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Mission-based online generation of probabilistic monitoring models for mobile robot navigation using Petri nets

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ABSTRACT

This paper presents a generic hybrid monitoring approach, which allows the detection of inconsistencies in the navigation of autonomous mobile robots using online-generated models. A mission on the context of the navigation corresponds to an autonomous navigation from a start to an end mission point. The operator defines this mission by selecting a final goal point. Based on this selection the monitoring models for the current mission must be generated online. The originalities of this work are (i) the association of classic state estimation based on a particle filter with a special class of Petri net in order to deliver an estimation of the next robot state (position) as well as the environment state (graph nodes) and to use both pieces of information to distinguish between external noise influences, internal component faults and global behaviour inconsistency (ii) the integration of the geometrical and the logical environment representation into the monitor model (iii) the online generation of the corresponding monitoring model for the present mission trajectory while the system is running. The model takes simultaneously into account the uncertainty of the robot and of the environment through a unified modelling of both. To show the feasibility of the approach we apply it to an intelligent wheelchair (IWC) as a special type of autonomous mobile robot.

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1. Introduction

Monitoring, fault detection and diagnosis play an important role for autonomous and intelligent robotic systems due to the increasing demands on dependable and fault tolerant real-time applications. This fault tolerant behaviour in mobile robots refers to the possibility to autonomously detect and identify faults early before they result in catastrophic failures as well as to the capability to continue operating after a fault has occurred by switching to a safe state. However, fault detection and identification for robots is a complex problem because of the large space of possible faults (e.g. robot sensors, actuators, the uncertainty of the environment-models). Mobile robots are best modelled as hybrid systems since their behaviours result from the interaction between continuous and discrete dynamics. Several methods have been developed to deal with the monitoring of such systems. The most important approaches are these that combine the basic model of continuous systems, which are differential equations, with the basic model of discrete event systems, which are automata or Petri nets. Using Petri nets to model hybrid systems offers advantages over finite automata when concurrency and complexity issues are of concern. Multiple comparisons from the literature between Petri nets and automata show that the former model is powerful and it has several advantages over the latter, not only because it is more general but also because it offers a better structure for modelling. The combination of such discrete models with numerical filters eases the modelling of the interaction of discrete and continuous dynamics and enables the extension of these approaches to other aspects such as the probabilistic framework to cover uncertainties. Some approaches take account of uncertainties of the robot and its environment and detect faults using numerical filters such as a particle filter, which estimates the most probable state of the robot and detect faults by comparison with the robot model. Also a mixture of Kalman filters [1,2] was used for tracking multiple hypotheses about the state of the system. In these approaches the estimate is then compared with the measured value to generate a residual, which declares the occurrence of a fault when a certain threshold value is exceeded. However fault detection based on residual interpretation is not enough, because exceeding a threshold does not necessarily always correspond to a fault. Hybrid monitoring based on Petri nets has been developed, for example, in [3]. However, this kind of behaviour prediction does not really consider the hybrid system's nature consisting of a combination of discrete-event and continuous state evolution. All

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these restrictions make the approaches linking a discrete model to a numerical filter [4,5] more interesting. The approach, which seems to be the most interesting in the hybrid modelling and dealing with uncertainty is the particle Petri net [6,7]. It was used for the analysis of flight procedures and deals with situation monitoring. However this monitoring approach is not real-time critical and suffers from some restrictions that make it not quite suitable for the monitoring of real-time and safety-critical applications. In the classical particle Petri nets the numerical part is similar to differential Petri nets, where token colours are solutions to differential equations associated with numerical places. The symbolic part is a possibilistic Petri net [8], in which a token in a place is associated with a possibility value denoting the possibility that the token is really in this place. It estimates the system state using the particle filter for the numerical state and the possibilistic formalism for the symbolic state. However it doesn't considerate the interaction between both parts of the model and in addition to this restriction particle Petri nets were used to describe concrete flight procedures which means that corresponding models must be developed offline. For mobile robots, which navigate arbitrarily in the environment or for autonomous systems that perform various tasks this technique is unsuitable since the model would have to describe all possible paths. To make the approach suitable for the monitoring of such systems under uncertain conditions several modifications and extensions were required. For this purpose we defined in [9] a new class of Petri nets called modified particle Petri nets (MPPN). They use the basics of the classical particle Petri nets but with an additional transition type called a hybrid transition which has specific firing rules. The main concept of the MPPN is the consideration of the influence of the numerical state when estimating and correcting the symbolic state. This dependency enables a symbolic estimation in a probabilistic framework unlike the classical particle Petri nets, which use the possibilistic formalism (by ranking the configurations according to a partial preorder) for the symbolic state without taking into account the interaction between both parts of the model. Since the user can select a different mission each time, a generic xml-description of the model allows the online generation of the models. This is very useful in the mission monitoring because it allows an online adaptation of the monitor model to each change in the mission or to a re-planning step. The concept is shown on an autonomous wheelchair on the navigation level, where the position as well as the mission-execution has been monitored.

2. Problem formulation and solution approach

The navigation process in the context of mobile robots [10] includes finding a safe path given a start and goal positions, guiding the robot safely along this path and updating the robot's position from time to time. The problem we are interested in concerns the online monitoring of such navigation process by considering the uncertainty of the sensors and the environment models. Therefore, our formulation of the navigation monitoring problem requires:

- Estimating robot and environmental states, as they change over time, from sensor measurements that provide noisy, partial information about the states and considering the close coupling of robot–environment interaction.
- Online generation of the corresponding monitoring models for the computed paths using a textual description of the Petri net [11], which eases the online generation of the corresponding monitoring model for the present mission trajectory while the system is running.
- Fault monitoring and detection mechanism enabling the distinction between external noise influences, internal component faults and global behaviour inconsistency.

The solution for the problem statement will be based on the following steps:

- The integration of the geometrical and topological paradigms in a hybrid environment model and solving the find-path problem using a graph-search algorithm.
- The combination of a Monte Carlo method, such as particle filters with a discrete model, such as a Petri net in order to monitor the robot together with its operating environment under consideration of the uncertainty and to provide the probability of the robot being in each of the states given by the Petri net model.
- Development of a hybrid monitoring and fault detection mechanism, which uses both the continuous information (the residual) and the discrete information (the Petri net marking) in order to detect inconsistencies in the navigation process.

The paper is organized as follows: In Section 3, we introduce our probabilistic hybrid monitoring approach and we define a new form of Petri net called the modified particle Petri net (MPPN). In Section 4, we apply the method in the mobile robotic area to an intelligent wheelchair in order to monitor its position and path execution. Experimental results are presented in Section 5. Some concluding remarks are offered in the final section.

3. Probabilistic hybrid monitoring using modified particle Petri net

3.1. Modified particle Petri net (MPPN)

We define the modified particle Petri net (MPPN) as a 9-tuple $\langle P, T, \mathrm{Pre}, \mathrm{Post}, X, F, \gamma, \Omega, M_0\rangle$, where:

- P: the set of places partitioned into numerical places P_N and symbolic places P_s.
- T: the set of transitions (numerical, symbolic or hybrid).
- Pre and Post are the pre-incidence and the post-incidence matrices, respectively, of dimension $|P| \times |T|$. The incidence matrix of the net is defined as: $\forall p \in P$ and $\forall t \in T\, C(p,t) = \mathrm{Post}(p,t) - \mathrm{Pre}(p,t)$.
- $X \subset \Re^n$: is the state space of the numerical state vector.
- F: difference equation system associated with numerical places and representing the continuous state evolution.
- $\gamma(p)$: is the application that associates a configuration with each symbolic place $p \in P_S$.
- Ω: a set of conditions associated with the transitions.
- M_0: is the initial marking of the net.

A numerical place $p_n \in P^N$ is associated with a differential equation representing the continuous evolution of the system state (e.g. position, temperature, ...). Numerical places are marked by a set of particles $\pi_k^i = [q_k^i, w_k^i]$ defined by their corresponding continuous valued state $q_k \in X$ and weights $w_k \in [0, 1]$ at time k and representing the uncertainty distribution over the value of the numerical state vector (Fig. 1). A state change from one numerical place to another occurs when the process state exceeds the boundary of its state space. After the state change, the process follows the solution of the differential equation that may be different from the previous one, until the next jump occurs. A symbolic place $p_s \in P^S$ is marked by configurations (black token) $\delta_{k+1|k}^{(j)}$ representing the symbolic state of the system itself resulting from external events or the symbolic state of another system, which is in interaction with it (a human, an environment, a technical system,...). The marking of the Petri net $M_k = \{\Pi_k, \Delta_k\}$ is the marking of the MPPN at time k consisting of the set of configurations Δ_k in symbolic places and the set of particles Π_k in numerical places.

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