

An Adaptive Approach to Self-Healing in an Intelligent Environment

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Abstract— In this paper, we address the management of sensor faults in an intelligent environment. Our proposed approach aims to introduce self-healing as a method of fault management. This approach is based on the use of adaptive finite state machine automata which handle suspicious sensor behavior. These state machines communicate with a mobile robot which investigates the error states detected through the sensors in the environment in order to learn from the anomalies and adapt to the changes in sensor behaviors. Additionally, we have determined that two types of fault may arise: systemic faults which the system may learn from and adapt to, and random faults which the system may compensate for through the use of a mobile robot as a sensor substitute.

Keywords-fault tolerance; self-healing; sensor substitution; intelligent environment.

I. INTRODUCTION

Since the introduction of the concept of intelligent environments, we have seen an increase in the applications of the sensor technologies synonymous with these environments. A promising application of those technologies is within the smart home for the delivery of pervasive care [1]. These environments aim to facilitate the monitoring of elderly occupants who suffer from cognitive impairments or degenerative conditions, such as dementia [2], and to support independent living [3]. In order for these environments to function effectively they must be tolerant of faults. The efficient functionality of sensor technologies in care homes for the elderly is crucial to ensuring the safety of the environments occupant. Those who suffer from dementia are often prone to wandering behavior [4]. As a consequence, there is great potential that those who leave their homes undetected may place themselves in danger [2]. For this reason, this research focuses on the monitoring of activity about a door in an intelligent environment. This work is motivated by the widespread instances of dementia patients who have left their care homes undetected [5] [6].

The prevalence of sensor technologies coupled with the increasing complexity of information systems is leading us to the need for systems that are capable of self-management and self-adaptivity [7]. Our approach aims to take the initial steps in introducing the first of four key properties of an autonomic system: self-healing. This research aims to achieve this through the introduction of sensor substitution and adaptivity to the sensor technology about a door in an intelligent environment in order to provide the self-healing and self-management of sensor faults and anomalous

behavior respectively. The proposed approach makes use of multiple finite state machines coupled with the use of a fuzzy logic rule base and adaptive learning techniques in order to provide intelligent adaptive fault management. This is achieved through the systems own investigation of its error states from which the system may learn new behaviors and adapt its policies accordingly.

The remainder of this paper is organized as follows: Section II provides an overview of related work. In Section III we present our design. Section IV discusses some preliminary results. We conclude with Section V in which our future work is outlined.

II. RELATED WORK

A comprehensive summary of the use of finite state automata in the design of reliable software is presented by Wason et al. [8]. Whilst the use of finite state machines for the purpose of introducing fault tolerance is not a new concept [9], there exists a research gap in terms of the need to further explore the extent to which a system may be made autonomic through the use of state machines so that a system may investigate and learn from its error states [8], in order to create a stronger awareness of the conditions under which the system is expected to perform. In order to achieve this, a system must be both self-aware and environment aware [10].

A popular approach to the management of faults is the use of redundancy [11]. These approaches focus on the use of additional hardware as a fail over mechanism when their counterparts degrade. These sensors are capable of measuring identical or closely related values. This approach does not resolve the underlying fundamental problem that hardware is subject to failures and even redundant components have the potential to be subject to a fault or failure; particularly if their data is only incorporated into the monitoring process periodically. For this reason, we propose that the use of adaptable software to compensate for the shortcomings of hardware devices as their behavior degrades is a practical and cost-efficient approach. Indeed, the large volume of research that is undertaken in the area of robotics for pervasive care suggests that in the future robots will have a more prevalent role [12], particularly in care home environments. We can utilize these robots to not only assist in the delivery of pervasive care, but to also assist in ensuring fault tolerance in an intelligent environment by providing a mobile means of delivering sensor substitution and the investigation of anomalous sensor behavior at the point of need.

III. DESIGN

In this section, we will describe the design of our system in terms of both the hardware and software topologies.

A. Hardware Topology

In our previous work [13], we investigated the viability of using an ultrasonic array mounted on a mobile robot as a means of substituting for a radio-based door mounted contact sensor. From this work, we concluded that two door states, opened and closed, could reliably be determined by the mobile array. Previously, our topology consisted of a radio contact sensor, pressure mat and the mobile robot Pioneer 3-DX from Adept Mobile Robots [14]. We extended this to include an additional pressure mat in order to detect when a person had passed through the door threshold. Our hardware topology is depicted in Figure 1.

1) *Static Sensors*: Based on our observations of the sensor data generated by the static sensors, we determined that these sensors may be viewed as “black and white” sensors as their readings dictate one of two states; the radio door contact sensor can return a “door opened” or a “door closed” value. Similarly, the pressure mats can return a true or false binary value to denote their activation or dormancy.

2) *Mobile Sensors*: In contrast to the static sensors the mobile sensors with which the robot is equipped, which include an ultrasonic array and an infrared sensor, may be viewed as “grey” sensors. This stems from the fact that whilst the static sensors can provide a simplistic piece of information depicting that they are in one of two possible states, the mobile sensors require pre-processing in order to derive information from their data about their perception of the world.

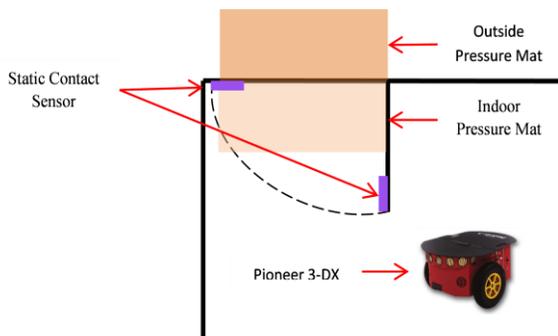


Figure 1. Hardware topology in experimental environment.

B. Software Topology

A high-level conceptual overview of the software system structure is presented in Figure 2. It is made up of two communicating finite state machines and two feedback loops. Each of the state machines communicates with the static sensors and mobile sensors respectively. It is through this continuous feedback that the states in the machines are driven. This is discussed in the following sub-section.

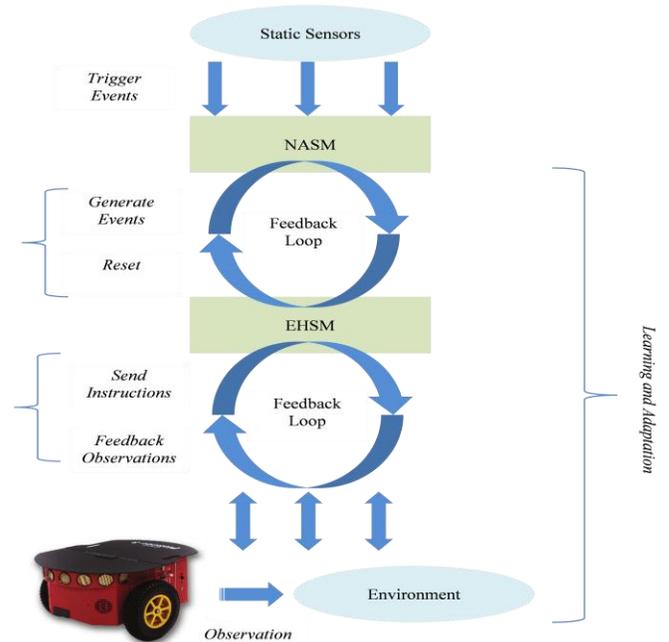


Figure 2. High-level overview of self-healing system structure.

1) *Finite State Machines*: We have designed two finite state machines based on our physical topology. It was determined that two state machines were required in order to allow for the concurrent monitoring of normal activity and the investigation of anomalous sensor behaviour. By designing the state machines to facilitate concurrency, effective monitoring can be delivered irrespective of the detection and investigation of anomalous behavior.

a) *Normal Activity State Machine*: The first finite state machine is the Normal Activity State Machine (NASM). This machine handles the expected pattern of static sensor activations about a door. It was determined that based upon the combinations of the static black and white sensors that eight possible states could exist, given that each sensor could be determined to be in one of two states, which denote normal activity about a door. The number of possible sensor events is: $2^3 = 8$ possibilities, where there are two possible events which may fire for each of the three sensors and no event may be repeated in the course of a normal traversal of a doorway. The states in the NASM are:

- S0 Door closed
- S1 Door opened
- S2 Person inside & closed
- S3 Person outside & closed
- S4 Person inside & outside & closed
- S5 Person inside & open
- S6 Person outside & open
- S7 Person inside & outside & open

The states S2, S3, S5 and S6 correspond to a single person approaching the door. The states S4 and S7 correspond to the possible presence of another person on the outside

pressure mat in addition to the presence of a person on the indoor pressure mat. These states are driven by seven events: six of these events are the static sensor events and the seventh is a reset event which may restore the state machine to a specified state. The Reset event may only be generated by the Error Handling State Machine (EHSM).

b) Error Handling State Machine: The second state machine; the EHSM, consists of nine states and ten events which drive those states. The states in this machine are derived from the combinations of the environment sensors which may exhibit anomalous behaviour. The events in this state machine stem from two sources. The first source is the NASM from which events are generated via its actions to the EHSM upon the receipt of anomalous sensor readings. The second source of the events in the EHSM is the mobile robot. Upon the detection of anomalous behaviour the mobile robot is deployed to the site of the sensor failure where its role is twofold: in the first instance the robot must deliver feedback of its sensor readings. This data is processed in order to provide a corresponding value for the sensor it is investigating so that normal monitoring of activity about a door can continue whilst the anomaly is being investigated. The results of this analysis are input to the EHSM through a feedback loop. This, in turn, generates an event into the NASM via a second feedback loop instructing it what state to transition into based on the robot's sensor readings. Secondly, the robot's sensor data is processed in parallel with the monitoring activity in order to identify patterns in changes in sensor behaviour. It is through this reflective analysis over time that adaptive learning is facilitated.

2) Anomaly Identification: From our observations of our static sensors' behaviour over time, we determined that two types of anomaly may be exhibited: random anomalies and systemic anomalies.

a) Random Anomalies: Random anomalies are defined as those which occur sporadically such as the absence of an expected sensor activation. These anomalies are addressed directly through the mobile robot, which positions itself at the door and provides substitution of the sensor in question. Whilst providing substitution, the robot feeds back its own sensor data. This data is then pre-processed and correlated with that of the static environment sensors for anomaly verification and fault diagnosis.

b) Systemic Anomalies: Systemic anomalies are defined as those which occur as sensor behaviors change over time. Our current research leads us to believe that these changes in behavior may be attributed to the degradation of hardware resulting in behaviors such as slower relay time, battery deterioration or the receipt of multiple sensor events for one real-world event. This requires further investigation in order to verify the validity of this hypothesis. It is these anomalies that the system must investigate fully in order to learn about the changes in the behavior of the sensors in the

environment. To this end, adaptive learning [15] must be applied so that the system may adapt its policies.

IV. DISCUSSION

When an anomalous sensor reading is received by the NASM, a corresponding action, dependent on sensor type, inputs an event to the EHSM. A feedback loop operates between the NASM and EHSM whereby, upon successful investigation of the anomaly, the EHSM may then generate a Reset event into the NASM in order to restore its function. Alternatively, the EHSM may generate a new action into the NASM which corresponds to a systemic anomaly which has been detected in a given static sensor so that the NASM may handle the occurrence of that sensor behavior in future without reporting the event to the EHSM as a new anomaly.

By utilizing a feedback loop, actions may be dynamically generated into the NASM. These actions are the result of the investigation by a mobile robot and analysis by the system of the sensor behaviors. By providing the dynamic generation of actions into the NASM, the adaptivity of the state machines policies can be achieved. This approach has the potential to bring greater flexibility to the system and more robust fault tolerance without the need for human intervention. Therefore, the adaptivity in this system will be achieved through the NASM. This is facilitated by the feedback of the results of the robot's investigation of the environment sensors via the EHSM.

When the EHSM receives an event from the NASM, it will then trigger a transition to the relevant state dependent on the sensor or sensors that have been deemed suspicious. The EHSM then performs an action relevant to the anomalous sensor. Initially, the EHSM's action will instruct the robot to navigate to the site of the sensor. In order to do this, the robot requires a-priori knowledge of the environments structure. The method of navigation is not pertinent to this research piece as it is an area which is widely covered by roboticists. We are concerned only with the fact that the robot can consistently navigate to a pre-designated position, which is dictated by the unique identifier of the specific sensor in question, using a map of the environment and collision avoidance. Before the results of the robot's observations can be fed back to the EHSM, pre-processing and analysis is required. It is through this pre-processing and analysis that investigation of the anomalous behavior takes place. This, in turn, facilitates the systems learning about anomalies and changes in sensor behaviors.

The analysis of the data received from both the robot and the static sensors provides the system with the ability to begin to identify systemic anomalies. Subsequently, the system may then learn about its faults and adapt its policies to account for the new behaviors exhibited by the static sensors. For example, if the door contact sensor develops behavior whereby it fires three sensor events for one real-world door opened event instead of once, as would ordinarily be expected, from the correlation of the robot's observations with the static sensor events the system may then learn that this pattern is a systemic anomaly and accordingly adapt its

policy to allow three door opened events to occur, through the adaptation of actions in the NASM, before an anomalous contact sensor event is passed to the EHSM in future.

In the course of our research we have observed the door contact sensor which is part of our system topology. From these observations, we have determined that there are instances in which sensor events are not received. During our experiments, it became evident, for example, that the sensor signals were lost on occasion when a door was closed. However, this occurrence was not consistent. As a result it is difficult to adapt to this system behavior. Consequently, the mobile robot was instructed to navigate to the door site location. Once there the robot's role is two-fold in this instance: it must use its ultrasonic array to determine the door state and it must also verify the anomalous behavior. When the robot's data from its ultrasonic array is fed back it takes over the role of the contact sensor in the finite state machines, following pre-processing of the data, until the issue with the door contact can be verified as either a random or systemic anomaly.

It is evident from the above that the utilization of a mobile robot as a means of investigating and verifying anomalous sensor behavior has the potential to address two types of anomalous behavior in the sensors about a door. We have used anomalous readings from the door contact sensor by way of example here, however; our approach would also hold for the investigation of anomalous pressure mat readings. Whilst the implementation is incomplete, we believe that we can contribute to the adaptive management of sensor faults in an intelligent environment through our utilization of a mobile robot for investigation of the anomalous behavior coupled with the dynamic adaptation of system policies following the systems own investigation and analysis of its suspected error states.

V. CONCLUSION AND FUTURE WORK

In this paper, a proposed approach to the self-healing of door based sensors in an intelligent environment was presented. This research utilizes a mobile robot in order to provide sensor substitution and verification of anomalous sensor behavior. By utilizing a mobile robot to investigate its anomalies, the system may determine the nature of the anomalous behavior. We have devised that this behavior may be categorized into two types of anomalies based on observations of a mobile robot over time; systemic and random anomalies. It is through this process of investigation of its own anomalous events that the system may learn from the behavior of the sensors contained therein and adapt its policies accordingly.

The ideas presented in this paper are in the process of being implemented, and subsequently require further evaluation. The preliminary results are promising and appear to offer a useful means of introducing self-healing through sensor substitution and software adaptation into an intelligent environment in order to ensure the tolerance of static sensor faults.

Our future work will consist of experimentation and evaluation of our approach, following the completion of our implementation. The performance of the proposed approach

will be qualitatively evaluated in order to establish a clear picture of the performance of our approach in the real world. Adaptive learning for the dynamic generation of system policies through the use of a fuzzy rule-base [16] will be further investigated in order to establish how well the system learns using this approach.

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