FAST ABSTRACT: Stochastic Model-based Testing for Human-Robot Interaction

Akbar Siami Namin
Department of Computer Science
Texas Tech University
Lubbock, TX, USA
Email: akbar.namin@ttu.edu

Barbara Millet
Department of Industrial Engineering
Texas Tech University
Lubbock, TX, USA
Email: barbara.millet@ttu.edu

Mohan Sridharan
Department of Computer Science
Texas Tech University
Lubbock, TX, USA
Email: mohan.sridharan@ttu.edu

***Abstract*—In recent years, algorithms have been developed to enable robots to operate autonomously and to interact with humans. However, the uncertainty associated with sensing and actuation on robots makes reliability a formidable challenge to their widespread deployment in critical real-world applications such as health-care. This paper outlines a stochastic testing framework to assess the reliability of mobile robots in human-robot interaction domains. It introduces a two-stage adaptive scheme for test case generation and a probabilistic representation of the status (i.e., passing or failing) of the test cases. The proposed approach is illustrated using a scenario where a mobile robot monitors the status of elderly residents.**

I. Introduction

Advancements in sensor technology and the algorithms that process sensory inputs have fostered the deployment of mobile robots in a diverse set of domains such as navigation, healthcare and disaster rescue [1]. However, the uncertainty associated with sensing and actuation on mobile robots makes reliability a major challenge to their deployment in critical application areas. For instance, any errors in the robot's operation while interacting with an elderly resident in a nursing facility can lead to disastrous consequences.

In decision-making systems with uncertainty, reliability is a formidable challenge. Although software testing research has produced a rich set of techniques for testing deterministic systems, these techniques are not effective for non-deterministic systems that add a new dimension to the testing challenge. A significant change is required in the research paradigm in order to meet the needs of real-world non-deterministic systems [2].

Recent research in probabilistic model checking has been effective in revealing the desired properties that are not satisfied in a system with uncertainty [3]. However, even these probabilistic verification techniques can become intractable for complex non-deterministic systems. Similarly, though existing validation techniques are capable of efficiently analyzing the system under consideration, they are not well-suited for testing non-deterministic systems.

This paper outlines a stochastic model-based testing approach for the non-deterministic domain of human-robot interaction (HRI). Similar to other probabilistic model-based testing schemes, Markov chains are used to model probabilistic state transitions. However, the HRI domain is characterized by transition probabilities that change dynamically over time, posing a major challenge to test case generation and test oracle generation. The proposed approach addresses these challenges by incorporating a two-stage adaptive scheme for test case generation and a Probabilistic Approximate Testing (PAT) approach.

II. Stochastic Model-based Testing for Non-deterministic Systems

Model-based testing [4] is an instance of model-driven design where models are built to describe some aspects and the functionality of the system being tested. These models are used to generate abstract test cases, which are (in turn) used to derive executable test cases. The generated models are often in the form of finite state machines (FSMs), where nodes represent the states of the system being analyzed and the arcs between the nodes represent the state transitions caused by system events. Model-based testing has been implemented successfully in many application domains such as automotive testing [5] and reactive systems [6]. The FSMs are the primary source of test case generation—each executable path represents a possible scenario or functionality that needs to be tested. However, these paths are typically deterministic in traditional model-based testing, i.e., the occurrence of an event will cause a specific state transition, which is not the case in non-deterministic systems.

A. Simulation and Interaction-based Test Case Generation

Existing test case generation methods such as theorem proving, constraint programming, model checking and symbolic execution are based on logical expressions. These methods are not well-suited for non-deterministic systems, where event flow models and FSMs, especially those based on Markov chains [3] are more suitable for accounting for the inherent uncertainty.

Markov chains are finite state machines with probabilistic state transitions. Test cases can be generated using a stochastic procedure based on the transition probabilities (also known as the profile or usage model). However, in human-robot interaction scenarios, the transition probabilities may not be known in advance and change dynamically based on the interactions. The proposed approach therefore uses a

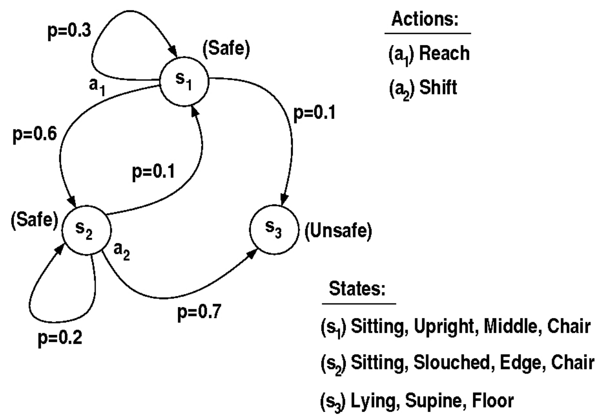

Figure 1. Illustrative Example.

two-stage process for estimating these transition probabilities. First, a computer simulation estimates initial values of these probabilities based on prior (e.g., human) knowledge. The probability values are then revised dynamically as the robot interacts with humans and acquires additional knowledge. The key challenge here is that the test suite evolves over time and the test cases currently in use can soon become obsolete. Though this challenge cannot be addressed using existing automatic test case generation methods, stochastic adaptive random testing methods can be utilized to generate test cases that target the most likely paths in the Markov chain model of the system. In addition, the coverage-based test case generation methods developed for context-aware systems can be enriched to account for the uncertainty of non-deterministic systems, thereby providing the termination conditions for adequate testing [7].

B. Probabilistic Approximate Testing (PAT)

Though the proposed adaptive two-stage test case generation scheme can be utilized to ensure a thorough analysis of the target system, generating a test oracle is still a challenge. It is infeasible to state with complete certainty whether a specific test case would pass or fail in a dynamic non-deterministic system. The proposed approach therefore includes a Probabilistic Approximate Testing (PAT) scheme that is inspired by the Probably Approximately Correct (PAC) learning method in stochastic learning theory [8]. The labels of test cases are change from "passed" and "failed" to "probably-approximately passed" and "probably-approximately failed". The system specifications based on verified models of system (or human knowledge) can be used to generate a distribution of expected performance of different types of test cases. This expected performance can function as a *probabilistic test oracle* for the test cases generated by the two-stage adaptive process described above.

III. Illustrative Example

Consider the illustrative example of a robot monitoring the safety of an elderly resident. Assume that the state space consists of four components: (a) posture, which can be $\{upright, slouched, supine, leaning\}$; (b) activity, which can be $\{sitting, lying\}$; (c) location, which can be $\{bed, chair, floor\}$; and (d) position, which can be $\{middle, edge\}$. A specific state could be: $\{sitting, upright, middle, chair\}$, i.e., a particular patient could be sitting upright in the middle of a chair. Transition between states can occur due to "actions", i.e., events that change the state. Examples could include: (a) voluntary actions (e.g., stand, lean, reach); (b) external stimuli (e.g., push); (c) health hazards (e.g., stroke or heart attack); and (d) involuntary actions (e.g., shift, fall).

A model of a *small* subset of the possible state transitions in this scenario is shown in Figure 1. For instance, when the event "reach" (i.e., action a_1) occurs in a *safe* state s_1 $\{sitting, upright, middle, chair\}$, the transition to *safe* state s_2 occurs with probability 0.6, the transition to *unsafe* state s_3 occurs with $p = 0.1$ and the state stays unchanged with $p = 0.3$. Generating test cases to cover all valid paths becomes intractable as the system becomes more complex, especially since the probabilities can change over time based on statistics of observing human patients. The proposed two-stage adaptive scheme automatically adapts to the changing probabilities. Similarly, the PAT approach represents test outcomes probabilistically to obtain a reasonable test oracle. The proposed approach is currently being implemented and evaluated in a simulated domain that has a mobile robot assisting caregivers in a nursing facility for the elderly.

IV. Conclusion

Testing non-deterministic systems such as mobile robots poses a major challenge to their deployment in critical applications such as human-robot interaction in healthcare. This paper outlines a stochastic testing scheme that models the inherent uncertainty in order to achieve robust operation.

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