitoring approach had also been published which was similar to this paper but the novelty of this paper is the sophisticated diagnosis system along with the architecture.

- **Situation Calculus** In this section the paper builds up the epistemology and reviews the requirements needed for understanding the work done. Situation calculus describes the sequence of actions that leads up to a certain world state. It has 5 fundamental parts:
    1. Mapping a situation and action to its successor situation.
    2. Initial state axioms specifies values before execution.
    3. Valid action precondition certain axioms.
    4. The effect of an action is defined by a successor state axiom.
    5. Unique name axioms for actions.

- **IndiGolog** This is a logic based agent programing and planning language based on situation calculus. The plus points are the ability for one to select planning or specifying a set path of execution depending on the available computational resources.
- The paper then explicates the working of IndiGolog with a sample case.

- **History Based Diagnosis** Due to dynamic environments, a conflict is developed between the robots internal set of beliefs and of what it perceives. To deal with this, the set of action leading up to the conflict is analyzed.
- A set of artificial valid actions are then generated to create history variations in which there is no conflict with the observation, this is known as 'Explaining Diagnosis'.

- **Robot Belief** The paper expands on the importance of a robots belief state and how its internal belief state can repaired according to what it has externally detected through the use of an alternate history which describes of how it came to its current state. Repair in terms of this paper is a current situation that has been replaced by an adapted situation.
- As for the indGolog system, the program generates valid hypothesis based on the initial situation which are tested against the data base until a scenario matches the current situation.
- The hypothesis are generated by variation of execution paths and additionally by introducing exogenous events which are all developed on the basis of the history diagnosis. Each true hypothesis is then compared with other true hypothesis and each have their own weight. So any hypothesis with less cost in regards to its development based on the history are more plausible and are the likely candidates to be selected.
- The number of hypotheses developed are limited to a certain pool limit. The drawback is that no guarantee can be provided of whether a hypothesis is true as several hypotheses may explain an inconsistency.
- Additional information may help pruning weak hypothesis but does not solve this problem which is a general problem in diagnosis.

- **Experimental Results** A simulated case utilizing the defined framework showed that a robot with the framework out performs a robot without the framework under occurrences of faults where fault is the dynamic environment. Following the simulated case, two real world test cases were conducted which showed similar positive result as the simulated test case.

- **Future Direction** The ability of an agent to prune discriminatory action independent of the information in the current system. A robot that can perform complex task in complex environments (i.e. kitchens). Compact representation for planning models.

Keywords

dependable perception-decision-execution cycle, autonomous robots, dependable operation, nondeterministic robot, malfunctioning hardware, inaccurate sensors, exogenous events, incomplete knowledge, robot belief inconsistency

Notes

A new approach to the typical sense-plan-act by amalgamating two techniques using logic programming and history based diagnosis which resulted in positive test case both within the simulation and real world test cases.

Contributions

A control architecture with history based diagnosis that corrects the belief state of a robot.

Deficit

A well composed paper. It is difficult to point out a deficit.

Safe and Dependable Physical Human-Robot Interaction in Anthropic Domains: State of the Art and Challenges
Reference

DOI: 10.1109/IROS.2006.6936985

Year: 2006

Author: R. Alami ; A. Albu-Schaeffer ; A. Bicchi ; R. Bischoff ; R. Chatila ; A. De Luca ; A. De Santis

Abstract

In the immediate future, metrics related to safety and dependability have to be found in order to successfully introduce robots in everyday environments. The crucial issues needed to tackle the problem of a safe and dependable physical human-robot interaction (pHRI) were addressed in the EURON Perspective Research Project PHRIDOM (Physical Human- Robot Interaction in Anthropic Domains), aimed at charting the new "territory" of pHRI. While there are certainly also "cognitive" issues involved, due to the human perception of the robot (and vice versa), and other objective metrics related to fault detection and isolation, the discussion in this paper will focus on the peculiar aspects of "physical" interaction with robots. In particular, safety and dependability will be the underlying evaluation criteria for mechanical design, actuation, and control architectures. Mechanical and control issues will be discussed with emphasis on techniques that provide safety in an intrinsic way or by means of control components. Attention will be devoted to dependability, mainly related to sensors, control architectures, and fault handling and tolerance. After PHRIDOM, a novel research project has been launched under the Information Society Technologies Sixth Framework Programme of the European Commission. This "Specific Targeted Research or Innovation" project is dedicated to "Physical Human-Robot Interaction: depENDability and Safety" (PHRIENDS). PHRIENDS is about developing key components of the next generation of robots, including industrial robots and assist devices, designed to share the environment and to physically interact with people. The philosophy of the project proposes an integrated approach to the co-design of robots for safe physical interaction with humans, which revolutionizes the classical approach for designing industrial robots – rigid design for accuracy, active control for safety – by creating a new paradigm: design robots that are intrinsically safe, and control them to deliver performance. This paper presents the state of the art in the field as surveyed by the PHRIDOM project, as well as it enlightens a number of challenges that will be undertaken within the PHRIENDS project.

Summary

- **Introduction** This paper is about interaction of humans with robots. The paper starts by describing the increasing dependency and interaction of humans with the autonomous systems and how it has an exponentially growing effect in human lives. Robots that are used for physical assistance and that operate within close proximity require critical safety and dependability. For this, due to the impossibility of modeling each and every scenario of the world which the robot can face, robots are required to perform intelligent actions based on perception (i.e. autonomous system). However, due to the mechanical structure of a robot, any accident with them results in catastrophic repercussion for their biological counterparts. Despite of the need for robots to be autonomous, an exercise of caution should be made regarding the social and ethics. A difference of a robot is also clarified as to why it is not viewed as a mobile computer, reason being is due to human mentality (i.e. our nature to associate things with anthropomorphism). Other factors depend on the role and interaction of the robot with the person.

- **Physical Human Robot Interaction (pHRI)** is an important domain for paving the path for safe and dependable robots. This domain includes workshops, projects and conferences. A expansion based on this domain physical human-robot interaction which is dependable and safe (PHRIENDS). This domain is for the development of key domestic and industrial robots. PHRIENDS pushes the state of art in two directions:

  - Integration of dynamic and more efficient algorithms within existing robots.
  - New architecture for core components of robots that have been well designed and tested.
- **PHRIENDS** requires involvement of diverse fields and is research focused. This enables effective and efficient applicability of robots in various environments.

- **Safety and Dependability** The aspects focused is to prevent collision with the robot and its user. The criteria used has been borrowed from the automobile industry in which the acceleration of human body parts are correlated with the severity of injury. The main field that can effectively deal with this is the mechanical domain through design. Another aspect for enhancing safety is the introduction of sensors which intelligently supervise the manipulators and actuators. The drawback of safety is the loss of fast and precise movement provided by the robot. This is an open question.

- **Safety Standards** Currently, for robotic industries, the ANSI (American National Standard for Industrial Robots and Robot Systems – Safety Requirements) is used as the go to standard. The downside of this standard system is when a robot shares the operational space with humans and is not very useful in unstructured anthropic domains. Currently a number of organizations (at the time this paper was being written) are attempting to consolidate a standard for safety with humans robots. Important aspects that are being investigated are as follows:
  - Control reliability
  - Safeguarding and clearance
  - New modes of operation
  - Risk assessments in place of fixed rules
  - Safety critical software
  - Dynamic limits
  - Emergency stops
  - Man-Machine Interface

- **Injury Criteria** This criteria is specifically for injuries caused by a robot directly or indirectly. As mentioned previously the automotive industry have predefined a criteria known as Abbreviated Injury Scale (AIS). If more than one body part is involved, the one with the maximum injury severity is the overall injury named (MAIS). The downside is there is no way to measure the injury provided by the index, only the severity is provided. Each body part has their own criteria for measuring the severity (e.g. Head Injury Criterion (HIC).)

- **Issues for pHRI Design** The major issue for pHRI can be dealt with proper mechanical design. The issues which cannot be offset by the design are handled by sophisticated robot architecture. However, even with robust architecture and well designed components, system faults and in-predictable human behavior present a challenging task.

- **Mechanics and Actuation for pHRI** The first and most important aspect is to minimize injury caused by collision of robot with a human. This can be done in the transmission phase of the power of relocating the weights. This can be done by transferring the inertia between the links of the robotic arm. Variable impedance actuation allows mechanical components to varies its stiffness, damping and gear-ratio which ensure minimal damage. Distributed Macro-mini actuation allows to reduce inertia of a manipulator arm while preserving performance. Real time motion planning allows for the most viable way of prevention of damage. Fault handling is the main aspect which when handled properly can provide maximum dependability and safety.

Keywords

Anthropic Robotics, Physical Human-Robot Interaction, Safety and Performance, Dependability

Notes

A comprehensive review of the state of the art of in safety and dependability.

Contributions

Current development in dependable robots.

Deficit

A more in depth review of the approaches and techniques discussed.

Toward a More Dependable Software Architecture for Autonomous Robots
Reference

URL: https://homepages.laas.fr/felix/publis-pdf/ieee-ram-ser08.pdf

Year: 2008

Author: Saddek Bensalem, Matthieu Gallien, Félix Ingrand, Imen Kahloul

Abstract

Autonomous robots are complex systems that require the interaction/cooperation of numerous heterogeneous software components. Nowadays, robots are getting closer to humans and as such are becoming critical systems which must meet safety properties including in particular logical, temporal and real-time constraints. We present an evolution of the LAAS Architecture for Autonomous System and its tool GenoM. This evolution is based on the BIP (Behaviors Interactions Priorities) component based design framework which has been successfully used in other domains (e.g. embedded systems). In this study, we show how we seamlessly integrate BIP in the preexisting methodology. We present the componentization of the functional level of a robot, the synthesis of an execution controller as well as validation techniques for checking essential safety properties. This approach has been integrated in the LAAS architecture and we have performed a number of experiment in simulation but also on a real robot (DALA).

Summary

- **Introduction** The paper begins with an introduction to autonomous robots. It defines an autonomous robot as machine that performs complex task in order to achieve a goal independently, specifically in cases where it is unfeasible for humans or if it is more cost effective. Currently, the issue of safety and dependability is backed by only two factors being simulation and testing.
- **Architecture and Tools** For the development of architecture a number of things must be kept in mind such as the context of the working environment, software integration, temporal requirement etc. The typical architecture within robotics is layered architecture which allows control of flow. More advanced architecture are able to translate symbolic language into low level functions in languages like C or C++. Along with these features, countless others have similar features in varying degrees with their own benefits and deficiencies. However, all these architectures have a formal safety criteria which can be checked by certification bodies to ensure safety and dependability of the robots.
- **Desired Properties** A few properties which are desired within a robot are as follows:
  - Deadlock Detection (Prevention of deadlock during execution)
  - Temporal Constraints (Guarantee that in an initialization action 1 will be performed before action 2)
  - Timed Constraints (An action will perform within the given time limit)
- **Formal Methods** The methods that are in use are currently model checking and theorem proving. Model checking has been successfully used and implement for hardware designs which ensures a system is working as intended. It is much better than the typical testing method due to its cost effectiveness and efficiency compared to testing. An issue with these methods are that model checker are limited by the state space where as theorem proving requires a lot of time investment by humans for a very little gain and it cannot be ported into other systems. The biggest shortcomings are design, validation and maintenance.
- **Proposed Solution** This paper proposes a modified architecture of the existing LAAS architecture which ensures online safety properties. This modified architecture can be verified offline with verification and validation tools and suites. This however, cannot deal with silent failures (i.e. situations where sensors or actuators go out of control and the main controller cannot observe this behavior). The architecture is based on component based design approach (BIP).
- **LAAS** This a multi layered architecture that allows addition of different process at various levels. It has 3 main levels, decisional level that deals with task planning, functional level that contains all the pre-built modules of action and perception of the robot and finally the execution level that is the interface for the decisional level and functional level. The paper deals with 2 level, the functional level and the execution level. The paper goes on to explain in depth the working structure of the LAAS, defining relevant components which have subjected to modification.
- **Component Based Design** Is very critical for large and complex systems as it allows cost effective and evolvable systems. Its advantages range from re-usability, modular analysis, validation, reconfigurability and controllability. This is especially useful in robotics as it allows a structured approach in the development process.

- **Behaviour Interaction Properties (BIP)** It is a software that is used for diverse real time components. It has three layers: the lowest layer describes it behavior through transitions, the middle layer describes the interactions between the transitions and the upper layer consists of a set of priority rules used to describe the scheduling policies of the interactions.
- **Work Done** In this paper the, one of the works that have been done is the replacement of the typical R2C module which is in the LAAS architecture with the BIP model which allows for the interaction between modules while give a great deal of control and flexibility. The method of how this has been mapped into the existing LAAS structure has been discussed in great detail with the research paper. The next section deals with the implementation of the architecture in real robots and simulation.
- **Conclusion** The crux of the paper is the proposition of a mathematical basis for autonomous robot system modeling and analysis that enables seamless validation of robotic systems. The model proposed is a modified version of LAAS which is component based and has been test in a simulation case and real world case. The test case proved successful structural analysis techniques for deadlock detection and for verification of safety features. Similar approaches can be developed to enable and extend the current model for error recovery.

Keywords

robot, evolution, methodology, validation, properties, architecture, safety, interactions, priorities

Notes

This paper describes the state of art upto its period while presenting a modified architecture for safety and dependability.

Contributions

A new architecture which is the synthesis of LAAS and BIP.

Deficit

A more coherent and clear explanation of the implementation of the proposed architecture.

4.2 Fault Detection

Robotic fault detection and fault tolerance: A survey
Reference

DOI: 10.1016/0951-8320(94)90132-5

Year: 1994

Author: Mattias Nyberg and C Mattias Nyberg

Abstract

Fault tolerance is increasingly important for robots, especially those in remote or hazardous environments. Robots need the ability to effectively detect and tolerate internal failures in order to continue performing their tasks without the need for immediate human intervention. Recently, there has been a surge of interest in robot fault tolerance, and the subject has been investigated from a number of points of view. Ongoing research performs off-line and on-line failure analyses of robotic systems, develops fault-tolerant control environments, and derives fault detection and error recovery techniques using hardware, kinematic, or functional redundancy. This paper presents a summary of the current, limited, state-of-the-art in fault-tolerant robotics and offers some future possibilities for the field.

Summary

•**Introduction** This papers presents the research trends that were goingon that time focusing on fault detection and fault tolerance specifically focused on the robots with rigid links, though the method is generally applicable to all bots.

•**Robotic Systems** The paper starts off by describing a robotic system whichin the current trend of papers is rare. It classifies the robots according to the number of their links and their type of links. It then describe the typeof drive for the robotic link and then discusses the degrees of freedoms within the robot.

•**Modelling** The paper then talks about the robotic control and how itcan be modeled. This is focused more on the newtonian based modeling.In this type of modeling the robot uses sensors to detect errors and itcompensates for these errors. Though these internal monitoring sensorsadd additive cost. More advanced robots have more sensors.

•**Robotic Failure** The next topic discussed is the robotic failure. This is highlighted by a test case in which one of the encoders froze up and caused the robot to move around wildly. This occurred due to the compounding of errors accumulated through noise and disturbances. Another point to note is if the sensor fails then the controller will continue feed wronginformation that can lead to catastrophic failure. This information is relevant because the freezing of encoders at that time were fairly common. Another limitation is that the robot would have no information on which hardware component has failed but will be only aware that the action hasn't been executed. To enhance the fault tolerance within a system, multiple sensors effectively increases the fault tolerance of the robot.

•**Prevention** Detecting failures are paramount as these chain up and cause system wide failure very quickly. This can be prevented brakes and locks.The surviving joints then can be modified to take over the workload of failed joint.

•**Failure of Critical Components** The paper moves on to feature the critical components of a robot and their most likely failure rates along with possible solutions. The paper indicates that usually the error occurs due tohuman error and improper algorithms. It highly stresses the fact of need of perfection of fault isolation and fault tolerance. They hint towards the future possibility of knowledge based modeling.

•**Failure Analysis** Failure analysis is the next area in which the paper focuses on. As in this point in time there was no concrete models for failure analysis, hence, they were utilizing the Failure, Mode, Effect and Criticality Analysis to deal with failure analysis. This method implements tabulation formulation of all possible failures and develops a chart. This is done for the design phase and this is an on-line tool(dynamic structural database). The paper goes on to explain the advantages, limitations and the versatility of FMECA. A FMECA is only as good as the analyst who creates it, so needless to say, the better the analyst, the better the result.

•**Alternate** FMECA a more detailed form of FMECA is the Fault Tree Analysis FTA. It is as the name suggests a tree which one can follow a sequence event to reach a failure alternatively back track to the route. These detailed trees can help pin point the fault within a system very quickly.The paper gives a very relevant figure which demonstrates the FTA. Another method is Failure Environment Analysis Tool FEAT developed by NASA that employs digraphs instead of logic gates in FEAT.

•**Noise** The data gathered from failure analysis, could then be used to generate probabilities of failures for each of its sub components and thena tolerance system then may be developed to counteract such failures.Though all this sounds, "sound". The complexity of this grows exponentially, the trees, probability, redundant sensors, common failures, commonmodes etc... Therefore, the designer must take into account static failures in which the unlikely possibilities can be ruled out.

•**Reliability** Reliability data and standards are present but only for specifications of parts and implementing systems as well as procedures that mayhelp designers. This field is very expansive and goes beyond the scope ofhardware standards and software standards. A common reference to lookto is the Military hand book for electronic component as suggested by theauthor.

•**Expert Systems** The paper then describes Expert Systems and Long term Analysis. Expert systems simply can be thought of as a comparator of fault diagnosis and fault tolerance and is aware of everything going on within its system. It is meant to be highly intelligent and perform optimum actions and decisions. Basically a expert system can be equated to a highly trained person capable of developing logical, intelligent and feasible decisions and then implementing them while dealing with any issues that pop up.

•**Fault Tolerance** The second last topic that the paper deals with is with fault tolerance. It emphasizes on sensors for fault tolerance. Some other ideas presented were adding duplicates which work in coherence but if one fails the other can take up its load (Structural Redundancy).Similarly this can be done with joint for increasing the degree of freedoms DOF's. (KinematicFault Tolerance). However, for Functional redundancy when the controllerreceives inconsistent data it simply turns off as there is no room for failure, an example would be the system used in the space shuttles. Some ingenious solutions use dissimilar components with some modification toperform the same function like the tachometer and the encoder. In Roboticcomputer fault tolerance is induced by artificially elongating run time sothat other task can perform their fault handling. A lot of techniques are possible such as set switches, isolation of the processor core etc.

The most ideal thing is to have a robot to successfully switch between the various parallel core available within it during or before the failure.

•**Fault Detection** The last section of the paper deals with Fault Detection,it is similar that a hypothesis is developed via residual generation throughtechniques like kalman filter, then based on the pattern failures are de-tected. Apparently redundancy is the golden word that can describe thesolution of this paper. It solves almost everything but is limited only by the application. It goes on to explain fault detection with state space modeland how redundant components are modelled in. It then also touches onhow to avoid false alarm caused by the modelling of uncertainty and thatis done by setting a thresh hold.

Keywords

Automobile, Classification, DC motor, Diagnostic reasoning, Fault diagnosis, Fault-detection, Fuzzy logic, Health monitoring, Inference, Lateral driving behavior, Neural networks, Outflow valve, Parameter estimation, Parity equations, State observers.

Notes

This paper despite its age presents the very foundation and basics of fault tolerant systems and all the methods and implications used within the time. As it is a survey, surveys are always useful to get an idea what was going on within that time span as well as the culmination of the research of the previous years. This paper is especially useful because it answers the questions when one would look to modern research papers and say why not use this simple technique or use that technique. Once a person reads some of the modern literature and comes back to read this, all the difference progress becomes clear and how researchers like the authors of this paper have paved the way for robotics.

Contributions

A detailed survey that has the culminated knowledge of robotics up to 1994.

Deficit

For that time, I would consider that there is no deficit and I presume this paper would be on par with the state of the art.

Expert System Framework For Fault Detection and Fault Tolerance in Robotics
Reference

DOI: 10.1016/0045-7906(94)90035-3

Year: 1994

Author: Visinsky, M. L. and Cavallaro, J. R. and Walker, I. D.

Abstract

Fault tolerance is of increasing importance for modern robots. The ability todetect and tolerate failures enables robots to effectively cope with internal fail-ures and continue performing assigned tasks without the need for immediatehuman intervention. To monitor fault tolerance actions performed by lowerlevel routines and to provide higher level information about a robot;s recov-ery capabilities, we present an expert system and critic which together form anovel and intelligent fault tolerance framework integrating fault detection andtolerance routines with dynamic fault tree analysis. A higher level, operatingsystem inspired critic layer provides a buffer between robot fault tolerant opera-tions and the user. The expert system gives the framework the modularity andflexibility to quickly convert between a variety of robot structures and tasks. Italso provides a standard interface to the fault detection and tolerance softwareand a more intelligent means of monitoring the progress of failure and recoverythroughout the robot system. The expert system further allows for prioriti-zation of tasks so that recovery can take precedence over less pressing goals.Fault trees are used as a standard database to reveal the components essentialto fault detection and tolerance within a system and detail the interconnectionbetween failures in the system. The trees are also used quantitatively to providea dynamic estimate of the probability of failure of the entire system or varioussubsystems.c©1994.

Summary

•**Introduction** This paper deals with expert systems for robots that havethe flexibility and intelligence to prioritize and adapt during operations, specifically in fault recovery. The paper starts out by pointing out the importance of fault tolerance in real world applications and how its development may very well be crucial for success in certain tasks.

•The proposition of the paper is of a critic monitor which monitors all interactions between the human and the robot as well as all the other failures including failures that may disrupt the robots mission. The novelty of this approach is the modularity and applicability of it. The paper discusses how the expert systems use fault trees, digraphs etc.

•**Robots Software Composition** After the introduction the paper talks in stages about the various composition's of a robotic system. Initially itstarts off by the fault tolerance framework. The framework is usually dependant on the computer architecture. It defines and discusses the fundamental Operating Systems architecture which basically is that it allows users to communicate with the robot. The interaction of the users go through a shell and is then passed onto the kernel. So, OS>Shell(Critic Shell in this case)>Kernel. The kernel is where the expert system lies and where it performs a check through the fault tree data base.

•**Kernel** The kernel shell has three layers.

1. Layer 1 is the continuous servo layer.
2. Layer 2 is the interface monitor layer
3. Layer 3 is the discrete supervisor layer.

Layer 1 deals with the robot and the robot controller.Layer 2 deals with the motion planning, fault detection and the fundamental fault tolerance. Layer 3 deals with the upper capability of fault tolerance and general commands for the robot.

•The expert system allows for the removal of obsolete nodes within a fault tree data base based on information acquired from interface layer. It then informs the user and user can keep an eye on the fault tolerance of the system and apply corrective measures if necessary.

•Along side the expert system also suggest recovery actions based on the faults. Usually which each fault in the fault tree, it has a corresponding recovery action which the expert system carriesout. Whilst the components are failing the expert system continues toupdate the probability informing the operator of the status of the fault.

•The proposed solution has the culminated knowledge of NASA's expert system and the traversing scheme through the fault tree provides a structured approach for the supervisor layer. The parts of the expert system is modular and can easily be integrated.

•**Fault-Trees** The paper then elaborates on fault trees. Fault trees are basically a data base that encapsulate a fault and its recovery action andit consists of faults ranging from software to hardware along with interaction. The expert systems is based on ”AND” or ”OR” gate, when a branch is pruned, it is not lost permanently but only for the duration until the recovery action has been implemented. This entire process is than explained via four link robot example. Future direction for the expert system is that its system task can be expanded and updated due to the nature of its modularity. The further possibilities includes monitoring the work space and preventing of immobility of joints.

•**Probability of Failure** The paper then goes on to explain the probabilityof failure and how it is inserted within the fault tree. The method of calculating the failure is also presented along with the probability rate.

•**Critic Shell** The final thing discussed in the section is the critic shell. Itis like the linux systems concept of normal user and super user in thatany command that can compromise the system or alter core function isrestricted unless the operator/user has complete access. The process issimilar to that which has been explained as to how it updates system layer. A thing to note is the warnings can be over ridden by super users. A critic shell maybe composed of two things User Interaction Finite StateMachine and Critic Finite State machine.

•**Finite State Machine** A User Interaction finite state machine awaits command inputs which are inserted into a list and when they are ready torun, it enables the critic finite state machine. Once the critic finite statemachine gives the green signal then the next command is run. The criticfinite state machine analyzes and provides suggestion based on a poste-riori knowledge of automated systems. The critic is held accountable forthe safety of the robot system. It monitors both the user and the robot kernel. The paper then moves on to provide an example on this.

•**Conclusion** Summing up the paper, it introduces a process to sequentially add errors as well as proposes a novel OS critic shell architecture which can prevent failure and damage. The key to this is the fault tree data base utilized by an expert system. The fault tree is multi purpose and can be used for fault detection, recovery as well as diagnosis. Since the system is modular, it can be easily expanded and upgraded.

Keywords

Robotics,expert systems,fault detection,fault tolerance

Notes

An interesting approach of how early researchers worked upon expert systems and introduced knowledge based systems to deal with faults within a robot.

Contributions

Critic Shell that monitors the user and the kernel of a robotic system.

Deficit

No clear deficit based on its time.

A Survey of Fault Detection, Isolation, and Reconfiguration Methods
Reference

DOI: 10.1109/TCST.2009.2026285

Year: 2010

Author: Hwang, Inseok and Kim, Sungwan and Kim, Youdan and Seah, Chze Eng

Abstract

Fault detection, isolation, and reconfiguration (FDIR) is an important and chal-lenging problem in many engineering applications and continues to be an activearea of research in the control community. This paper presents a survey of thevarious model-based FDIR methods developed in the last decade. In the paper,the FDIR problem is divided into the fault detection and isolation (FDI) step,and the controller reconfiguration step. For FDI, we discuss various model-basedtechniques to generate residuals that are robust to noise, unknown disturbance,and model uncertainties, as well as various statistical techniques of testing theresiduals for abrupt changes (or faults). We then discuss various techniquesof implementing re-configurable control strategy in response to faults.c©2006IEEE.

Summary

•**Introduction** This paper is a survey that discusses the Fault detection, Isolation and Reconfiguration Methods(FDIR). It provides a complete overview on methods employed within the last 10 years of its publication. It attempts to explain as many techniques used instead of selecting a few techniques and explaining them in detail. Initially the paper introduces and clarifies the need of FDIR and its implications in various fields. Then it goes on to expand on the methods used within FDIR and the gives a brief overview the research that has been done and improved on it mainly on the quantitative models.

•**Why FDIR?** The paper explains that FDIR is a control methodology which allows continued operation when a fault is detected where as fault being defined as a deviation from the acceptable standard. This is achieved by either hardware redundancy or analytical redundancy. In hardware redundancy duplicate signal that are produced by multiple sensors are processed by methods like cross channel method or residual parity. For analytical redundancy mathematical models are used. This removes the need for extra hardware, though it is quite a bit more challenging to ensure robustness. It has mainly two models qualitative model and quantitative model and this paper focuses on the quantitative side of things.

•**Analytical Redundancy** The analytical redundancy can be broken downinto 3 steps:
Step 1, Generate data of residues ideally with no fault condi-tion that are immune to noise and disturbances. Each residue should besensitive to only a specific type of fault.
Step 2, Decision step in where alogical decision is made whether a fault has occurred or not, notably thisstep is the fault detection and fault isolation step.
Step 3, The control is then configured for appropriate response.

•**Approaches For Dev. of Residues** Ways to develop residues is throughmodelling a system but due to reality being inconsistent with ideal environments, two other approaches are usually employed.
Approach 1: Robust residual generation: residues are immune all but to time specificfaults.
Approach 2: Robust Residual Evaluation: Hypothesis algorithmsthat test residuals as random variables. This is done by testing to see if a residue exceeds a certain limit.

•**Basic Building Blocks** In the next section of the paper a brief run-down of fault detection, isolation and reconfiguration is given. The paper gives a general test case scenario and describes the system along with residues linearly via state space representation. It goes through the modelling and requirements of each of the five stages being system fault modelling, residual generation, fault isolation, decision making and reconfiguration. After formulating a sample state space of a system with a fault. They define the number of methods that can be employed for residual generation. These methods are later discussed in greater depth in a later section. The nextstep is to pin point the fault. Second last step is to make a decision ofwhat actions to execute, this is done usually on statistical methods and the final step is reconfiguration in which the controller adapts to the changes provided by the decision unit.

•**Residual Generation Method** The paper then goes on to discuss the residual generation methods. It starts out with the most basic of methods being the full state observer based methods. In this system eigen structure assignment method is used or fault detection filter method is used.

•**Methods Principle** This residual method deals with the unknown input observer. In this method the input disturbance the residual generation is independent from the noise and disturbance. Selection of ideal parameters are given by researchers who have worked on optimizing this method. Each researcher positively contributed to this paper by introducing transformations, convergence techniques etc...

•**Working of Other Methods** The paper then goes on to explain the working, research and improvements on the remaining residual methods being parity relation approach, optimization based approach, kalman filter, stochastic approach, system identification model, non-linear systems, discrete event systems and hybrid systems and A.I techniques.

•**Detecting Variation in Residues** The paper now deals that once the residues are developed, how to detect the variation within them and how to shed light on the indicated faults. This is done by testing the residue against abase hypothesis. For each fault there will be a separate hypothesis. This is done over a sequence of time. The hypothesis techniques that are discussed are SPRT, CUMSUM algorithm generalized likelihood ratio testand local approach.

•**Reconfiguration** The final critical area of the paper deals with how a controller performs reconfiguration: This is done by Multiple Model approach and adaptive control approach. The first one is similar to a switching mechanism when failure occurs or mode switching whilst the second one is closer to reconfiguring itself and adapting to the new situation.

•**Conclusion** The paper closes by discussing the comparing all the papers that it talked about while making the pros and cons prominent discussed earlier.

Keywords

Analytic redundancy, fault detection, fault isolation, fault reconfiguration, Survey

Notes

It is like a dictionary in which I can look up the optimal technique for dealing with a fault and implement the solution although it out dated. It provides the solid background knowledge required to go further within fault detection and isolation.

Contributions

10 years of research in Fault detection and Isolation compressed into 18 pages.

Deficit

The paper could have covered every single technique available.

Fault Detection and Localization Method for Modular Multilevel Converters
Reference

DOI: 10.1109/TPEL.2014.2348194

Year: 2015

Author: Fujin Deng ; Zhe Chen ; Mohammad Rezwan Khan ; Rongwu Zhu

Abstract

The modular multilevel converter (MMC) is attractive for medium- or high-power applications because of the advantages of its high modularity, availability, and high power quality. However, reliability is one of the most important issues for MMCs which are made of large number of power electronic submodules (SMs). This paper proposed an effective fault detection and localization method for MMCs. An MMC fault can be detected by comparing the measured state variables and the estimated state variables with a Kalman filter. The fault localization is based on the failure characteristics of the SM in the MMC. The proposed method can be implemented with less computational intensity and complexity, even in case that multiple SM faults occur in a short time interval. The proposed method is not only implemented in simulations with professional tool PSCAD/EMTDC, but also verified with a down-scale MMC prototype controlled by a real-time digital signal controller in the laboratory. The results confirm the effectiveness of the proposed method.

Summary

- **Modular Multilevel Converters (MMC)** are devices that generates voltage at multiple levels while reducing switching frequency, which is a useful and attractive option for high voltage and high power application. Reliability is an important and core aspect for MMCs which makes detecting and locating the fault critically vital. The typical method for fault detection is model based, artificial intelligence based and signal processing based. The disadvantage of some of these are high level of processing requirement, accuracy and complexity.

- **Proposed Solution** This paper applies Kalman Filter (KF) for fault detection in MMC to improve their dependability. Due to the high amount of noise generated by the multitude of sensors within MMC. The KF is an ideal candidate for this task. An positive case for KF is that when it is applied to MMC open circuit, it is able to locate faulty modules precisely and effectively while other modules are also at fault without increase of implementation and calculation complexity.

- **Structure of MMC** A three-phase MMC has six arms in which each arm has a series of sub-modules (SMs), an arm inductor and a arm resistor. The upper arm and lower arm in the same phase make up the phase unit. Each SM has a bi-polar transistor half-bridge and a dc storage capacitor. Each SM is controlled by a switch into an ‘ON’ or ‘OFF’ state. In the ‘ON’ state the capacitor is either charged or discharged depending on the direction of flow of the current.

- **Kalman Filter for MMCs** Kalman filter working is that it takes two data sets, computes the covariance and then constructs a Gaussian distribution then computes the kalman gain (optimal estimate) which is an amalgamation of both datasets into a single more precise Gaussian distribution.
- From each data set it takes more data from the dataset that has more weight while weights are based on the Gaussian distribution of the data set.
- In this paper KF takes data of the inner difference current. Due to the nature of power electronics, it can remove the noise due to the iteration as KF is a recursive estimator and its framework is base predict-sense-update.
- The proposed solution is applied that when a fault occurs during the operation of MMC, the difference of inner current diverges from the average and when it goes above a certain threshold then an error is registered.

- **Failure Characteristics** In MMCs the following types of faults may occur, first is the open circuit fault in the first transistor of SM, second is the open circuit fault in the second transistor of SM and the third is the open circuit fault in the first and the second transistor in the SM. The reason for knowing these types of fault is that when type I or type II or type III fault occurs, each have their own separate voltage output which can be utilized for identification.

- **Phases of Fault Detection and Localization** Once a fault is detected using kalman filter, the fault localization algorithm is executed in both the upper and the lower arms of the MMC in which the voltage will be compared and as discussed earlier that the voltage signature for each type of fault is unique. For verification of the fault a tool PSCAD/EMTDC is used.

- **Simulation Studies** In normal situation the KF continuously computes the inner current difference in real time. In fault situation with type I fault, the inner current difference breaks the threshold and activates the fault localization algorithm. As mathematically proved within the paper, the voltage shows its unique signature and can be precisely located. Similarly for type II fault and type III fault, the inner current difference breaks the threshold and activates the fault localization algorithm in which the voltages are compared and based on their unique signature they are triangulated.
- **Experimentation Studies** For the experimental test cases an MMC prototype with 4 SMs, a DC power supply (SM 600-10) is used. The switch and diodes are the typical (IXFK48N60P) MOSFETS. In normal test conditions without any faults, the voltage of upper and lower arm are kept in balance whilst the inner current difference is continuously monitored by the kalman filter in real time. When open circuit fault in cell21, the difference in the inner current and predicted current and as expected the voltage levels change of the upper arm and the lower arm. The localization algorithm pinpoints the location of the error. Similarly, for type II and type III faults similar results were acquired.
- **Conclusions** MMC are devices that are widely used in high powered applications and due to the large number of sensors kalman filter is ideal . The failure within MMC are detected with kalman filter and the location is identified using a localization algorithm. The proposed solution has been verified by simulation and experimental test cases.

Keywords

fault detection method, fault localization method, modular multilevel converters, MMC, high power quality, power electronic submodules, Kalman filter, failure characteristics, computational intensity, computational complexity, PSCAD tool, EMTDC tool, real-time digital signal controller

Notes

Practical implementation of fault detection technique using kalman filter in high powered electronics. This research might be applicable when designing large scale robots that require high power regulation.

Contributions

Implementation of fault detection technique in a unique application for fault detection which demonstrated the portability of fault detection in different domains.

Deficit

The results of different test case were repeated quite a bit within the paper and a simple indication to the results would have sufficed.

Incipient fault detection and diagnosis based on Kullback-Leibler divergence using principal component analysis
Reference

DOI: https://doi.org/10.1016/j.sigpro.2014.06.023

Year: 2015

Author: Author links open overlay panelJinaneHarmouche, ClaudeDelpha, DembaDiallo

Abstract

Most of fault indicators are devoted to detect deviations related to specific features but they fail to detect and estimate unpredictable slight distortions often caused by incipient faults. The Kullback–Leibler divergence is characterised with a high sensitivity to incipient faults that cause unpredictable small changes in the process measurements. This work has two main objectives: first estimate the amplitude of incipient faults in multivariate processes based on the divergence and second evaluate, through detection error probabilities, the performance of the divergence in the detection of incipient faults in noisy environments.
Throughout all the paper, the Fault-to-Noise Ratio (FNR) has been referred to as a comparative criterion between the fault level and noise; particularly the region around 0 dB of FNR is of interest in the evaluation. A theoretical study is developed to derive an analytical model of the divergence that considers the presence of Gaussian noise and allows obtaining a theoretical estimate of the fault amplitude. After application on a simulated AR process, the fault amplitude estimate turns out to be an overestimation of the actual amplitude, therefore guaranteeing a safety margin for monitoring.

Accurate fault severity estimation for an eddy currents application shows the effectiveness of this approach.

Summary

- **Introduction** Fault detection and diagnosis are typically model based or history based. Some of the techniques used are statistical approaches in which trends are monitored. Amongst these statistical approaches, a powerful and classic approach known as ‘Principal Component Analysis’ (PCA) exists.

- **PCA** deciphers and reduces the dimension of a multi dimensional data set uncovering its hidden information. The PCA divides the the data into two subspaces, one principal subspace and the second residual subspace. This paper uses PCA to deal with the issue of incipient faults which can be equated to noise in data. Standard statistical methods are unable to detect unpredictable changes. PCA typically uses the statistics of ‘Hotelling’ and ‘Prediction Error’.
    - The T^2 within hotelling contains all the relevant information and is only able to detect the fault within independent variables.
    - The SPE detects faults within correlated variables. The shows the instantaneous variation and catches fluctuations. The issue is that SPE is always non zero, due to which the estimation is always biased.

- **Previous Literature Paper** that use the PCA techniques with hotelling and SPE have been discussed which can be summarized that the ‘missing’ piece or failing point of previous literature is due to noise and when the data is highly correlated then it is unable to detect the angular index, hence the error goes undetected. Another issue highlighted is that depending on the sensitivity and threshold set, false alarm/ misses plague the fault detection capabilities.

- **Categorization of Faults** This paper defines faults into two areas, first is abrupt faults and the second is incipient faults, where abrupt faults show clear indication within the measured data in the form or impulse or clear deviation whilst incipient data are masked with noise and remain hidden within the given dataset. The incipient faults are very subtle and an example would be that of a material failing before its prescribe life. Catching these faults enables the prevention of future abrupt faults. The key to catching incipient faults lie within the amplitude within the dataset.

- **Kullback Leibler (KL)** The amount of difference of one probability distribution from a second reference distribution is know as KL. This paper is part II of the series of enhancing fault detection using KL. In this paper an analysis model is developed and tested using the KL.

- **Fault Modeling** Faults that affect variables are modeled in such a way that its signature is in accordance with its signal properties.

- **Assumptions**
    - The incipient fault contribute very less to the signal characteristics and does not change the direction of the PCA model.
    - Gaussian distribution is assumed along axes. The subspace is directed along the first eigen vector of of the sample covariance matrix.

- **Calculation of the FDD Probabilities** Fault detection using KLD depends on the estimated divergence value produced by the decision function. This value is compared to a preset threshold value for making a decision. The predetermined value for the threshold is null in faultless case theoretically but due to noise there is always a small off-set. The threshold is based on the mean value and the standard deviation of the faultless dataset. Noisy dataset spoils the fault detection sensitivity, which can be mitigated by using a larger sample or filtering noise using a priori knowledge.

- **Simulation Results and Discussions** A data matrix of the input had been supplied to the proposed system in which when processed, the first principal component is accountable for 86.6% of variations and while counting the second principal component along with the first component, the variation is about 97%. The fault detection will be based on the divergence on both these components. Steps for minimization of the error has been done by taking a relatively large sample of $N=10^6$.

- **Fault Detection Performance Analysis** The error probabilities attained by applying the proposed method are considered as the random variables with a normal distribution. Mapping them into a graphical presentation and histograms through which the performance of this measured.

- **Applications** The proposed approach can be used within structural health monitoring systems, material engineering, aeronautics and any critical applications which require the detection of these masked faults. The entire procedure of applying this approach has been enumerated within the paper.
- **Conclusions** The KLD process is applied on a dataset that has been preprocessed with PCA. An estimation is then made based on divergence and the PCA's parameters. This estimate provides an accurate estimation of the fault amplitude very close to the actual value with a bit of overestimation which is used as a safety factor.

Keywords

Incipient fault Detection and diagnosis, Fault estimation, Kullback–Leibler divergence, Detection error probabilities

Notes

An Implementation of a fault detection technique to uncover subtle faults.

Contributions

A step by step procedure is provided for fault detection using the kullback-leibler approach.

Deficit

A more coherent structure for the paper.

Fault Detection Filtering for Nonhomogeneous Markovian Jump Systems via a Fuzzy Approach Reference

DOI: 10.1109/TFUZZ.2016.2641022

Year: 2018

Author: Fanbiao Li ; Peng Shi ; Cheng-Chew Lim ; Ligang Wu

Abstract

This paper investigates the problem of the fault detection filter design for nonhomogeneous Markovian jump systems by a Takagi-Sugeno fuzzy approach. Attention is focused on the construction of a fault detection filter to ensure the estimation error dynamic stochastically stable, and the prescribed performance requirement can be satisfied. The designed fuzzy model-based fault detection filter can guarantee the sensitivity of the residual signal to faults and the robustness of the external disturbances. By using the cone complementarity linearization algorithm, the existence conditions for the design of fault detection filters are provided. Meanwhile, the error between the residual signal and the fault signal is made as small as possible. Finally, a practical application is given to illustrate the effectiveness of the proposed technique.

Summary

- **Introduction** Currently, fault detection, isolation and reconfiguration has become a a vital and critical gear for safe and dependable systems. Amongst the multiple methods employed, model based, particle filter algorithms are the most trending and popular. The implication of fault detection has spanned into multiple fields and has greatly improved the performance various autonomous systems and industrial processes. Non homogeneous Markovian Jump Systems (NMJS) are based on time based transition probabilities matrix. Takagi-Sugeno (T-S) fuzzy model is a fuzzy dynamic model that deals with non linear system and models them into a framework. T-S fuzzy models are less effected by high dimensional data.
- **Contributions**
  - Construction of residual signal methodology used to deal with fault detection filter design, along with weight H_2 performance index for scrutinizing the noise fading performance. Additionally a developed algorithm for fault detection filter design.
  - Novel implementation of sojourn time dependent Non homogeneous Markovian jump systems.
  - Dimension reduced fault detection filter design.

- **System Description and Preliminaries** A stochastic non linear system over probability space can be represented in the T-S fuzzy model with a equation in which it has a state vector, control input, disturbance input, measured output, fault to be detected and constant matrices. An assumption is placed that the variable vectors have no dependency on the input variables. The equation model and its parameters are given in the paper. In the system a stochastic variable is used for the lacking measurement. The state vector is the fault detection filter and delta is the residual signal. Within this system an additional matrix called the weight matrix is added into the fault vector to optimize the fault detection system.
- **Fault Detection Filtering**
  - For non homogeneous Markovian jump system, we use the T-S fuzzy modeled system to generate a residual signal. Where this system is stochastically stable bounded with and H_2 norm.
  - An evaluation function will then compute the generated residual signal from with an existing predefined threshold. Depending on the threshold value, the fault can be detected.
- **Results** The paper goes on to prove some theorems in depth. The premise for theorem I is when given a noise that is fading and is greater than zero, it is possible to solve the containment problem if a definite positive matrix exists. The result of theorem I is that it provides sufficient parameters and ground for designing a fault detection filter. The premise for theorem II is that if we have a non homogeneous Markovian jump system, then for this system exists a fault detection filter in which its filtering error system is stochastically stable provided the system parameters meet the prescribed requirements.

- **Fault Detection Filter Problem** The fault detection filter problem can be represented by two condition for the system which have been presented within the paper. As it is difficult to solve these problems, the paper utilizes an iterative method to deal and solve the fault detection filtering problem which is terminated by checking a termination condition.

- **Simulation** For the simulation test, an inverted pendulum system is used.
- In the modeled system, there is the resultant force of the damper track, the random extension caused by the rough track, mass M which is connected to slider frame, mass m which is for the bob on the pendulum, length l that is for the length of the pendulum, g which denotes the acceleration due to gravity, angle theta, the vertical displacement y and u the applied force.
- Using state variables, this system is modeled with the Takagi-Sugeno (T-S) fuzzy model.
- To verify the working, a stuck fault is considered. The model is taken in discrete time as has been described within the previous section of the paper. Within the model the disturbance is denoted by omega, and T denotes the sampling time.
- Non uniform sampling periods were used for this simulation.
- The transition probabilities are given in a matrix where the unknowns are denoted by ‘?’.
- Plugging in the values and going through the steps, the residual function delta response is shown in which it can be observed that the faults can be detected in time and effectively.

- **Conclusion** This paper solves the fault detection filtering problem of the non homogeneous Markovian jump system by applying a Takagi-Sugeno fuzzy approach in which the fault detection is stochastically stable with noise attenuation level. Along with this an algorithm has been provided in linearizes the procedure, while additionally projecting the fault detection filter design problem into a minimization problem. This is backed up by a test simulation case along with proofs and theorems.

Keywords

Fault detection (FD), filtering, nonhomogeneous Markovian jump systems (MJS), Takagi–Sugeno fuzzy

Notes

An interesting implementation and application of fuzzy logic for fault detection.

Contributions

Proof along with design and implementation of Takagi-Sugeno Fuzzy model for solving fault detection filtering problem for Non-Homogeneous Markovian Jump Systems. A plus point was that the pseudo code was provided with which one can implement and test the proposed solution.

Deficit

80~90% of the paper is full of mathematical proofs which in of itself is valid but more meaningful and supportive contextual information could be provided that discusses aspects of the work done. In short, the remarks they provided in the paper was invaluable and more elaborate form of those remarks would be much appreciated as it is difficult to ease a person with no specialization in the subject into this paper.

A Dependency Detection Method for Sensor-based Fault Detection
Reference

URL: https://pub.h-brs.de/frontdoor/index/index/docId/4660

Year: 2019

Author: Bhat, P.; Thoduka, S. & Plöger, P. G.

Abstract

In Sensor-based Fault Detection and Diagnosis (SFDD) methods, spatial and temporal dependencies among the sensor signals can be modeled to detect faults in the sensors, if the defined dependencies change over time. In this work, we model Granger causal relationships between pairs of sensor data streams to detect changes in their dependencies. We compare the method on simulated signals with the Pearson correlation, and show that the method elegantly handles noise and lags in the signals and provides appreciable dependency detection. We further evaluate the method using sensor data from a mobile robot by injecting both internal and external faults during operation of the robot. The results show that the method is able to detect changes in the system when faults are injected, but is also prone to detecting false positives. This suggests that this method can be used as a weak detection of faults, but other methods , such as the use of a structural model, are required to reliably detect and diagnose faults.

Summary

- **Introduction** Fault detection and diagnosis is a core and critical topic as it paves the way for safe and dependable robots amongst the growing complexities of robotic systems. This paper approaches and tackles fault detection and diagnosis utilizing the spatial and temporal dependencies of the data gathered which frees it from the requirement of a priori knowledge.

- **Autonomous System** An agent that maps what is perceived into action by repeated sensing, building a belief based on the observed patterns. A complex system like this, with a multitude of hardware and software components working in parallel is prone to faults which in turn reduces the reliability of the system. Dynamic and variable environments introduce a new set of complexities and fault due to which, neutralizing the fault at the lowest level is vital for prevention of propagation of the fault.

- **Granger Causality** This test indicates whether previous values of a set Y is able to predict better future values for X rather then simply using the past values of X. This paper proposes a granger causality approach as a replacement for the traditional modeling of dependency approach. The paper users sensor data to apply the granger causality with fault injected into them (the internal system) which can also be further extended to external faults. The granger causality can be simply explained by an auto regression model as shown in the paper.

- **Previous Literature** The go to method for fault detection and identification is through the validation of data gathered from a sensor or multiple sensors. For single sensors it is ordinarily done by limit filtering or filter checking within a defined threshold whilst methods that use multiple sensors utilize information from the redundant sensors and is similar to as how physical redundancy works (i.e. data is adjusted based on the reading of multiple sensors on the same parameter).

- **Approaches for Fault Detection** MMAE Multiple Model Adaptive Estimation is the trendy approach in which parallel predictions are made for a multitude of faults and is normally used in wheeled robots. This model uses a multiple kalman filters for a single fault and has been used initially only for mechanical hardware failure but has been extended to sensor failures as well. Some other methods that are discussed are the supervised structural model Sensor-based Fault Detection and Diagnosis (SFDD) which is a hybrid between data driven and model based approaches. Metric-based distributed fault detection (MCDFD) correlates sensor data to metrics. Further details are mentioned within the paper but a thing to keep note of is that this method despite being widely used is highly susceptible to noise and the threshold limit.

- **Modeling Dependency** For modeling a statistical test is applied in which a null hypothesis is accepted if the past values from Y do not provide a better prediction and vice versa that the null hypothesis is rejected if past values from Y do provide a prediction. This is tested using restricted regression with an un-restricted model which has dependent and independent variable. The pseudo code is provided for this in the paper.

- **Comparative Study of Granger Causality with Correlation of Simulated Signals** For the comparison, the Pearson correlation co-efficient is compared with the Granger Causality method on simulated sine waves that contain lag and noise. The result with lag for this experiment is that the Granger causality method accurately detects dependency while the the correlation fails to draw appropriate conclusive results. This is for high frequency, in low frequency both methods have similar results. As for the result of the experiment with noise is similar to the one with lag that is, the Granger causality is more consistent, accurate and robust.

- **Experimental Evaluation and Results** An real world experimental test case is conducted using a ropod which is injected with faults consisting of internal faults like disconnecting encoder cable and external faults like inducing wheel slippage. The result of the test cases that a change to granger causal relation was observed for all test cases except for the wheel slippage. The Granger causality works much more accurately and effectively in real time but is slower than the correlation dependency.

- **Conclusions** This paper proposes Granger causality as an alternative approach to standard correlation for dependency detection for sensors. Based on the simulated cases using both Granger causality and Correlation dependency, Granger causality proved to be more effective and accurate with detecting faults especially with high frequencies. Some of the downsides of Granger causality is that it does not use information of redundant sensors but depends on predictions, is also computationally slower as well as susceptible to false alarms though it overcomes the disadvantages of Correlation dependencies.

Keywords

detection, sensor, method signals, faults dependencies, diagnosis

Notes

A new approach which I have not seen in other papers, though a link to a video that projects the process of fault detection in real time would be nice even with primitive interface.

Contributions

A new approach for fault detection.

Deficit

None.

Model-based fault-detection and diagnosis – status and applications
Reference

DOI: https://doi.org/10.1016/j.arcontrol.2004.12.002

Year: 2005

Author: Rolf Isermann

Abstract

For the improvement of reliability, safety and efficiency advanced methods of supervision, fault-detection and fault diagnosis become increasingly important for many technical processes. This holds especially for safety related processes like aircraft, trains, automobiles, power plants and chemical plants. The classical approaches are limit or trend checking of some measurable output variables. Because they do not give a deeper insight and usually do not allow a fault diagnosis, model-based methods of fault-detection were developed by using input and output signals and applying dynamic process models. These methods are based, e.g., on parameter estimation, parity equations or state observers. Also signal model approaches were developed. The goal is to generate several symptoms indicating the difference between nominal and faulty status. Based on different symptoms fault diagnosis procedures follow, determining the fault by applying classification or inference methods. This contribution gives a short introduction into the field and shows some applications for an actuator, a passenger car and a combustion engine.

Summary

- **Introduction** The classical approach for dealing with undesired behavior of a system is to implement three standard functions, which are, monitoring: It measures data and outputs an alarm if tolerance are breached, automatic protection: Based on the threat presented automatic counteraction kicks in and finally supervision with diagnostic: Analyzes data and produces an output decision based on the analysis.

- **Process Model-Based Fault-Detection Methods** Past work in fault detection haven been done using methods that measure the difference of dependencies among the variables. These dependencies are usually shown through mathematical models, where the core components are the input signal, the output signal, a detection method that creates residuals and parameter estimates known also as features. Comparison of change in features with the normal features lead to the detection of a fault within a system.

- **Fault** '*A fault is defined as an unpermitted deviation of at least one characteristic property of a variable from an acceptable behavior'.* If the fault goes unresolved it may eventually lead to a system failure. The paper has categorized faults as abrupt faults, incipient faults and intermittent faults. If viewed through the lens of a process models, then faults can be further classified into additive faults and multiplicative faults.

- **Fault Detection with Parameter Estimation** Process model based usually requires mapping a dynamic system into a model, however, this is not always viable as in the real world, cases are rarely fully known. To deal with this parameter estimation method is used in which estimates for the model is made based on the measurement value of the input and output values. A type of the parameter estimation approach is minimizing equation error and output error by parameters. If the parameter is linear it can be directly estimated. Another method uses optimization method for the data and is an iterative procedure.

- **Fault Detection with Observers** When a state parameter is fully known a state observer can be used or and output observer. Where state observers have a variety of ways which they can be implement as in using one state observer for one output or using multiple state observers for one output etc. An output observer is used when recreation of variables are not of use. So, simple linear transformation can be used for gaining the new state variables. This, however, requires precise information of the parameters.

- **Fault Detection with Parity Equations** This is a model based fault detection model in which a fixed model is utilized and is run simultaneous developing an output error. Another method similar to this is to generate an equation error. All the residues developed are additive and high dimensional data can be dealt by using state space model. These fault equations are known as parity equations and when they are modeled independently for input of the system and output of the system then residuals that are developed do not affect all the residues.

- **Fault Detection with Signal Models** The nature of signal whether it be electrical or mechanical in nature is that it display either harmonic or random behavior or a mixture of both. Fault detection is based on extracting certain features from the signal which is ordinarily the amplitude or the amplitude density. This achieved by imposing certain bandpass filters. Parametric estimations are also a valid option which allows for direct estimation.

- **Fault Diagnosis** To determine the type of fault based on information received from fault detection is known as fault diagnosis. It typically involves analytical and heuristic knowledge. The standard procedure is using relation between features or patterns, if these fail recognition is used. Typically the input is screened for any certain faults which have been stored or experimentally trained to detect. This is done by comparison of statistical feature or geometric features of the input with the fault features. Some methods utilized are the Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). These trees are usually searched by forward chaining or backward chaining. These normally require heuristic knowledge which have been developed by other researchers. In this paper, for fault diagnosis, it is limited to linear processes but some can be used in non-linear process but for real life and practical situations, a combined process is required to ensure fulfillment of requirement.

- **Conclusion** The paper discusses and provides a brief introduction to model based fault detection methods, parameter estimation, observers and parity equations and fault diagnosis methods. It then touches upon the expansive applications of how fault detection can be put to use in different domains. The disadvantage is that typically the fault detection processes have to be hand crafted to suit physical attributes. Amongst all the methods presented, the combined use of parameter estimation and parity equations have proven to be the most efficient and effective method.

Keywords

Fault-detection, Fault diagnosis, Supervision Health monitoring, Parameter estimation, Parity equations, State observers, Neural networks, Classification Inference, Diagnostic reasoning, Fuzzy logic, DC motor Outflow valve, Lateral driving behavior, Automobile, Combustion engine

Notes

It is a great paper that eases one into fault detection and diagnosis.

Contributions

Introductory paper.

Deficit

It would have been much appreciated if all the methods were discussed or at least mentioned in the appendix of the paper.

4.3 Fault Diagnosis

Real-Time Diagnosis and Repair of Faults of Robot Control Software
Reference

DOI: 10.1145/3146389

Year: 2006

Author: Gerald Steinbauer, Martin Mörth, and Franz Wotawa

Abstract

The use of robots in our daily lives is increasing. Different types of robotsperform different tasks that are too dangerous or too dull to be done by hu-mans. These sophisticated machines are susceptible to different types of faults.These faults have to be detected and diagnosed in time to allow recovery andcontinuous operation. The field of Fault Detection and Diagnosis (FDD) hasbeen studied for many years. This research has given birth to many approachesand techniques that are applicable to different types of physical machines. Yetthe domain of robotics poses unique requirements that are very challenging fortraditional FDD approaches. The study of FDD for robotics is relatively new,and only few surveys were presented. These surveys have focused on traditionalFDD approaches and how these approaches may broadly apply to a generictype of robot. Yet robotic systems can be identified by fundamental charac-teristics, which pose different constraints and requirements from FDD. In thisarticle, we aim to provide the reader with useful insights regarding the use ofFDD approaches that best suit the different characteristics of robotic systems.We elaborate on the advantages these approaches have and the challenges theymust face. To meet this aim, we use two perspectives: (1) we elaborate on FDDfrom the perspective of the different characteristics a robotic system may haveand give examples of successful FDD approaches, and (2) we elaborate on FDDfromthe perspective of the different FDD approaches and analyze the advantagesand disadvantages of each approach with respect to robotic systems. Finally,we describe research opportunities for robotic systems' FDD. With these threecontributions, readers from the FDD research communities are introduced toFDD for robotic systems, and the robotics research community is introduced tothe field of FDD.

Summary

•**Overview** This paper talks about fault detection, diagnosis and recovery in real time. It discusses the importance of this topic and how previous researches dealt with real time recovery and how there are a lack of researchpapers related to real time recovery in robots. It also conveys the message that this paper and any paper that deals with fault detection, diagnosis and recovery should deal with both the hardware and software side. It also backs up its proposed model by providing experimental data. It defines the control software that it uses and then introduces it's diagnosis

system which is based on old but proven model based diagnosis system. It follows three steps which are as follows.
Step (1) is to have observerunit that detects and recognize deviation within inputted data stream.
Step (2) It performs a diagnosis on the given deviation and contradictionswithin the system.
Step (3) It performs a corrective action which maybe restarting the operation, all the while being careful not to disrupt anyother systems which are dependent on it.
This point is especially emphasized of dependencies. The test case scenarios which they performed wereon two particular conditions, one was killing service whilst the Other reason deadlock service. The first is basically when the service crashes while the latter is about how the service malfunctions. They then go on to talk about how a well though fault detection, diagnosis and recovery system can actually be exported to other systems, mainly other control systems.In the end they indicated that the control systems that are able to recover from permanent faults may very well be the next step for the future of this subject.

•This paper is about:
–This paper uses model based diagnosis system for fault detection andlocalization for autonomous mobile robot systems.
–This paper also presents a solution for the autonomous robots to recover from located faults.

•This paper is relevant because:
–The solution is unique because all of the detection and recovery takes places during the run time of the autonomous robot.
–The method presented has also been tested experimentally during a competition. The data plotted and presented is the data collected from the robot that has participated in the competition.

•Previous works on this:
–A number of previous researchers have worked on fault diagnosis anddetection using a variety of methods including kalman filter, rulebased approach etc...

•Previous works deficiencies:
–Despite the amount of research papers on fault detection and diagnosis, very few researchers have implemented recovery system. Most of previous work focuses on the methodology for fault detection and diagnosis while few of them actually deal with recovery and even fewerof them deal with recovery in real time.

•Paper’s proposed solution:
–This papers proposed solution is real time fault detection and diagnosis as well as repair of the control software of autonomous robots. This follows the model based fault diagnosis.
–It has 3 main units,
(i) An observation unit that observes the change.
(ii)A unit that measure deviation via input from the observation unit.
(iii) A unit that implements restorative action.

•Paper solution is good because:
–The papers proposed solution is good because unlike the previous works done relating to fault diagnosis. This paper provides a realtime recovery system along with the diagnosis.
–The system for recovery and be applied also in non-robotic soft waresdue its general model.
–The model that has been formed is able to detect, diagnose crashes and deadlocks in the service and is able to repair and recover from them on the go.

•Future direction
–Improving the models by increasing the knowledge of the environmentas well as the the models for fault detection and diagnosis themselves.
–Automatic reconfiguration of hardware and software to recover frompermanent faults.

Keywords

Diagnosis, Control Software, Repair

Notes

This paper is interesting because it deals with fault detection and diagnostic in real time for the purpose of a robot competition. Due to the nature of the competitions, boundaries and innovations are usually pushed and it is quite intriguing to see the results they obtained during this competition.

Contributions

A practical and tested system for fault detection and diagnosis with "Real time recovery". Their data and contribution is especially interesting as it as said before has been collected during a competition which mimics real test case scenarios.

Deficit

Currently, In Robotics, expert systems, fault detection,fault tolerance not have enough knowledge to say what is missing. Though from what I have read up-till now, the fault is not with paper itself. The issue is that the paper is comparatively old and much research as been done on real time diagnosis and recovery, however, the points that have been raised are valid even today of system recovery from permanent faults and the ex-portability to other systems.

Real-Time Fault Diagnosis
Reference

DOI: 10.1109/MRA.2004.1310942

Year: 2004

Author: Verma, Vandi and Gordon, Geoff and Simmons, Reid and Thrun, Sebastian

Abstract

A number of complementary algorithms are now available for improving theaccuracy of fault detection and identification (FDI) with a computationallytractable set of samples in a particle filter. Each algorithm provides an inde-pendent improvement over the basic approach. All of these approaches requiredynamic models representing the behavior of each of the fault and operationalstates. The models can be built from analytical models of the robot dynamics,data from stimulation, or from the real robot.

Summary

•**Introduction** This paper offers a number models and algorithms for robots fault detection and diagnosis. Initially it talks about the need of such type of models and algorithms pointing out that through experience, the most well thought out and designed robots also encounter fault due tothe degradation and uncertain elements. Another thing they point outthat due to limited computability power available in a robot, the need for efficient and effective algorithms and models are paramount. Current methods (2004) like bayesian solution and other similar methods provide unrealistic information as doing an exact bayesian is difficult task.

•**Models** The models and algorithms presented increase the fault detectionand identification and has been experimentally verified. The models and algorithms used are exclusively particle filters as particle filters can handle noisy data, non-linear systems and provide a probability distribution. The method provided are also compatible with classical distribution methods like Markov decision process.

•**Fault Detection and Identification** The paper then goes on to briefly introduce and describe the basic definitions of Fault Detection and Identification (FDI). Fault is deviation from expected behaviour, Fault detection iswhere the fault has occurred and Fault identification is what type of fault has occurred. The paper is geared towards mechanical failures, brokenmotors, gears, environmental interactions, sensor failures etc. The next definition presented is State estimation which is determining a state of asystem based on a sequence of system data. There are two methods Batch and Recursive estimation methods. Batch treats all data similarly and is computationally expensive and is slower which is not ideal for FDI. However, recursive uses Markovs assumption of past, future and conditional independency to alter the data and uses this data instead of history forstate estimation.

•**Particle Filters** The paper then moves on to particle filters. Classical particle filters are discussed first using Markovs principles. Components are state, time and observation. These are for stationary models but if recursively used for continuous update. This method yields an approximation and no concrete solution. A proposed method of acquiring better results is by using transition probability in which the particles are given weights. The only issue is that a large number of particles is required to maintain reasonable probability.

•**Risk Sensitive Filter** Another type of particle filter is risk sensitive particlefilter in which the cost for generating the particles are correlated with costs, an example would be that tracking a particle which is rare and has a high cost but tracking a normal particle might not have any positive impact. This ensures a balance with a reasonable amount of particles being generated without any of them being in excess nor allowing critical particles to be missed allowing for efficient and effective computability.

•**Variable Resolution Particle Filter** The next filter that is discussed us thevariable resolution particle filter. The paper highlights some issues withthe classical particle filter that if there is a wheel failure, it will detect that there is a variance in the data but it will not be able to identify inwhich side does the variability of that data lies. For this a model knownas variable resolution particle filter has been developed in which a single particle filter is the amalgamation of a set of particles and can be used to represent a set of system states. This is has been verified experimentally that using this model enables lower errors in detecting the position of fault and increased performance. This particle filter requires a hierarchy while modelling it in state space. Each state representing a state of the hierarchy usually being physical or abstract or an abstraction of the physical state.After the abstraction of the particles is selected then update weigh and re-sample the distribution, re-assign the proper abstraction and finally estimate the final probability distribution.

•**Un-scented Kalman Filter** In this filter basically we for see the resultof the filter result and this method can vastly improve the diagnosis pro-cedure. This method utilizes the unscented particle filter approach forgetting an approximate distribution as close as possible to the originaldistribution. Since the UKF is recursive its approach is better than theExtended Kalman filter for non-linear models. Briefly the EKF linearizesnon linear models using Taylors theorem. Back to why UKF is better, it is because it uses the actual models and not their linearized version via Gaussian approximation.

•**Experimentation** The paper than utilizes each of these particle filters in a simulation and generate results which are as follows RSPF is an improvement on CPF but when they are numerous high state risk failures thenits performance degrades, along with side to side comparison with other filters in a variety of conditions.

•**Conclusion** The paper concludes by discussing some related papers andfinally close by saying that depending on the application, combining the basic approaches, domain specific hybrid algorithms can be generated and utilized currently.

Keywords

Efficient monitoring of hybrid dynamic systems, Particle filters, Real-time fault detection, Robot fault diagnosis, Tracking hybrid dynamic systems

Notes

The paper gives an in depth view of particle filters, why they are used, how are they beneficial and in which places they can be utilized effectively.

Contributions

Hybrid Particle Overview.

Deficit

I do not have sufficient knowledge to point out the deficits. Though pseudo algorithms would have been much appreciated.

On fault detection and diagnosis in robotic systems
Reference

DOI: 10.1145/3146389

Year: 2018

Author: Khalastchi, Eliahu and Kalech, Meir

Abstract

The use of robots in our daily lives is increasing. Different types of robotsperform different tasks that are too dangerous or too dull to be done by hu-mans. These sophisticated machines are susceptible to different types of faults.These faults have to be detected and diagnosed in time to allow recovery andcontinuous operation. The field of Fault Detection and Diagnosis (FDD) hasbeen studied for many years. This research has given birth to many approachesand techniques that are applicable to different types of physical machines. Yetthe domain of robotics poses unique requirements that are very challenging fortraditional FDD approaches. The study of FDD for robotics is relatively new,and only few surveys were presented. These surveys have focused on traditionalFDD approaches and how these approaches may broadly apply to a generictype of robot. Yet robotic systems can be identified by fundamental charac-teristics, which pose different constraints and requirements from FDD. In thisarticle, we aim to provide the reader with useful insights regarding the use ofFDD approaches that best suit the different characteristics of robotic systems.We elaborate on the advantages these approaches have and the challenges theymust face. To meet this aim, we use two perspectives: (1) we elaborate on FDDfrom the perspective of the different characteristics a robotic system may haveand give examples of successful FDD approaches, and (2) we elaborate on FDDfromthe perspective of the different FDD approaches and analyze the advantagesand disadvantages of each approach with respect to robotic systems. Finally,we describe research opportunities for robotic systems' FDD. With these threecontributions, readers from the FDD research communities are introduced toFDD for robotic systems, and the robotics research community is introduced tothe field of FDD.

Summary

•**Overview** This paper provides a complete survey which is a stepping stonefor the robotics community into the realm of fault detection and diag-nosis. This paper first defines the relevance, diversity and application of robots and characterizes them according to their autonomous ability and the difficulty that is faced while detecting and diagnosing problems within robotic systems. This paper also categorizes the types of robots by degrees based on their automation and level of complexity for fault detection and diagnosis. They go on to classifying faults and then attempt to merge the types of faults with different robotic systems. They highlight the issue of sensors especially with the noise, interference and un-reliability within them. They further categorize the autonomity of a robotic system.They move on to bring robot navigation and the architectures used within them and describe the common method used to deal with the faults. An emphasis is made that on multi-robot systems the fault detection and diagnosis becomes significantly more complex and challenging. The context and environment in which a robot operates is then explained. Previous related surveys are then presented along with their positive contribution and limitations. They move on to explain the three major methods of dealing with fault detection and diagnosis which are data based, model based and knowledge based. They further go on to explain the intricacy of each model and expand upon it advantages and limitations and touchupon the previous literature pertaining to it.

•This paper is about
–This paper provides information on the useful and viable methodologies required to deal with various robotic systems as the robots themselves are of a wide variety and cannot be approached using ”only” the classical approaches.

•This paper is relevant because
–The paper is relevant because it explains and deals with a variety ofdifferent robotic systems, expanding the diverse knowledge for implementing fault detection and diagnosis.

•Previous works on this
–Previous works pertaining to this have been done for the typicalrobots.(i.e. fault detection, diagnosis and recovery for wheeled or armed robots)
–The implementation of dealing with fault detection and diagnosisby the use of model based techniques, data drive techniques and knowledge based techniques.

•Previous works deficiencies
–There is no deficiency per say, this paper expands on previous surveys and provides additional and compacted information.
–Very few surveys if this type have been conducted.

•Paper's proposed solution
–It provides the associated methodological approaches required forvarious types of autonomous robots like an un-manned UAV or the mars rover etc...
–It emphasises on the usefulness of the data based approach in fault detection and diagnosis.
–They point out the concerning and likely cause of faults i.e. the extroceptive sensors.
–This item provides the basic building blocks for an introduction tofault detection and diagnosis. i.e. It explains all the methods and the current trends of applying these method within the fault diagnosisand detection field.

•Paper solution is good because
–No other paper deals with the diverse nature of robotics for examplethe robotic exoskeleton which has null autonomy but is quite a crucialcomponent in the future of industries.
–This paper tackles the issues of fault occurrence in different typeof robotic systems and how they are dealt with and focuses on thepointing out that faulty sensors and fault in algorithms are the major cause of issue within most robotics. This fact is supported by previous researchers work.

•**Future direction**
–An active fault detection diagnosis system for reduction of development time of robotic systems.
–Investigation in the interaction between humans and robots.
–A robot team who has no prior knowledge of fault detection anddiagnosis performs behaviour detection, recognition and modelingon other bots.
–Research on fault detection and diagnosis on deliberated faults.
–Enhancing current fault detection and diagnosis models.
–Reducing development time for robotics systems.

Keywords

Fault Diagnosis, Fault Detection, Robotic systems

Notes

A good starting paper that introduces Fault detection and diagnosis(FDD), explaining the important terms, relations and difficulties faced in different approaches within FDD and in various robotic systems. This paper is especially relevant because it is quite recent and is up to date with all the relevant information.

Contributions

This is an excellent introductory survey to fault diagnosis and detection. It introduces the un-initiated to the core concepts of fault detection and diagnosis. It covers all the important basis and terms while explaining previous research and giving a good idea of what the current direction of the field is.

Deficit

Currently, I do not have enough knowledge to say what is missing

Fault Detection and Diagnosis in Engineering Systems
Reference

DOI: https://doi.org/10.1201/9780203756126

Year: 1998

Author: Janos J. Gertler

Abstract

Supervision, health-monitoring, fault detection, fault diagnosis and fault management play an increasing role for technical processes and vehicles, in order to improve reliability, availability, maintenance and life-time. For safety-related processes fault-tolerant systems with redundancy are required in order to reach comprehensive system integrity. This book gives an introduction into the field of fault detection, fault diagnosis and fault-tolerant systems with methods which have proven their performance in practical applications. It guides the reader in a structured tutorial style: supervision methods, reliability, safety, system integrity and related terminology; fault detection with signal-based methods for periodic and stochastic signals; fault detection with process model-based methods like parameter estimation, state estimation, parity equations and principal component analysis; fault diagnosis with classification and inference methods; fault-tolerant systems with hardware and analytical redundancy; many practical simulation examples and experimental results for processes like electrical motors, pumps, actuators, sensors and automotive components; end-of-chapter exercises for self testing or for practice. The book is dedicated to graduate students of electrical, mechanical, chemical engineering and computer science and for practising engineers.

Summary

•**Chapter 1: (Introduction)** This chapter initially dives into the history offaults and how the advent of digitization has allowed us for dealing with faults automatically and on the spot. It then discusses types of faults and their causes and then the systems which deals with these faults. It than highlights the qualities which makes an ideal fault detection and diagnosis system mainly being sensitivity, reaction and robustness. It then discusses the approaches of dealing with faults such as physical redundancy, special sensors, limit checking, spectrum analysis and logic reasoning. The paper then deals with the actual techniques used for dealing with these errors of which some are analytical redundancy(using two sensor information) out of which comes residual generation, parameter estimation etc. It then discusses the most relevant technique being residual generation methods and the models that use them like kalman filter, diagnostic observer, parity relation and parameter estimation. It discusses the history of the development of the use of fault detection and diagnosis and its applications specifically with mathematical modelling for a car and a chemical plant.

•**Chapter 2: (Discrete Linear Systems)** This chapter starts of by discussingthe modelling of the system creating a binary list. This is list is of four items being Static|Dynamic Model,Linear|Non−Linear Model and Continuous−time|Discrete−time Model. It then goes on to explain each of these model mathematically. In static systems it explains howa non-linear system can be linearized using state space and explains thevarious combination of single/multi inputs and single/multi outputs. It than discusses requirements of stable inputs and outputs and how they can be discerned. Main things to keep in mind with these topics are system response and system stability. it moves on to systems represented discretely and the method employed to make continuous them discrete. Matrix algebra and its fundamentals such as rank, linear independence are briefly touched upon. Further into the chapter state space, systemmatrix, invariant zeroes, rank condition are elucidated. It then proceeds to explicate system relation which is presenting a system in state space. Z-transformation has also been demonstrated.

•**Chapter 3: (Random Variables)** This chapter deals with noise and methodsto deal with noise. First it deals with the distribution, probability, mean, mean square and variance and how all these are related to the variables collected from the data and how can these mathematical methods can aid us in giving meaning to the variables collected. Bivariate distribution and conditional distribution methods are then illustrated as it is not enough to give meaning to a data set but to provide a meaningful way to correlate to data sets and develop a relation between them. Some additional subtopics related to them are the cross relation and co-variance which are also key topics along side time shifted distributions. Multivariate systemsare then touched upon along with its sub topic law of large numbers. Propagation of random signal in a linear dynamic system and the variousrelations are illustrated. The normal distribution then connects all that was talked about earlier in the chapter regarding the random variables.It then reaches the maximum estimation likelihood estimation in which generated distribution enables the user to estimate unknown parameters. The paper then engages the final topic of the chapter which is hypothesis testing which is a core concept of mathematics statistics. It is to make decisions based on empirical observations and time series from where the observations are said to have originated. This hypothesis is tested and the tests usually has a standard towards them or it is better to say quality of testing. A type of the hypothesis test is the likelihood ratio test. Another type is composite hypotheses test.

•**Chapter 4: (Parameter Estimation Fundamentals)** There are two approaches for modelling, one way is apply mathematical models on a system based on its physical condition and characteristics, the second way is to observe a system and then fit a mathematical model to match the experimental data. This chapter deals with the latter though the distinction between the both chapters is a bit blurry as both borrow from each other. This chapter is similar to chapter 2 the catch being it will be basedon parametric modeling which is a widely used fundamental approach infault detection diagnosis. The static model, dynamic model, input/outputmodels and their various hybrid types are represented in the parametric system as well as mathematically modeled. The interesting part starts atthe recursive algorithm which takes advantage on the fact that parameter estimation depends on the length and time of observation. It recursively generates and computes matrices to provide an estimation. Due to memory consumption some techniques as forgetting factor are also sometimes introduced. Some more advanced techniques utilize recursive matrix in version and full recursion. Existence conditions are then mentioned inwhich the invertability of a matrix acquired either by batch algorithm or implicitly by recursive function is paramount. Persistent excitation, rank defects, in dependency from multiple inputs, over parameterization and experiment feedback are then talked about. As the chapter closes in to completion, it talks about noise, its attributes and how it appears mathematically within data sets, variance estimates, distributions etc. The types of classes to deal with these inconsistencies are also mentioned being extended or generalized least squares. output error least squares, instrumental variable methods and maximum likelihood methods. The chapter concludes by elaborating the criteria required for the selection of model structure.

•**Chapter 5: (Analytical Redundancy Concepts)** After building up the basic knowledge, the book finally brings in fault detection and diagnosis which includes fault isolation. The chapter starts off by defining the terms likefault, error, noise, disturbance etc. It then describes the types of faults and correlates them with noise and disturbances and yields mathematical modelling for them. Further in, residual generators are linked with types of faults, noise and disturbances along with its characteristics and implementation. Finally parity relations are touched briefly discussed.

•**Chapter 6: (Parity Equation Implementation of Residual Generators)** This chapter deals with in depth modelling and formulation of parity relations. It deals with the types of faults, state space modelling, various methods of implementation, constraints, input-output relations and examples. The second topic reviews is Fault system Matrix in which the fault/ disturbance matrix is used to alter the residual generator alongside its subtopics like inverse fault system matrix. Alternate methods such as systematic implementation with transfer functions are also discussed which are straight upgrades compared to previous methods. Various other methods are discussed like the ARMA implementation polynomial implementation from ARMA representation. A quick overview of this chapter is available in which everything is compared and summarized.

•**Chapter 7: (Design for Structured Residuals)** This chapter deals exclusively with residues and their structures. The chapter pointing out the importance of residual structures and then goes on to define all relating facts related to residual sets all whilst giving examples as it goes along. After definitions it discusses the structures like canonical structures which is the shape of the residual matrix, its constraints and examples inclusiveof dealing with disturbances. Multiple fault isolation as well as parity equations relating to the residuals are described specifically their implementation and modelling with examples. Cases and special cases are also dealt with of parity equations.

•**Chapter 8: (Design for Directional Residuals)** In chapter 5 fault isolationwas elaborated. Similar to that chapter, this chapter deals fault isolation in which each fault is constrained to linearly in the space of residues. The modelling, special cases, cases with disturbance and without disturbance are discussed. Following up is parity equations and its implementation for directional residual generators. Finally linear dependency, its types andtypes are clarified.

•**Chapter 9: (Residual Generation for Parametric Faults)** This chapter starts out with the presentation of parametric faults in state space specifying its characteristics, representation and input output relation. It carries on to designing of the parametric fault residual generation, conditions permanent rank defect and permanent rank defects. It then moves forward with fault isolation for output filtering and its identification and finishes up cases that have both additive and multiplicative faults.

•**Chapter 10: (Robustness in Residual Generation)** This chapter deals withthe idea of robustness of residual generation and off the bat illustrates the difficulty in making a robust RG. Despite several papers being pub-lished demonstrating some robust fault detection algorithms, the author of the book labels them as semi robust. Critical factors for robustness defined by the authors are perfect decoupling of disturbances, rank reduction and design. Types of faults along with the types of residual generatorsare put in the mix where each is elaborated and a relation is formed.Techniques like SVD, Least Mean Square and $H\infty$. Dealing with Multiple Errors by Multiple Models, Combinatorial Optimization, PerformanceMeasure, Structure Performance, Optimal Sets, Max/Min criterion and Local Search procedures are also discussed.

•**Chapter 11: (Statistical Testing of Residuals)** This chapter deals withthe statistics of propagation of noise. The first step is to model noiseand then compute its co-variance. Detection testing is then performed where residues are tested by the zero mean hypothesis.(i.e. zero mean= no fault) Definition and test case are then defined. Fault sensitivity is then elaborated the factors that effect it. Filters are then discussed which serves one of two purpose, low filter = reduce variance in residual set, whitening filter = eliminate correlation in residual set. The chapter goes on to discuss some test cases with conditional likelihood, it talks about test implementation in which the difference between fault isolation and detection is clarified(i.e. test is symmetrical and choice is between anumber of faults.) Plausibility test and properties of conditional estimates are expanded before the chapter moves on to whitening filter. In whitening filter the concept is it easier to deal with un-correlated problem than correlated problems, This is done by a matrix filter which is explicated within the end of the chapter.

•**Chapter 12: (Model Identification for Diagnosis of Additive Faults)** Thischapter deals with the special features and characteristics of model errors in light of designing a plant model for fault detection and isolation. Initially the chapter discusses the parameter model, least square method andthe parity relation. An important point of parameter bias is highlighted as how it reacts to plant faults. Deep into the chapter linear dependency is explained and its entailing difficulties and the possible solutions do also infact disturb the plant model. The final section deals with the techniques for identifying parity relations.

•**Chapter 13: (Diagnosing Multiplicative Faults by Parameter Estimation)**The observant reader who has scanned through all the chapters will realize that parameter estimations highly influence plant parameters. The estimation will be based on the comparison of a reference model and the real world model. Initially Least Square Algorithm and its cases will be discussed. Next section deals with the estimation of parameter change and all its correlated topics. Finally identification of continuous time model is discussed which are differential equations transformed into linear function(in this case by Laplace transform) A simple case where this is modeled and explained is available in the end of the chapter.

Keywords

Fault detection, Fault diagnosis, Fault Tolerance, Residuals

Notes

This book is vital because it puts one into the proper track of building the epistemology. Self-note page 327.

Contributions

Building Blocks of Fault Diagnosis, Detection and Tolerance.

Deficit

I do not have sufficient knowledge to list out the deficits of this book. I personally think its fantastic!

Fault Diagnosis in Robot Task Execution
Reference

URL: http://www.banerjs.com/pdf/banerjs_aaai2019sss.pdf

Year: 2019

Author: Banerjee, Siddhartha and Chernova, Sonia

Abstract

Robots operating in human environments can be made more dependable andreliable by automated fault diagnosis. In this work, we focus on the specific di-agnosis problem of fault isolation, with the goal of isolating those faults that arecauses of a robot task execution failure. Our method extends existing multiple-fault isolation processes by adding heuristics for matching fault residuals tohuman-expert specified fault signature matrices. We also extend the existingisolation processes to generate time-series of fault diagnoses. In doing so, we areable to isolate non-fatal faults that can sometimes be the causes of task failure.Finally, we describe a dataset of mobile manipulation tasks in simulation thatwe plan to use for future development and benchmarking.

Summary

•**Introduction** The paper starts off by elaborating on the importance ofdependability and how the increase in their dependability is beneficial.The paper focuses producing a method to automatically isolate a fault.Ultimately catching all critical and non-critical faults for prevention oftotal failure. The paper then defines a set of mechanisms that are requiredfor effective fault isolation namely, fault forecasting (done by fault tree analysis, failure modes effects and criticality analysis.), model free, dealing with time-dependent faults, independent task execution and be able to utilize human expertise as well as data obtained. The method will be produced while adhering to set of rules as described.

•**Related Work** Related work done by researcher are talked about. The first paper that is talked about is relatively recent paper (at the time ofwriting this report), which is about the complexity and challenges faced in fault detection and diagnosis, namely, acquiring training data, different behaviour of fault in simulation compared to real world, modeling, context of fault, environmental influences, introduction of redundant sensors that may be prone to faults themselves, low computational cost, low time cost and ease of development.

•**Background** The next topic that is discussed is a book, which is one of the fundamentals of the field. The book deliberates about the conflicts between a modeled system and an observed system and builds up the basic foundation of the field. The next work that is conversed upon is the methods which are employed in fault detection and diagnosis which are of course Model based, knowledge based and Data based. The types of models and their predecessors are discussed and how previous researcher's implemented on different systems (i.e. dynamic systems, static system's etc.)

•**Problem Domain** The theme of this section is problem formulation. The following types of faults are analyzed which are a common trope, error that causes failure of robot task execution, pre-designed fault detector and finally identification and characterization of faults.

•**Test Case** A test case scenario is developed in which a robot is given a set of tasks to achieve, mainly fetching and placing a cube. The test case scenario has both been verified via simulation and within the real world and the fault cases were thetypical faults which will be re-touched below. The environment was also pre-defined as well as other nuances. The common fault cases were component faults, contextual faults, multiple correlated faults, multiple un-correlated faults, distal root faults, belief faults and un-detectable faults.The finalization of the topic is residual fault detection in which residuesare sensitized to various faults meaning that they amplify any fault detected. Each residue is sensitized to a set of faults.

•**Residues** The paper used residues for belief state, fault state and task state. The fault residues that were generated performs the basic sanity check i.e. the robot is not colliding, components are running in their designated frequencies etc. These residues are in Boolean form and maybe noisy. The generated belief residues are developed when the internal world generated models do not match the external real world model. The value assigned for these residues depend on the context. The final task residues are helpful for diagnosis and encompass activation, completed status and sub-task residuals.

•**Fault Isolation Method** The second last topic of this paper deals withfault isolation as the heading suggests. The aim is to use the generated residues to perform a diagnosis and pinpoint the cause of the task failure.The method employed is a five step method which is:

1. Decompose residues of signature matrix into belief residues.
2. Assign context to the signature matrix via task residuals.
3. Apply fault isolation at multiple time-stamps
4. Iterate over time series for diagnosis and isolation of distal root faults.
5. Re-iterate step 4.

The signature matrix uses knowledge based modelling to incorporate human expertise and experience to set values of residues to certain values. An interesting thing the paper did was to introduce non-Boolean values into the signature matrix from the task residuals. These residues help in filtering possible fault hypotheses. Distal roots are unique as this method does not have trajectory of fault residue overtime, however, particle filters are able to do this or by implementing heuristics. Two heuristics that the paper applied were forward propagation/backward propagation and knowledge based search for distal root using a posteriori.

•**Future Work** Automation of surface distal fault diagnoses without a posteriori.

Keywords

fault, isolation, failure, task, diagnosis

Notes

New relevant techniques for fault isolation.

Contributions

Proven and implemented test case of proposed technique for fault isolation.

Deficit

More data pertaining to implementation via mathematical models and/or pseudo code, so that other researcher may be able to test, verify and re-enforce claims of the paper.

Active probing for diagnosis of emergent faults
Reference

DOI: 10.3182/20090610-3-it-4004.00055

Year: 2009

Author: Johnson, Timothy L. and Genc, Sahika and Bush, Stephen F.

Abstract

This paper addresses the use of active probing as a tool for implementing life-cycle dependability growth concepts in networked control systems. In the con-trols field, the potential benefits of active probing in stochastic control were firstrecognized by Tse and Bar-Shalom [1974]. Significant practical development ofactive probing techniques, however, occurred in the networking field and wasonly rarely advanced by control theorists. We propose that active probing be in-corporated into future

dependable system designs as a method that is suitableboth for new large-scale network phenomena such as emergent behavior, andalso to support life-cycle dependability growth in conventional systems. Manyopen research and application opportunities will be noted.c©2009 IFAC.

Summary

•**Introduction** The paper starts off by elaborating the history of the dependability of robots and their implications. The evolution and unprecedentedbehaviours that are emerging of automated systems have been highlighted.The paper expounds the need of utilizing a method to ensure the dependability of robots to cope with the exponential growth of complex control systems. This paper proposes active probing as a method to resolve this.

•**Previous Research** The paper starts out by talking about contributions of previous researchers. It discusses the methods employed by the previous researchers and how it has positively impacted the field.

•**Control Probing** The first topic they discuss is of two researchers who actually proposed active probing and performed case studies using these techniques. The result of their work proved successful as it performed exceptionally as compared to the previous methods that have been used. The system worked on the basis of a posteriori while the key point is that it was conditioned on active adaptation instead of passive adaptation,which was commonly being done at the time. Due to the computational limitations at the time, those researchers were only able to produce viable results in military applications, specifically pertaining to missile control systems. Compressing their research to a few lines would be to say that, in a closed system, when insufficient information is available then using prior experience, a future plan can be generated as compensation. This type of Active Probing translated very well into computer networks which is the next topic that is touched upon by this paper.

•**Active Probing Networks** In this section of the paper defines the term active probing as it can be interpreted in a broad sense. The definition defined by the paper is”It is the near real-time definition of experiments with the goal of diagnosing a system anomaly.”Then the individual components are further explained individually. Quickly summarizingthe authors definition on the individual definitions are probing = remotemeasurements and active = real-time/intelligence/autonomy. The paper then move on to discussing communication networks and how they workand then then ties it all up by talking about researcher who worked on implement active probing in the communication networks. An example of forecasting is explained and the algorithms used for them namely, Kolmogorov Smirnov technique, Plateau algorithm, Holt-Winters and MarkBurgess technique. Plateau algorithm is given preference by the paper due it more adjustable configuration parameters.

•**Emergent Behaviour** This section of the paper starts off by drawing apicture of the wireless communications world. The need for robust and efficient systems are especially highlighted. The paper goes on to explain emergent behaviour which can be summarized as the global behaviour that is observed by the interaction of local entities of that system. An interesting point to note is that emergent behaviour cannot be broken down into components in isolation. The paper then goes to describe some analytical models employed and how these same models and algorithms for emergent behaviour can be utilized to generate Emergent Faults.The emergent faults can be combated using active probing modules thatare equipped with evaluators for diagnosing emergent behaviours.

•**Active Probing Concepts For Dependability Growth** The implementability of active probing and how it influences dependability is discussed here. The open ended issues relating to this are illuminated as follows.
-The issue of careful designing is also addressed.
-The decision factor of how the biased information from active probing should be less then the total information received as well as whether it would be beneficial is stressed.
-The factors on which probing depends on is also clarified i.e. discrete time command and the need of blending and synchronizing continuous state with discrete state.

Criterion are defined for what is required within an active probing system and the type of analysis required and what the goal should reflect. The implementation of fault discriminators are illustrated and how to negate the ripple effect caused by a known fault from affecting other active probing modules. A strategic planner and the importance of a loggeris also stated and the open areas for research are also pointed out.

•**Future Research Direction** The suggest future direction by the paper is in loggers, use of active probes for the estimation of aging no-centered operation, web based equipment, statistical process control, probe design,probe selection ,probe timing and high level control and a number of other topics.

Keywords

Active networks,Active probing,Emergent behavior,Fault diagnosis,Nano-networks,Network management

Notes

A paper that covers behaviour of global faults and their patterns and possible methods that can be employed to prevent the faults from spreading.

Contributions

A survey of emergent faults.

Deficit

More discussion on the methods.

Fault diagnosis for industrial robots based on a combined approach of manifold learning, treelet transform and Naive Bayes
Reference

DOI: https://doi.org/10.1063/1.5118000

Year: 2020

Author: You Wu*,* Zhuang Fu*, and* Jian Fei

Abstract

This research introduces a novel fault diagnosis method for an industrial robot based on manifold learning algorithms, Treelet Transform (TT) and Naive Bayes. The vibration signals of an industrial robot working under three working conditions are acquired as the raw data. Three typical manifold learning algorithms, Principal Component Analysis (PCA), Locality Preserving Projections (LPPs), and Isometric Feature Mapping (ISOMAP), are utilized to extract three-dimensional features from the vibration signals. Then, these features were combined into nine-dimensional features and, these nine-dimensional features were reduced to three-dimensional feature vectors by TT. Finally, a Naive Bayes model is trained with these three-dimensional feature vectors. Experimental results show that compared with the three methods, PCA, LPP, and ISOMAP, the accuracy of the proposed combined method is higher than the single method. The fault diagnosis method presented in this paper is easy to implement and can effectively identify the fault types.

Summary

- **Introduction** The growing use of robots in industry has spurred a dire need for effective fault detection and fault diagnosis for online systems. Fault diagnosis ordinarily utilizes various types of data ranging from motor current, acoustic signals, temperature etc. This paper focuses on fault diagnosis using vibrational data as it’s use is more widespread. The data generated from vibration has a lot of useless data due to which feature extraction is a vital part for fault diagnosis.

- **Manifold Learning** is a type of dimension reduction which has three types, linear methods, local methods and global methods. In linear methods the most famous technique principal component analysis (PCA) is used for dimension reduction and uncovering hidden information from the provided data set. In local methods locality preserving projections (LLPs) are used in which the internal structure is maintained while reducing the dimension, although it depends on the proximity of data to each other. The final type is the global method which uses isometric feature mapping (ISOMAP), it preserves everything and at all scales. This paper utilizes all the manifold learning methods.

- **Treelet Transform (TT)** High level features need to be reduced to low dimensional features, for classification and for the visualization of the classification. Treelet transform is a new technique that reduces dimension along computation of the data regression. For pattern recognition the old trusty Naive Bayes classifies is used. Other approaches like support vector machines (SVM) can also be used, however, Naive Bayes classifier provides the same precision as the support vector machine, is easier to implement, and works faster than the support vector machines.

- **Paper Proposition** This paper proposes a new technique for fault diagnosis for industrial robots in which methods of manifold learning, treelet transform and Naive Bayes are used. These approaches are supported by experimental test cases.

- **Methodology** The methodological approach has three steps: Step 1 is feature extraction. All three feature extraction methods are used principal component analysis, locality preserving projection and isometric feature mapping.

- **Principal Component Analysis** In PCA there is five steps that are performed 1. We first need to find the covariance matrix of the m-components of X the covariance matrix is usually denoted by ‘Sigma’. 2. We then look for the eigenvalues and eigenvectors of ‘Sigma’. 3. The eigenvalues are sorted in decreasing order and the k largest ones are taken. 4. The eigenvectors corresponding to the k largest eigenvalues are put in a matrix W 5. We finally project the original data onto the k dimensional subspace.

- **Locality Preserving Projection** For LPP a graph with nodes is created and the distance between the ith node and jth node is defined in the paper as the norm divide by t which is a constant whose value is determined based on experience. After passing this through the function LPP, the smallest eigen value is taken from the diagonal matrix which provides the optimum projection of the data set provided.

- **Isometric Feature Mapping** In ISOMAP a graph is developed in which nodes are connected to each other. The shortest path between all the nodes is than calculated which is then put into a matrix. After a few iterations, the shortest path distance will be convergent which extract the low dimensional data from.

- **Dimension Reduction by Treelet Transform** Once the features have been extracted using the manifold methods, they are then consolidated into a high dimensional feature vector. Treelet transform first initializes the data where the data is put into the required forms, second step is that it computes a similarity matrix between the variables of k. Once processed by acquiring the geodesic distance which demonstrates the correlation, it is normalized and PCA is applied to the result and the parameters are updated.

- **Fault Classification Naive Bayes** This model is used for training the fault diagnosis for noise. The classifier are made by the user according to the signal. After being trained, results are predicted by Bayes using posterior probabilities.

- **Results of Experimentation** The result of the experimentation on two test cases is that the combined approach gave better results than independent analysis of the manifold methods in varied conditions. First test case was on a hybrid robot and the second test case was on a delta robot. The reason for the better results is that each manifold specializes in extracting certain features and loss of information occurs during this process, but when all 3 are used, the loss of certain feature by 1 method is made up by the other 2 methods and hence a more coherent and complete set of useful features are maintained.

- **Conclusion** This research paper proposes a novel approach for fault diagnosis for robot. This is a 3 step approach in which manifold learning, TT and Naive Bayes are combined. The developed method prevents the loss of information and improves accuracy significantly. The framework is simple and easy to implement which can be ported and used in any other robot.

Keywords

algorithms, manifold, vectors, vibration, method, diagnosis, pca, signals, mapping, fault

Notes

A simple and easy approach to improve the fault diagnosis of robots that can be immediately applied to all robots that have fault diagnosis implemented.

Contributions

An upgrade for fault diagnosis methods that utilize feature extraction.

Deficit

Pseudo codes for the entire process would have been very beneficial and much appreciated so that other researchers can quickly and easily implement the proposed approach verifying and validating it.

Integrated Sensor Fault Diagnosis and Fault-Tolerant Control for Manipulator
Reference

DOI: https://doi.org/10.1155/2019/4751080

Year: 2019

Author: Bowen Hong, Lina Yao and Zhiwei Gao

Abstract

In this paper, an integrated scheme including fault diagnosis and fault-tolerant controller design is proposed for the manipulator system with the sensor fault. Any constant fault or time-varying fault can be estimated by the fault diagnosis scheme based on the adaptive observer rapidly and accurately, and the designed parameters can be solved by the linear matrix inequality. Using the fault estimation information, a fault-tolerant controller combining the characteristics of the proportional differentiation control and the sliding model control is designed to trace the expected trajectory via the back-stepping method. Finally, the effectiveness of the above scheme is verified by the simulation results.

Summary

- **Introduction** Development and implementation within the manufacturing industry has increased the demand of fault detection and diagnosis. Fault diagnosis is divided into three major areas, model based, knowledge based and signal processing based. The go to method that is typically implemented is the model based approach.

- **Past Literature** In recent years there has been a lot of focus in fault detection, diagnosis and tolerance for robotic actuators and there has been a deficiency of research papers pertaining to fault detection and diagnosis in sensors.

- **Related Research** Fault diagnosis methods using adaptive observers have been used in a range of application some of which include the fault diagnosis of wind energy system, satellite actuators, time delayed non linear actuators and much more which is listed in the reference of the research paper.

- **State of the Art** The latest trend currently, is that instead of measuring the faults in actuators directly, the sensor fault data is used to measure the fault in the actuator. This is done by applying a transformation filter which transforms the original system into an augmented system which has the actuators faults. This approach allows researchers to deal with non linear system. This paper also adopts this approach.

- **Papers Contribution** This paper presents a fault diagnosis system for a manipulator system with sensor fault that is an altercation of the adaptive observer system; this proposed approach performs exceedingly well independent of temporal constraints.

- **Modeling of Modified Adaptive Observer** The system is initially dynamically modeled after which it is converted into a state space model. As the faults in the sensors translates into the faults of a manipulator, a new filter state is introduced for ease of calculation. The final modeled will acquire use the adaptive state observer to estimate faults.

- **Diagnosis Scheme** The diagnosis scheme of the proposed model is dependent on a theorem which can be summed up to say when certain conditions are met than positive definite matrix exists from which the error gain can be computed. This theorem is ordinarily sufficient as it can be used for linear and non-linear systems but some issues like singularity and in ability to distinguish temporal faults is quite a drawback. The paper proposes that with the use of Lyapunov's stability theory, a new state is defined which allows the error (both the error state vector and sensor fault estimation error) to be bounded and convergent.

- **Fault Tolerant Controller Design** A part of the papers proposal is the conjunctional use of proportional differentiation control (PD) and slide mode control (SMC) with the modified adaptive observer. These controller are effective at limiting non linear systems; they are implemented by the back-stepping method. The modeled system in the previous step is further refined by integration of the proportional differentiation and slide mode control models which allow for finer and quicker response which has a great impact in terms of reduction of response time.

- **Simulation Test Case** The propose design and scheme is verified by three simulation test cases. case I has constant fault, case II has a sinusoidal slow time varying fault and case III has a time varying fault varying fault. Each of these test cases are diagnosed by two approaches, the first approach is the approach proposed by the paper and the second approach is the conventional approach. Case I is set to have a constant fault for thirty seconds while case II is set to have a fault for forty seven seconds and case III is set to have a fault for sixty seconds.

- **Simulation Results** For the proposed approach, the response time was very quick while the response time of the conventional approach lagged behind very heavily, as for the accuracy in the calculation value, the proposed approach demonstrated near perfect fault estimation while the conventional approach estimated a very noisy and inaccurate reading. This result was similar for all three test cases.

- **Conclusions** This research paper present a fault diagnosis and tolerance control scheme for the sensor fault within a manipulator system. The way this control scheme was achieved, was by the altercation of an adaptive observer system which allows for the estimation of faults that are constant and or time varying. Additionally proportional differentiation controllers and slide mode controllers have been integrated through the back stepping method. This significantly enhances the fault diagnosis capabilities within the sensors of a manipulator system. The fault diagnosis and control scheme has been verified through simulation models.

- **Future Research** Further research would involve a control scheme which would be designed for time delayed faults and uncertain faults within the manipulator system. This would greatly enhance the dependability and performance of the system.

Keywords

controller, fault diagnosis, parameters, differentiation, sensor estimation, simulation, trajectory

Notes

Amongst other papers that I have reviewed, this papers introduction was very solid especially due to disscussion of current research direction which surprisingly many papers that I have read, do not mention or indicate. That said the sections after the intro. felt lacking.

Contributions

A new and effective approach for fault diagnosis in sensors of manipulator systems.

Deficit

The paper should have a table that denotes all the notations that it uses and also it should publish its pseudo code so that other researchers can re-verify and validate the work done.

4.4 Fault Prediction

A Systematic Literature Review on Fault Prediction Performance in Software Engineering
Reference

DOI: 10.1109/TSE.2011.103

Year: 2012

Author: Hall, T.; Beecham, S.; Bowes, D.; Gray, D. & Counsell, S.

Abstract

The accurate prediction of where faults are likely to occur in code can help direct test effort, reduce costs, and improve the quality of software. Objective: We investigate how the context of models, the independent variables used, and the modeling techniques applied influence the performance of fault prediction models. Method: We used a systematic literature review to identify 208 fault prediction studies published from January 2000 to December 2010. We synthesize the quantitative and qualitative results of 36 studies which report sufficient contextual and methodological information according to the criteria we develop and apply. Results: The models that perform well tend to be based on simple modeling techniques such as Naive Bayes or Logistic Regression. Combinations of independent variables have been used by models that perform well. Feature selection has been applied to these combinations when models are performing particularly well. Conclusion: The methodology used to build models seems to be influential to predictive performance. Although there are a set of fault prediction studies in which confidence is possible, more studies are needed that use a reliable methodology and which report their context, methodology, and performance comprehensively.

Summary

•**Introduction** This paper utilizes prior research to provide an analysis and review for fault prediction. The scope of influence that fault prediction has and the multitude of disciplines that will benefit from the Systematic Literature Review (SLR) is one of the justification for the relevance of this paper. Another reason being the lack of state of the art comprehensive review papers. Within the time-frame of a few past decades, dissimilarity with some of the complied work has been highlighted as well.

•**Contributions** This paper provides 4 distinct contributions which are as follows:
1. A compiled set of two hundred and eight papers discussing fault prediction in software engineering.
2. A comprehensive study on thirty six papers discussing the context and methodology employed.
3. A criteria off of which can be utilized as a guide for other researchers on the same track.
4. An extensive review of the current state of the art in fault prediction.

•**Methodology** The methodology availed is of SLR. Firstly, research questions were identified for relevance. Secondly, inclusion criteria were defined in which only recognized English papers that were either published in journals or conferences were considered, along with the focus on empirical studies. This along a set of exclusions were the basis for the inclusion criteria. Thirdly, identification of papers. Papers within the past decadewere prioritized in which they were selected by utilizing well known searchengines as ACM, IEEExplore etc. This as well as other methods such assearching via popular authors within the field which are listed in the appendix of the paper.

•**Assessment of Suitable Papers** This section discusses the selection of potentially high value papers which were then subjected to highly scrutinized study. The assessment has been based on a number of factors ranging from quality checks all the way to the gritty details of numerical approach, contextual approach, validation, model building etc. Of these tight criterion that have been put in place, three criterias are worth keeping in mind, being context criteria, model building criteria and data criteria.

•**Extracting Data from Selected Papers** The papers which had been finally selected were studied on three major themes which were the context data, qualitative data and quantitative data. Context data, in short being the background and application area of the paper, qualitative paper, beingthe richness of the paper and quantitative paper focused on the amount of data acquired. All these tied together and subjected to the analysis of multiple researchers. Other parts being categorical studies and continuous studies which have been subjected for extraction of data.

•**Synthesis** The research findings for the thirty six papers have been amalgamated based on certain aspects, aspects such as research question as due to the diversity a simple synthesis would be a very challenging task as indicated by the paper.

•**Results of Assessment** The result for this has been presented in form of fourtables which are context study table, categorical mode table, continuous model table and qualitative data table. Some results that are interesting regarding the papers assessed is the modeling technique used by Arsiholm was completely different from the typical models that were used. The good performers of these models were of Naive Bayes models. It provided consistent and positive results compared to the other models that havebeen compared. An issue that is shed light upon is the fault prediction and the maturity of a system and how its reliability is dependent and what is the relation between the size of a system and the actual maturity of the system. The relationship between granularity and performance is also pointed out.

•**Additional Result Assessment** The performance and independent variable do indeed have a relation indicated by the study. Performance and modelling technique also have a relation as performance goes down with certain modelling techniques like Linear regression and performance goes up with other modelling techniques like the typical naive Bayes model.

•**Conclusion** The paper closes off by discussing and answering the research question based on the studies that have conducted and then continues to provide useful and informative feedback on topics like fault severity,predictive performance etc. It also talks about the requirements for de-validating this research paper and wraps up by providing a re-cap within its conclusion section.

Keywords

Bayes methods;regression analysis;software fault tolerance;software quality;systematic literature review;fault prediction performance;software engineering;cost reduction;software quality;independent variables;fault prediction models;contextual information;methodological information;simple modeling techniques;naive Bayes;logistic regression;feature selection;predictive performance;fault prediction study;reliable methodology;Predictive models;Context modeling;Software testing;Data models;Systematic;Analytical models;Fault diagnosis;Systematic literature review;software fault prediction

Notes

None

Contributions

A beneficial paper that can be used as a filter to acquire the most impactful and resourceful paper within fault prediction.

Deficit

I do not have the current expertise to judge the deficits within this paper.

Forecasting fault events for predictive maintenance using data-driven techniques and ARMA modeling
Reference

DOI: 10.1016/j.cie.2017.10.033

Year: 2018

Author: Baptista, Marcia and Sankararaman, Shankar and de Medeiros, Ivo P. and Nascimento, Cairo and Prendinger, Helmut and Henriques, Elsa M.P.

Abstract

Presently, time-based airline maintenance scheduling does not take fault predictions into account, but happens at fixed time-intervals. This may result in unnecessary maintenance interventions and also in situations where components are not taken out of service despite exceeding their designed risk of failure. To address this issue we propose a framework that can predict when a component/system will be at risk of failure in the future, and therefore, advise when maintenance actions should be taken. In order to facilitate such prediction, we employ an auto-regressive moving average (ARMA) model along with data-driven techniques, and compare the performance of multiple data-driven techniques. The ARMA model adds a new feature that is used within the data-driven model to give the final prediction. The novelty of our work is the integration of the ARMA methodology with data-driven techniques to predict fault events. This study reports on a real industrial case of unscheduled removals of a critical valve of the aircraft engine. Our results suggest that the support vector regression model can outperform the life usage model on the evaluation measures of sample standard deviation, median error, median absolute error, and percentage error. The generalized linear model provides an effective approach for predictive maintenance with comparable results to the baseline. The remaining data-driven models have a lower overall performance.

Summary

•**Introduction** This paper presents an addition to the Auto-regressive modelof moving average (ARMA) leveraging data driven techniques. The paper starts off by identifying the initial and critical role of fault prediction in engineering systems. The history is touched upon by the paper while theage old method of Life usage (LU) is highlighted. Unlike the typical LU model, the model presented is a fusion of ARMA and data-driven methods.This is an online model (i.e. works in real time)

•**Novelty of the Paper**
1. Inclusion of several statistical measures in the data driven methodology.
2. The entire precept history of faults are captured by the ARMA modelwhich are then merged into the data driven models.

3. The framework works in real time.
4. Addition of 13 statistical features for prediction.
5. One of the features is the utilization of PCA to gather raw data andreduce the set of un-correlated features.

•**Previous Literature** The paper then discusses related/similar literature and research performed within this topic. It clearly projects the contrast between the related literature, highlighting the deficiencies and missing components.

•**Motivation** The paper points to the combination of techniques to provide highly sophisticated prediction models as the root of motivation specifically mentioning the works of a researcher who integrated ARMA with neural networks and fuzzy logic to predict the life time of batteries based on impedance measurements.

•**Validation** The paper validates its data using real life test case of aircraft air management system. This method is also compared to the typical LU model specifically in this case being the Weibull model which is typically used in aircraft air management system.

•**Life Usage Model** The paper then focuses initially on defining and describing the methodology of the base line comparison Life usage model. This model characterizes failure in exponential manner within the probability distribution and the constant failure rates are expressed as Weibull or Log-normal. Further overview is provided as well as numerical functions used by this model.

•**Proposed Framework Description** The framework is composed of two models which are ARMA model and Data-driven model. The ARMA modelgenerates prediction model which in turn trains the data driven model. The models generated by the ARMA is based on the entire history of event fed into it. With the prediction model and statistics, Principle Component Analysis (PCA) enables for better prediction for the next fault event.

•**Feature Extraction** The features are extracted by 3 models which havetheir own unique objective. ARMA model projects the inputted history into predictive feature. Statistics model converts data into meaningful statics used for training the data-driven model. Finally, Principle Com-ponent Analysis utilizes the features from statistics and ARMA model togenerate, yet another set of features that can be distinctively identified.

•**ARMA model** This based on time series events and numerical equations.It captures the past history not as a function but the past noise and residual values. The model is fitted by linear least squares.

•**Statistical Features** In here, the aim to record the spread of distribution. This is done by some basic functions of acquiring the mean, median, quartile range, standard deviation along with the skewerness and kurtosis, this statistical implementation results in features correlating. To remove it we use PCA.

•**Principle Component Analysis** This method reduces the dimensionality of multivariate data sets. This allows the filtering of variables into their original un-correlated sets.

•**Data Driven Model** This can be defined as a function that tries to provide an estimate as close as the actual true function of interest. This has two phases, training phase and prediction phase. In the training phase a machine learning algorithm (random forest, neural networks, supportvector machines, k-nearest neighbours). This algorithm receives an input from the PCA and creates a data-driven model. In the prediction phase, past failures are used to estimate new failure.

•**Case Study** The case study as mentioned before belongs to the aeronautical discipline (aircraft air management system). The paper defines all the contextual information and parametric information related to the case study. All relevant functions of the system are explicitly mentioned and the relevance of the research paper is highlighted by the past issues that have occurred within the system. The paper then describes which param-eters it has used and why!

•**Methodology** The methodology employed was to use 10 samples of LifeUsage model and then 10 samples of the proposed framework.

•**Result** The result is that the proposed framework, overall is an improvement and/or comparable. The only negative result was through neural networks as it had the tendency to over fit the removal of data.

•**Conclusion** Improvement over LU models. Support vector machine algorithm has the overall best results

Keywords

ARMA modeling, Aircraft prognostics, Data-driven techniques, Life usage modeling, Predictive maintenance, Real case study,

Notes

A note with the algorithms that are used, there is no clear winner and each is suited to certain objectives and environments.

Contributions

Improvement on classical fault forecasting.

Deficit

Insufficient epistemology to point out deficiencies.

A study on software fault prediction techniques
Reference

DOI: 10.1007/s10462-017-9563-5

Year: 2017

Author: Rathore, Santosh S. and Kumar, Sandeep

Abstract

Software fault prediction aims to identify fault-prone software modules by using some underlying properties of the software project before the actual testing process begins. It helps in obtaining desired software quality with optimized cost and effort. Initially, this paper provides an overview of the software fault prediction process. Next, different dimensions of software fault prediction process are explored and discussed. This review aims to help with the understanding of various elements associated with fault prediction process and to explore various issues involved in the software fault prediction. We search through various digital libraries and identify all the relevant papers published since 1993. The review of these papers are grouped into three classes: software metrics, fault prediction techniques, and data quality issues. For each of the class, taxonomical classification of different techniques and our observations have also been presented. The review and summarization in the tabular form are also given. At the end of the paper, the statistical analysis, observations, challenges, and future directions of software fault prediction have been discussed.

Summary

•**Introduction** This paper aims to provide a comprehensive and highly detailed review of fault prediction techniques. The review is completed in 3 phases: software metrics, fault prediction techniques and data quality issues. The papers begins by grounding its motivation to previous literature, specifically the issues and deficiencies of the previous literature.

•**Similar Literature Review** The paper points towards similar research that have been done within the scope of this topic and highlights the lack of appropriate methodology adopted and lack of empirical evidences.

•**Software Fault Prediction** It is defined as the software modules prone to faults that can be predicted by the underlying attributes of a software project. The cycle is as follows: extract data, process it by machine learning and statistical techniques and lastly build and evaluate prediction model.

•**Software Fault Data Set** The fault data set is used as a training data set for the machine learning. It has 3 components: Software Metrics, Fault In-formation and Meta information.

•**Fault Information** This informs the user on how faults are provided to the software module, the severity of the fault etc. It has 3 types:
1. Private/Commercial
2. Partially Public/Freeware
3. Public

•**Software Metrics** For assessing the software quality assurance, a metric system is used to quantitatively and qualitatively evaluate a property of the software by assigning functional attributes to qualitative attributes.The metrics followed by this paper are ISO, FP, SLOC, KSLOC, CBO,WMC, IOC, EOC etc. Additionally, traditional metrics, object oriented metrics and dynamic metrics have been followed from the product metrics and code delta metrics, code churn metrics, change metrics, developer based metrics, requirement metrics and network metrics have been followed from the process metrics.

•**Meta Information** It consists of various properties of a software projectas well as information regarding the quality of the fault data set used to construct the fault prediction model. Key features of meta informationis their ability to hold contextual information. Examples of contextual information would be source of data, maturity of the system, size of the software project, application domain and the granularity of prediction. In meta information extraction some key issues are attaining proper quality data sets. More often then not, issues occur with the data set such as: outlier, missing values, repeated values, redundant and irrelevant value, class imbalance, data shift problems and high dimensionality of data.

•**Methodology of Software Prediction Models**
1.Software Fault Prediction
–Intra Release Prediction
–Inter Release Prediction
–Cross Project/ Company Prediction

2.Prediction in the form
–Binary Class Prediction
–Number of Faults/ Fault Density Predictions
–Severity of Faults Predictions

3.Techniques Adopted for Prediction
–Statistical Techniques
–Supervised Learning Algorithms
–Semi-Supervised Learning Algorithms
–Un-Supervised Learning Algorithms

•**Performance Evaluation** The evaluation performed has been of two types:
1.Numerical Measure:
This measures accuracy, specificity, f-measure, G-means, false negative rate, false positive rate, precision, recall, j-coefficient, mean absolute error and root mean square error.
2.Graphical Measure
This measures the Receiver Operator Characteristics and Precision Recall curves and Cost curve.

•**Statistical Survey** The study on software metrics resulted in the following:
1.Metrics Used: Overall Object-oriented metrics have been widelyused and validated by researchers 34%.
2.Types of Data Sets: Public data has been utilized the most 64%.
3.Approaches: Most approaches used statistical techniques 70 %.
4.Focus of Research: Fault proneness have been effectively the hottopic for researchers having a lead of 61%.
5.Issues: The most defined issues which researchers face are high datadimensionality with a 39% occurrence.

•**Challenges** The challenges can be listed as follows:
–Adoption of Software Fault prediction for Rapidly Changing Environment.
–Fault Prediction models that are capable of coping with code baseevolution.
–More informative Fault Prediction models.
–New approaches to Fault prediction models.
–Cross company vs. within Company prediction.
–Search based approaches for Fault Prediction.

•**Conclusion** A recap of what has been discussed is the activities of fault prediction some of which are software metrics, fault prediction techniques, data quality issues and performance evaluation. Also the crux of this work is the tables that answer the query of the evaluation methods utilized, performance evaluation parameters, data set used, advantages and dis-advantages. The challenges presented are the future direction for the field as well.

Keywords

Software fault prediction, Software metrics, Fault prediction techniques ,Software fault data sets, Taxonomic classification

Notes

It provides a solid comparison chart of fault prediction that have been over the years with tables that allow for easier visualization and comparison of fault prediction techniques.

Contributions

Statistical survey on fault prediction.

Deficit

I do not have the current expertise to judge the deficits within this paper.

Software fault prediction metrics
Reference

DOI: 10.1016/j.infsof.2013.02.009

Year: 2013

Author: DanijelRadjenović, MarjanHeričko, RichardTorkar, AlešŽivkovič

Abstract

ContextSoftware metrics may be used in fault prediction models to improve software quality by predicting fault location. ObjectiveThis paper aims to identify software metrics and to assess their applicability in software fault prediction. We investigated the influence of context on metrics' selection and performance. MethodThis systematic literature review includes 106 papers published between 1991 and 2011. The selected papers are classified according to metrics and context properties. ResultsObject-oriented metrics (49%) were used nearly twice as often compared to traditional source code metrics (27%) or process metrics (24%). Chidamber and Kemerer's (CK) object-oriented metrics were most frequently used. According to the selected studies there are significant differences between the metrics used in fault prediction performance. Object-oriented and process metrics have been reported to be more successful in finding faults compared to traditional size and complexity metrics. Process metrics seem to be better at predicting post-release faults compared to any static code metrics. ConclusionMore studies should be performed on large industrial software systems to find metrics more relevant for the industry and to answer the question as to which metrics should be used in a given context.

Summary

- **Introduction** This paper focuses on a systematic literature review of metric based fault prediction. The paper defines Fault prediction as a means to enables more safer and dependable systems by enhancing the software quality and fault detection and isolation, by utilizing a knowledge base which has been pre-built or by means of machine learning.

- **Past Literature** In metric based fault prediction, a large number of approaches are frequently used such as that of MOOD metric suite, QMOOD metric suite, CK metric suite etc. Much of these approaches have never been used or have had very few test cases and have generally been lacking. This paper assesses the features and characteristics of these models based on the standards of industrial and academic value.

- **Related Work** Similar works have been done pertaining to analysis and classification of the metric based fault prediction. The results of these studies were that Object Oriented (OO) metrics performed exceptionally well compared to the other methods and methods that used a combination of range of metric gave the best result. This paper is unique in that it aims to evaluate and validate the core metric methods based on their properties and context. Further deficiencies of related work and issues are highlighted in the paper, specifically their cause being that the categorization done was standard and generic and was not based on the domain which it was developed for an example being that process metrics was shown to be the lowest rank amongst other metric based approaches, however, studies from others papers shows that in specific conditions, the process metric method out performs all other methods.

- **Research Methodology** The paper follows Kitcheham's guidelines for the analysis of metric based papers. The following steps are used for the overall approach:

1. Identification of the reason for a systematic review.
2. Making a review protocol.
3. Analyze the review protocol.
4. Gather required study material
5. Select relevant papers.
6. Identify and extract required information according to protocol
7. Quality inspection of work done.
8. Compile the data.
9. Distribute results

- **Research Question** The process of step 6 was carried out according to regulation of PICOC criteria, which is:
  - Population: software application, software project
  - Intervention: fault prediction models and techniques
  - Comparison: None
  - Outcomes: Accuracy and success rate
  - Context:Academia and Industry

- **Selection of Primary Studies** The paper selected the primary studies by selecting trusted and well known digital libraries like ACM, IEEE Xplore, Inspec, ScienceDirect etc. Keywords were used in the search and based on the materials found, the keywords were further refined. A list of studies initially found was 13,126 papers. Next steps involved trimming the papers down and creating a final list which would be than reviewed in depth (106 papers). The evaluation of these papers were done on the basis of empirical and contextual criterion. An example provided is the amount of data used during the research papers, its domain (Industry or Academic) and performance comparison. The paper points out that initially it set out to classify all the metric but due to the massive amount of metrics that were observed, a categorization was done as:
  - Traditional: Size and complexity metrics.
  - Object-Oriented: Coupling, Cohesion and class level type metrics.
  - Process: Code delta, code churn, combination of source codes etc.

- **Properties** The properties main categories for evaluation were as follows:

1. Metrics
2. Data set Availability
3. Data set size
4. Programming Language
5. Software Development Life Cycle
6. Researchers
7. Organization
8. Modeling Technique
9. Dependent Variable
10. Dependent Variable Granularity

- **Results** Alongside the properties, an important aspect of this papers systematic literature review is that it aimed to answer certain research questions like what type of software metric is mentioned within the paper in question? What is the validation? Are the metrics used useful? Are there any benefits? Etc. The amount of results discussed within this paper is out of the very numerous and is not viable to mention within this report. A conclusive fact that can be mentioned is that industrial organizations prefer OO metrics and similarly researcher in academics also prefer OO metrics.

- **Conclusions** This paper provides a complete and coherent review for research papers pertaining to fault prediction using metric. It evaluates and validates these papers based on 10 properties as well as on carefully meticulated research questions. Unlike other research papers, there is no clear winner or anything of the sort but all metrics that are eligible to be selected 'depend' on the real life constraints.

Keywords

Software metric, Software fault prediction, Systematic literature review

Notes

The paper provides a complete overview of past literature and is beneficial for researchers who wish to get an overview of fault prediction metric techniques. An intersting point mentioned within the paper is that despite the fact that 13,126 papers were found, only through contacting the authors additional and highly relevant papers were found which were not available in any of the big data bases. Also a large number of keywords were utilized.

Contributions

A hefty and compact review of fault prediction models using metrics.

Deficit

None that can be pointed out currently.

Software fault prediction: A literature review and current trends
Reference

DOI: https://doi.org/10.1016/j.eswa.2010.10.024

Year: 2011

Author: Cagatay Catal

Abstract

Software engineering discipline contains several prediction approaches such as test effort prediction, correction cost prediction, fault prediction, reusability prediction, security prediction, effort prediction, and quality prediction. However, most of these prediction approaches are still in preliminary phase and more research should be conducted to reach robust models. Software fault prediction is the most popular research area in these prediction approaches and recently several research centers started new projects on this area. In this study, we investigated 90 software fault prediction papers published between year 1990 and year 2009 and then we categorized these papers according to the publication year. This paper surveys the software engineering literature on software fault prediction and both machine learning based and statistical based approaches are included in this survey. Papers explained in this article reflect the outline of what was published so far, but naturally this is not a complete review of all the papers published so far. This paper will help researchers to investigate the previous studies from metrics, methods, datasets, performance evaluation metrics, and experimental results perspectives in an easy and effective manner. Furthermore, current trends are introduced and discussed.
Research highlights
► 90 software fault prediction papers have been reviewed. ► Most of the studies use method-level metrics. ► Models are mostly based on machine learning techniques.

Summary

- **Introduction** Software fault prediction approaches use an independent metric data set and a dependent fault data set which are stored and computed for generating fault models that gives a probability of a fault occurring in the future. This research paper focuses on a literature review of software fault predictions of past researchers. The core reason for the need of fault prediction is for dependability and quality of a system. The parameters of a fault prediction is generated based on the computation of prior software metric and fault data.

- **Background** Fault prediction according to some of the papers reviewed showed that fault detection were 60% reliable and inspection are (71% ~ 95%) effective. For the range of inspection, there seemed to be a conflict of results. This paper focuses on the reviewing the literature of not only fault prediction but related machine learning and statistical based methods. The papers that were selected was based on their similarity.

- **Reviewed Papers** A total of 90 papers were reviewed from the time period of 1990 – 2009. The papers are book chapters, journal articles and conference papers. The papers have been classified according to their publication along with certain other criteria’s. Papers that have not used in valid test cases or experimentation have been discluded.

- **1990 – 2000** The progression of the fault predictions is through the 90’s, a fault prediction system was developed which had a good success rate of about 79.3% but was only suitable for balanced and controlled datasets, another approach was that the application of logistic regression which when used for project cost estimation provided about 90% success, a study in which A.I neural networks for communication systems proved to show better results than typical the model.

- **2000 – 2003** In the early 2000's work on fuzzy logic, case-reasoning, logistic regression and programmed models (Expectation minimization algorithm and Boolean discriminant function) had major progress. The result of the fourteen papers have been briefly discussed in the paper and many of the techniques were on comparison with other techniques or testing a combination mainly of metric fault prediction models amongst a specific test case of which a bulk of the test cases within this year was focused on telecommunication sector.

- **2003 – 2005** In this period the typical methods that had a focus in the fusion of fuzzy fault prediction models with regression variants and as previous years this also focused comparison and evaluation between different approaches and the outcome was positive which demonstrated better fault prediction compared to the previous years.

- **2005 – 2007** In the years 2005 to 2007, the focus shifted from fuzzy logic to support vector machines alongside regression models. Due to the consistent and innate power of regression models it has and continues to be a powerful tool which researcher integrate within their fault prediction models. An interesting model utilized was the mean absolute residual model (MAR) which had an accuracy of 93% but only for models that had a balanced data set.

- **2007 – 2009** From 2007 to 2009 approaches using clusters and Naives Baye's had begun to pique the interest of researchers along with the staple of the decade, regression models. Most of the research done was focused on data from telecommunication companies within this time period.

- **Current Trends** In fault prediction, cases in which there are no prior data sets available, software fault prediction of unlabeled program modules are used, an example would be X-means clustering method. Supervised learning provides a very dependable fault prediction but it requires a sufficient amount data. Some data cannot be acquired in bulk due to cost or limitation of resource. For this a combined approach is required which involves semi supervised learning. A proposed idea for this has been provided in previous literature pertaining to the use of Naive Bayes.

- **Research Problem** A significant problem is the detection of a incipient fault in a data set. When the majority of the metric dataset and are within the acceptable threshold they are set by default to a non-faulty class. This is an issue which is still being researched. Out of all current trends, the Naive Bayes is the most promising for fault prediction.

- **Conclusion** The paper is a type of survey that highlighted the work done by past researchers for the past 20 years. It gives a brief and concise explanation of what the papers presented and what was the consequence of their work. From the survey it is clear that metric methods and machine learning based techniques dominated the research domain for the past twenty years although a shift towards other techniques can be seen based on the observed pattern of the last three years.

Keywords

Machine learning, Automated fault prediction models, Expert systems, Software quality engineering, Software engineering, Statistical methods

Notes

A very brief and quick review of 20 years of literature pertaining to fault prediction which is simple and easy to understand.

Contributions

A compact survey for fault prediction.

Deficit

The research paper was not coherent and the features and characteristics explained may as well have been the abstract of the past papers. A little table showing the comparison would have sufficed in making this paper meaninful.

Fault detection on robot manipulators using artificial neural networks
Reference

DOI: 10.1016/j.rcim.2010.06.017

Year: 2010

Author: Ikbal Eski, Selcuk Erkaya, Sertac-Savas, Sahin Yildirim

Abstract

Nowadays, gas welding applications on vehicle’s parts with robot manipulators have increased inautomobile industry. Therefore, the speed of end-effectors of robot manipulator is affected on each jointduring the welding process with complex trajectory. For that reason, it is necessary to analyze the noiseand vibration of robot’s joints for predicting faults. This paper presents an experimental investigationon a robot manipulator, using neural network for analyzing the vibration condition on joints. Firstly,robot manipulator’s joints are tested with prescribed of trajectory end-effectors for the different jointsspeeds. Furthermore, noise and vibration of each joint are measured. And then, the related parametersare tested with neural network predictor to predict servicing period. In order to find robust andadaptive neural network structure, two types of neural predictors are employed in this investigation.The results of two approaches improved that an RBNN type can be employed to predict the vibrationson industrial robots.

Summary

- **Introduction** The significant growth of the application of robotic manipulators within the industrial sector has increased the need for fault detection and prediction within these systems. The core issues for faults within robotic manipulators are the joint driving systems. This paper focuses on dealing with the vibrations during the operation of a robotic manipulator arm for fault prediction and fault tolerance.

- **Previous Works** Prior research on the field have involved the approaches using model-based diagnostic behavior, nonlinear analytical redundancy, H infinity etc. The aim of each approach was to develop fault tolerance for the robotic manipulators joint systems. Some successful and approaches involved installation of redundant revolute joints or modification of the kinematic layout of the robotic manipulators.

- **Related Work** Work related to this paper used neural neural networks that predicts the robot posture based on average in the next time step. Results were that the system had improved fault tolerance and stability. Most other works involved algorithms that dealt with successfully solving specific faults that ranged from the legs locking of a hexapod to the sudden burst of velocity with robotic manipulators.

- **Robotic Manipulators** The scope of the robots which are discussed in the paper are industrial six axis robotic manipulators that utilize point to point and continuous path kinematic models. Application areas are handling, assembly, applying adhesives and similar types of chemicals and machining. The specifications of the robotic manipulator has been enumerated in the paper along with its dynamic model as wells as the functions.

- **Proposed Neural Networks (NN)** The neural networks proposed within this paper is a three layered feed-forward neural network that performs an analysis of the velocity of the welding robotic manipulator. The learning methods which would be used are self organizing map neural networks and radial basis neural network.

- **Self Organizing Map Neural Network (SOMNN)** It is a grid of map units where units represents a prototype vector. Each unit is connected to other close units by a relation. So all units map to other units and preserves the input. This is trained by the selection of a random z vector and distance is compared with prototype vectors. This is done iteratively.

- **Radial Basis Neural Network** (**RBNN)** This method has only one hidden layer which can be used with nonlinear data. It uses multi-layer perception neural networks. This NN is useful for data sets that have a lot of noise. The functions used, utilizes Gaussian distribution and produces a linear output.

- **Experimental Cases** The test cases for the proposed neural networks for the robotic manipulator had been done in two steps. Step 1 involved gathering the velocity and acceleration values of the robotic joints during operation and Step 2 used the self organizing map neural network and radial basis neural network to compute fault prediction models for the next time step using the operational data set as the training set. The information gathered used accelerometers which has been mapped to graphs. The experiment test case one had the robotic manipulator arm running at a speed of 1 rpm and the experiment test case two had the robotic manipulator arm running at a speed of 2 rpm.

- **Results** The test cases show the most variation between the prediction model and standard operation at the peak values of the experimentation. From the results it is clear that self organizing map neural network had sub-par results while the radial basis neural network algorithm provided very accurate data prediction. The radial basis neural network has been better able in dealing with the noisy data set as well as is more robust in the measurement of vibrations within the robotic manipulator joints given the variation of test cases that have been analyzed. A point of interest is that the robot is not the main contributor to noise but other components like the controller have a bigger hand in the noise. The radial basis neural network performed significantly better than self organizing map neural network due the use of the Gaussian distribution which gives a highly sensitive response based on the distance of input unit and the unit in the hidden layer.

- **Conclusions** This papers proposes a an approach for fault detection and fault prediction using neural networks to predict vibrations within a robotic manipulator arm. Two neural network algorithms were proposed in the paper self organizing map neural network algorithm and radial basis neural network algorithm. Test case on a six degrees of freedom, welding robotic manipulator was conducted in which the radial basis neural network significantly out performed the self organizing map neural network.

Keywords

Fault detection, Neural network, Robot manipulator, Vibration analysis

Notes

A well composed paper that is easy to understand, well structured and provides a good example of the application of fault prediction.

Contributions

A fault prediction approach for robotic manipulators which is backed by an experimental test case.

Deficit

Further explanation on the results of the experiments would have been beneficial as well as providing the pseudo code which had been used for testing.

Model-based fault detection, estimation, and prediction for a class of linear distributed parameter systems
Reference

DOI: https://doi.org/10.1016/j.automatica.2015.12.028

Year: 2016

Author: Jia Cai, Hasan Ferdowsi Jagannathan, Sarangapani

Abstract

This paper addresses a new model-based fault detection, estimation, and prediction scheme for linear distributed parameter systems (DPSs) described by a class of partial differential equations (PDEs). An observer is proposed by using the PDE representation and the detection residual is generated by taking the difference between the observer and the physical system outputs. A fault is detected by comparing the residual to a predefined threshold. Subsequently, the fault function is estimated, and its parameters are tuned via a novel update law. Though state measurements are utilized initially in the parameter update law for the fault function estimation, the output and input filters in the modified observer subsequently relax this requirement. The actuator and sensor fault functions are estimated and the time to failure (TTF) is calculated with output measurements alone. Finally, the performance of detection, estimation and a prediction scheme is evaluated on a heat transfer reactor with sensor and actuator faults.

Summary

- **Introduction** Improvement of system dependability and reliability rely on fault detection and fault prediction. Fault detection and prediction have been evolving substantially from the typical differential systems to data driven and model based approaches.

- **Past Literature** Fault detection systems that were developed by previous researchers in the early period that had a significant impact included approaches like fault modeling using system representation, model-based fault diagnosis by generating residuals, adaptive observer for fault distribution etc. Other works included the application of neural networks.

- **Distributed Parameter System (DPS)** Processes that change over a period of time and space i.e. fluids and thermal convection etc. are represented by ordinary differential equations (ODEs). Fault detection and prediction models that have been applied to them are reduction of the order of the system, detection observer, conversion into partial differential equation, residual generation etc. The deficiencies of these systems were that reduction of the order leads to inaccurate results and with residuals is the problem of false positives or false alarms.

- **Papers Proposal** This paper proposes an observer fault detection for distributed parameter systems that are represented by partial differential equations. The filter is based on the Luenberger type observer. It generated residues based on the difference of estimates from the Luenberger type observer and the measured value. A thing about DPS is that a fault within the system can simply be modeled as an external input to the system. Upon detection of a fault, the observer records the fault as part of adaptation. The observer uses a single input filter with two output filters (which is exclude dependency on input) which adjusts unknown faults estimations based solely on the output. The observation is that faults generated are always bounded despite noise and disturbance by which this paper also proposes an explicit formula for time to failure of a system (TTF) and remaining useful life (RUL).

- **Assumptions for Modeling**

1. Disturbance and constraints of a distributed state system are constrained.
2. A stabilization controller exists that ensures the system is bounded in normal non-faulty conditions.
3. When a fault occurs, its type is known. The system can have one fault at any given time and not more.

- **Detection and Estimation** In normal non-faulty condition, the estimated output of the system will converge with the measured value to zero. For faulty conditions in an actuator will the systems measured output deviate from the estimated output due to the observer generates data which is than tuned to the output compared to what is measured by in reality. For faulty conditions in the sensors, the measured values will directly impact on what the estimate outputs which exceeds the prescribed threshold and hence, based on the fault, it can be identified whether the fault is from a sensor or an actuator.

- **Estimation of Outputs** For a system that uses only the outputs for prediction, the detection observer has to be developed carefully. Some important points for filter based observers is as follows:

1. Dynamic system converted into observable form.
2. Filter must be based on the controlled input and measured output.
3. Testing where the filter works proper in normal non faulty conditions.
4. Adaptation system that incorporates unknown faults.

- **Simulation** For the simulation test case, a thin rod that was heated through conduction is considered. Initially the system is modeled in non heated conditions and parameters of the change in rod through heat are inserted. The simulation case lasts for twenty five seconds and for the numerical calculation the time is discretized into mini steps. Time parameters for fault occurrence are set along with the threshold of acceptable values.

- **Results** The result was as the expected outcome where; The expected outcome for the actuator case is that the residues decrease in the normal non fault condition but when the fault is introduced than the residues increase. Whilst in the case for the sensor, it is expected for the threshold value to be breached. Upon detection of sensor fault that breaches the threshold, the adaptive term kicks in; the observer records the parameters, tunes those parameters and then develops an estimation for the fault. The time to failure for both faults can be calculated according to the given mathematical model developed.

- **Conclusion** The paper discusses the progression of fault detection and fault prediction over the past decades. It specifically highlights the deficiencies of approaches for fault detection and prediction in distributed parameter systems. To overcome these deficiencies, it proposes a new approach using observers for dealing with DPS.

Keywords

Fault detection, Fault estimation, Fault prognosis, Partial differential equations, Distributed parameter systems

Notes

The application of observers for fault detection is not a new idea, though the application of it to systems for fluids and other entities that change with time and space is a novel idea. This paper supports all of its claims with mathematical proof as well consistent reference to previous literature (References which are valid and justified).

Contributions

A fault detection and prediction model for distributed parameters systems that depends only in the outputs with controlled inputs along with mathematical models that give the time to failure TTF and remaining useful life RUL.

Deficit

No pseudo code available for other research to test and re validate the simulation and test results.

Robot fault detection and remaining life estimation for predictive maintenance
Reference

DOI: https://doi.org/10.1016/j.procs.2019.04.094

Year: 2019

Author: Riccardo Pinto, Tania Cerquitelli

Abstract

In this work some possible solutions to implement a Robotics-oriented predictive maintenance approach are discussed. The data-driven methodology is described from the data collection to the design of an appropriate dataset and finally to the use of some of the most promising algorithms in the field of machine learning. The whole process is composed by several building blocks that can be combined to realize a data analysis on industrial robots. Some of the most promising techniques in Predictive Maintenance for Industrial machines were included in the proposed methodology, together with a Survival Analysis study, and then evaluated with proper performance metrics. Experimenting this methodology on a real use-case with Comau industrial robots showed the validity of the approach and opened to the inclusion of such a process in a service-oriented solution.

Summary

- **Background**
  - Industry 4.0 is the currently pushing the world towards a new industrial era. In industry 4.0, physical systems like machinery and equipments that are used will be upgraded or built in such a way that it allows them communicate with other systems that is to say that these systems become cyberphysical systems.
  - They will have the ability to intelligently map and execute the most efficient and effective path to the user set goal.
  - These systems will simplify many processes and drastically improve the effective life of all the technologies used within the industry.
  - Introduced by the Germans, industries around the globe are adopting the evolutionary shift towards the implementation of industry 4.0.
- **Past Literature**
  - Despite the recency of the industry 4.0, some companies have already successful integrated and implemented the technologies. Papers are currently being churned out about the application of predictive maintenance.
  - The approaches that are being focused on are industry big data analytics or the remaining useful life of a component; Researchers are working on how machine learning algorithms such as K-nearest neighbors, Random forest or Deep networks can be used for these applications.
- **Issues in Industry for Fault Predictive Maintenance**

- The problems for the industry currently is the acquisition of data for older robots.
- The issue stems from the fact that if the current industrial robots stop working, then non working robot entails no products which entails loss of profit.
- Businesses cannot afford this which is one of the problems this paper addresses.

- **Papers Proposition** The paper deals with solving the issue of data acquisition for older robots and the methodology of building them as well as presenting the results of a test case in which four algorithms (survival analysis, convolutional neural network (CNN), random forest and k-NN) are used to predict faults in an old robot.

- **Test Case**
  - For the test case, the NJ-X robot series was selected whose operation was spot welding.
  - The fault conditions considered are when the high powered cables attached along the joints of robot are choked.

- **Problem Definition**
  - With a limited data set the NJ robot has to perform its task in a way in which it predicts the choking problems and voids them.

- **Data Analytic Architecture**
  - The data analytic architecture used has three steps.

1. **Data Preparation** Step one is data preparation in which the data is preprocessed to acquire relevant and key features. The data sets are then normalized. The data used for the experimental test case has been provided by technicians from the industrial plant. Two types of data were used raw data which simply characterizes the motion of the robotic arm, the feature set that is used consist of data pertaining to the type of robot, the tool, if the robot is in fault condition etc. The preprocessing of the data is done in three ways. Simply applying data normalization, principal component analysis or conversion of data into images for the convolutional neural networks.

2. **Machine Learning Algorithm** This step utilizes machine learning algorithms the address the faulty robots. Survival analysis algorithm uses time components to compute the regression covariates for estimation of lifetimes. Extremely Randomized Trees algorithm uses randomly selected candidates with randomly generated threshold of which the best randomly threshold is selected during a split. K-Nearest Neighbors computes the distance of each data and its neighbor in a euclidean space. Convolutional neural networks is trained in which the output of the system is a linear multiplication matrix of filtered two dimensional input. In it data goes to a Polling layer, then through a activation layer which applies a non linear operation which is flatted and passed onto a dense layer that matches inputs to outputs by weights, it then passes through a final activation layer after which an output is received.

3. **Validation** For validation two techniques were used. First technique used was cross validation technique and data splitting and the second technique used was data splitting.

- **Results** The survival analysis, k-NN and extremely randomized trees algorithms were moderately effected by the preprocessing of principal component analysis. The accuracy of survival analysis is (76% with PCA, 80% without PCA), k-NN (95% with PCA, 98% without PCA), extremely randomized trees (95% with PCA, 98% without PCA) and as for CNN, measuring accuracy might misrepresent the result, so a confusion matrix is provided of which it predictions are very high and precise for when the data was converted to data image block.

- **Conclusions** This paper presents machine learning algorithms for predictive maintenance for industrial robotics. The experimentation performed was on a test case of NJ series robotic arm and the data set was provided by a company. The performance of the algorithms proved to be quite effective in the prediction of faulty robots.

Keywords

Industry 4.0, machine learning, data analytics, robot fault forecasting

Notes

This paper presents an interesting approach of how to deal with limited data for fault predictions.

Contributions

Application of fault prediction in robotic manipulators using machine learning algorithms in which their results are compared.

Deficit

An ordinary informative paper that provides comparative analysis in fault prediction approaches. No deficiency.

5 Conclusions

Conclusion

- Dependable robots are the key to evolving and sustaining future industries. Failure of robotic systems in todays world would have a much a larger and graver affect compared to a few decades ago.
- Major threats to dependable robots are faults, which can occur within the software or hardware of a robotic system during the design phase or run-time.
- The methodologies employed for dealing with fault is a fault detection, fault diagnosis, fault prediction and fault tolerance.
- Faults can be effectively completely removed in the design phase, however, more often than not faults occur which makes dealing with faults a vital process.
- No matter how well a system is developed and designed, it will always be susceptible to faults due to which, the best systems are those that are able to quickly and effectively weed out all faults and become immune to them, next time around.
- Generally the implementation for fault detection, diagnosis and other methodologies follow the same framework, that is to follow a model-based or data-driven/signal based or a knowledge-based approach.
- The difference in approach for fault detection, diagnosis and other methodologies lies within the context in which they are implemented, that is fault detection using signal-based approach detects irregularities where as fault diagnosis matches those irregularities to existing one to identify the ‘type’ of irregularity. Though the difference may seem subtle, the response and process time largely differ.

State of the Art

- In dependable robots the direction of the state of art discluding faults is the focus improvement of architecture of the robotic systems. The architecture that is being worked on prevents illegal actions from being performed incurred by internal commands.[13]
- For fault detection the current latest work involves the fusion of approaches to deal with drawbacks of a single approach. In this report, two works have been reviewed one in which the filter issue by Non Homogeneous Markovian Jump System is dealt by the application of fuzzy logic.[21] Another work reviewed is the application of Granger causality to compensate for the correlation dependency approach.[26]
- In fault diagnosis the state of the art that is being researched is the effective combination multiple methodologies, and example of this is the research paper that combines feature extraction with high dimensional data reduction and pattern recognition that enables vast improvements in fault diagnosis.[30]
- The work in fault prediction is mostly being done in the areas of machine learning. Of the first of two papers pertaining to fault prediction that has been reviewed (latest state of the art), an ARMA data driven model is combined with machine learning algorithms like fuzzy networks which process and generates an estimate of future fault data that is reprocessed with principle component analysis to give accurate predictions.[4] The second paper reviewed focuses on discovering the best machine learning algorithm for fault prediction and if applying principle component analysis with these algorithms actually effect the final result.

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7 Appendix

Glossary.pdf (78.68 KB)

7.1 Links to HTML tables

ISW 150 Academic Material Pertaining to Faults
150 Research Papers Dep. Rob. (337.66 KB)

7.2 Your link collection of online literature search

Top 30 Literature
TOP 30.zip (69.96 MB)

7.3 Sources

- CiteSeer.IST - Scientific Literature Digital Library
- IEEE Xplore - Online archive of IEEE publications
- The ACM Digital Library
- BASE (Bielefeld Academic Search Engine)
- Paperity
- Semantic Scholar

- Library Catalogue FH Bonn-Rhein-Sieg
- OPAC of the Union Catalogue of Serials (ZDB)
- KVK Karlsruhe Virtual Catalogue
- Library of Congress
- DBLP Digital Bibliography & Library Project
- Subito e.V. - Document copy and delivery service of the International Libraries
- Google
- GoogleScholar
- Get Cited
- Directory of Open Access Journal
- Plosone
- Science and Technology of Advanced Materials
- New journal of Physics
- ScienceDirect
- Microsoft Academics

7.3.1 List of searched journals

- CORE
- ScienceOpen
- Education Resources Information Center
- arXiv
- New journal of Physics
- Science Direct
- BASE
- plosone

7.3.2 List of searched conference proceedings

- International Conference on Control and Fault-Tolerant Systems
- International Workshop on Principles of Diagnosis
- The International Symposium on Advances in Fault Tolerance and Transaction Processing
- European Dependable Computing Conference
- International Symposium on Reliable Distributed Systems
- Fault Tolerance for HPC at eXtreme Scale (FTXS) Workshop
- International Workshop on Fault Tolerant Systems
- Workshop on Approximate Computing

7.3.3 List of searched magazines

- MIT Technology Review
- Servo Magazine
- IEEE Spectrum
- IEEE Robotics and Automation Magazine

7.3.4 Other searched publications

- WIRED
- Discover Magazine

7.4 Key words and key word combinations used for search

pictured either as structured list or as tree

- Faults
- Fault Detection
- Fault Diagnosis
- Fault Tolerance
- Fault Prediction
- Fault Forecasting
- Fault Isolation
- Fault Recovery
- Fault in Robotics

- Fault in Automated Systems
- Fault in Control Systems
- Dependable Robots

7.5 List of most important conferences

- International Conference on Control and Fault-Tolerant Systems
- International Workshop on Principles of Diagnosis
- The International Symposium on Advances in Fault Tolerance and Transaction Processing
- Fault Tolerance for HPC at eXtreme Scale (FTXS) Workshop
- International Workshop on Fault Tolerant Systems

7.6 List of most important journals and magazines

Journals

- IFIP Working Group 10.4 Dependable Computing and Fault Tolerance

Magazines

- IEEE Robotics and Automation Magazine

7.7 List of top research labs/researchers

Dependable Robots:

1. Félix Ingrand
2. Rachid Alami
3. Jérémie Guiochet

Fault Detection:

1. Rolf Isermann
2. Venkat Venkatasubramanian
3. Raghunathan Rengaswamy

Fault Diagnosis:

1. Zhengjia He
2. Steven X. Ding
3. Rolf Isermann

Fault Recovery:

1. Barbara Liskov
2. Miguel Castro
3. Irith Pomeranz

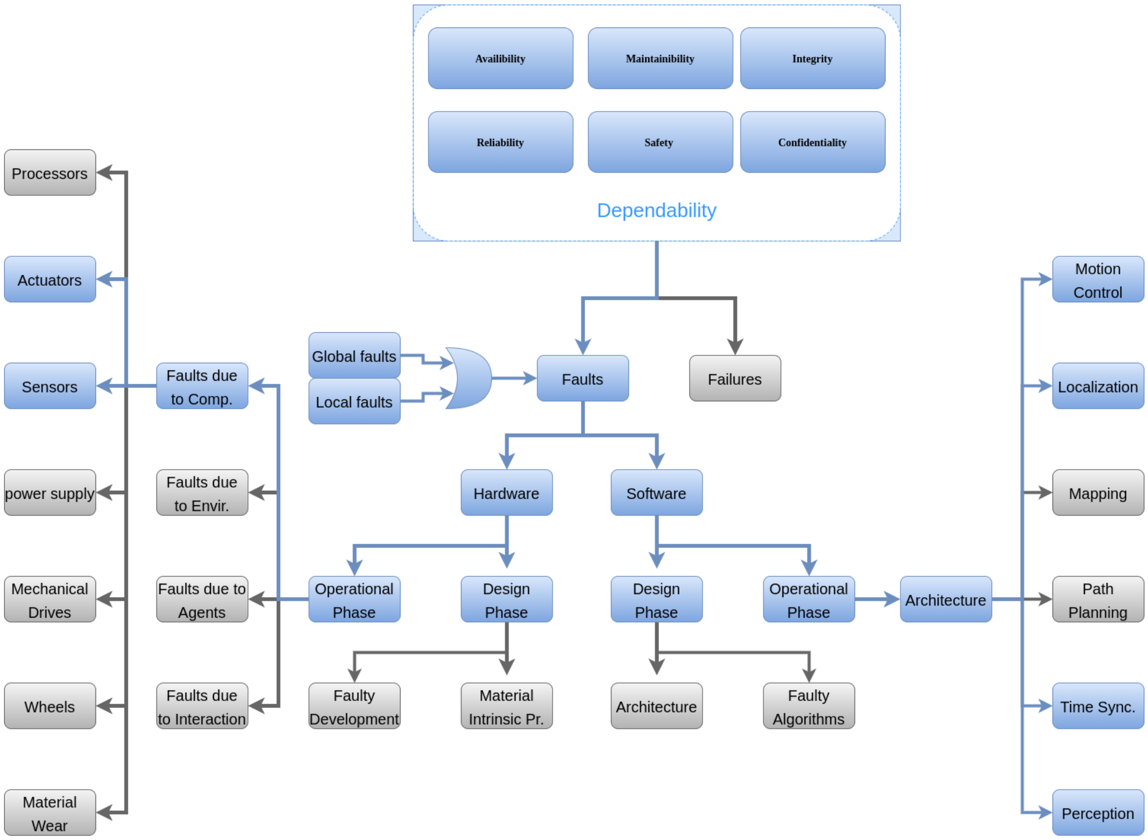
Fault Tolerance:

1. Ion Stoica
2. Michael J. Franklin
3. Scott Shenker

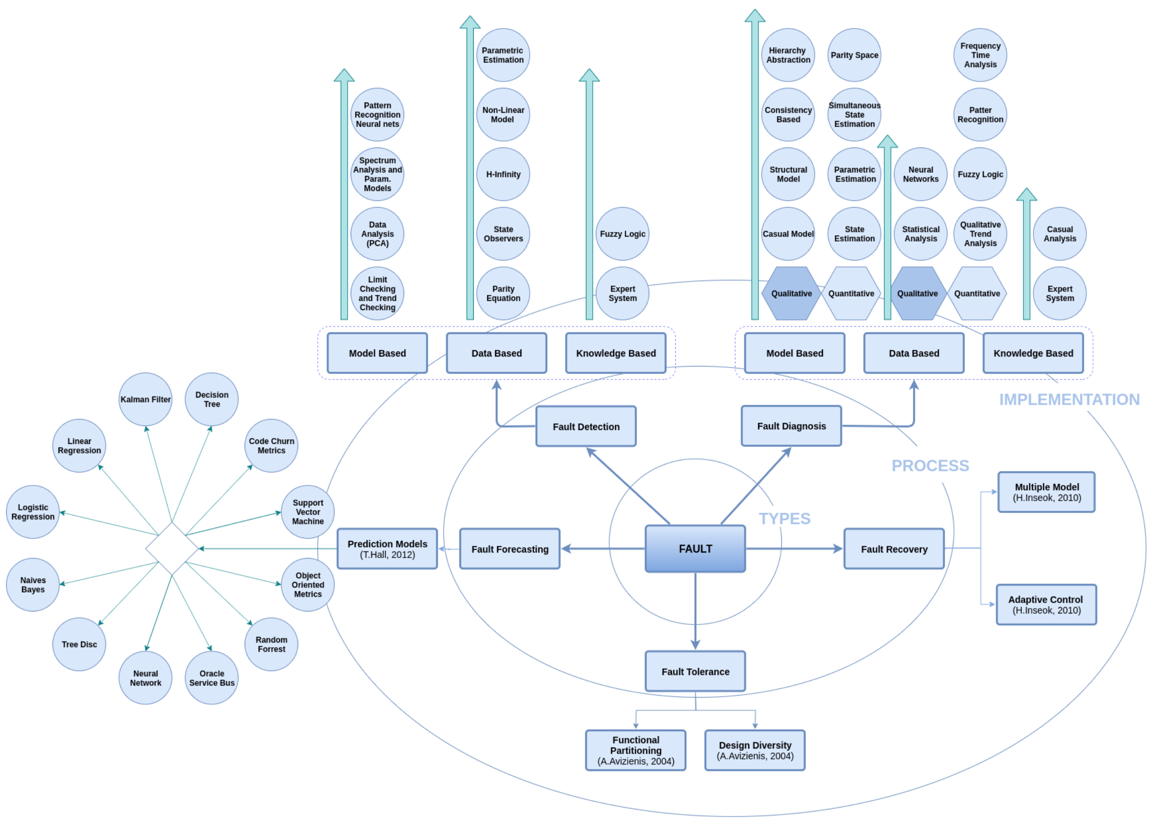
Fault Prediction:

1. Tracy Hall
2. David Bowes
3. Rudolf Ferenc

7.8 Mindmap



Availibility
Maintainibility
Integrity
Reliability
Safety
Confidentiality
Dependability
Processors
Actuators
Sensors
power supply
Mechanical Drives
Wheels
Material Wear
Faults due to Comp.
Faults due to Envir.
Faults due to Agents
Faults due to Interaction
Global faults
Local faults
Faults
Failures
Hardware
Software
Operational Phase
Design Phase
Design Phase
Operational Phase
Faulty Development
Material Intrinsic Pr.
Architecture
Faulty Algorithms
Architecture
Motion Control
Localization
Mapping
Path Planning
Time Sync.
Perception



Pattern Recognition Neural nets
Spectrum Analysis and Param. Models
Data Analysis (PCA)
Limit Checking and Trend Checking
Parametric Estimation
Non-Linear Model
H-Infinity
State Observers
Parity Equation
Fuzzy Logic
Expert System
Hierarchy Abstraction
Parity Space
Frequency Time Analysis
Consistency Based
Simultaneous State Estimation
Patter Recognition
Structural Model
Parametric Estimation
Neural Networks
Fuzzy Logic
Casual Model
State Estimation
Statistical Analysis
Qualitative Trend Analysis
Casual Analysis
Qualitative
Quantitative
Qualitative
Quantitative
Expert System
Model Based
Data Based
Knowledge Based
Model Based
Data Based
Knowledge Based
IMPLEMENTATION
Fault Detection
Fault Diagnosis
PROCESS
TYPES
Kalman Filter
Decision Tree
Linear Regression
Code Churn Metrics
Logistic Regression
Support Vector Machine
Naives Bayes
Object Oriented Metrics
Tree Disc
Random Forrest
Neural Network
Oracle Service Bus
Prediction Models (T.Hall, 2012)
Fault Forecasting
FAULT
Fault Recovery
Multiple Model (H.Inseok, 2010)
Adaptive Control (H.Inseok, 2010)
Fault Tolerance
Functional Partitioning (A.Avizienis, 2004)
Design Diversity (A.Avizienis, 2004)