CENTER FOR TRANSPORTATION INFRASTRUCTURE AND SAFETY

Quantitative Modeling of Failure Propagation in Intelligent Transportation Systems

by

Sahra Sedigh Sarvestani and Ali R. Hurson

Missouri University of Science and Technology
Rolla, MO 65409

NUTC
R346

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Technical Report Documentation Page

1. Report No. NUTC R346	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Quantitative Modeling of Failure Propagation in Intelligent Transportation Systems		5. Report Date August 2014 6. Performing Organization Code
7. Author/s Sahra Sedigh Sarvestani and Ali R. Hurson		8. Performing Organization Report No. Project #00042531
9. Performing Organization Name and Address Center for Transportation Infrastructure and Safety/NUTC program Missouri University of Science and Technology 220 Engineering Research Lab Rolla, MO 65409		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTRT06-G-0014
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Innovative Technology Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Unmanned vehicles are projected to reach consumer use within this decade - related legislation has already passed in California. The most significant technical challenge associated with these vehicles is their integration in transportation environments with manned vehicles. Abnormal or incorrect manipulation of the manned vehicles by their human drivers creates a highly non-deterministic environment that is difficult to consider in the control algorithms for unmanned vehicles.
The objective of this project was to develop a model that can capture stochastic elements of this environment, in particular failure propagation from manned to unmanned vehicles and vice versa. A general analytical model reflecting the effect of cyber or physical failures on reliability of a large-scale cyber-physical system was developed in the course of project activities. This model was validated through simulation of related applications an intelligent power grid and water distribution network, respectively. Both examples are topologically and conceptually analogous to an intelligent transportation system. A qualitative model was developed for intelligent transportation systems, and work was commenced on development of a quantitative Petri-net model and cyber-physical simulation environment for such systems.
Five refereed conference publications [1{5] and several presentations resulted from this project. Two related journal publications are under final submission and will be submitted in the near future. One MS thesis [6] was completed in conjunction with work related to the project. One undergraduate student, two doctoral students, and two MS students contributed to the research.

17. Key Words Intelligent transportation systems, unmanned vehicles, driverless cars	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.		
19. Security Classification (of this report) unclassified	20. Security Classification (of this page) unclassified	21. No. Of Pages 14	22. Price

Form DOT F 1700.7 (8-72)

Final Report on NUTC Project 00042531
May 15, 2013 – December 31, 2013

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Sahra Sedigh Sarvestani and Ali R. Hurson

Missouri University of Science and Technology
Rolla, MO 65409

{sedighs,hurson}@mst.edu

Summary

Unmanned vehicles are projected to reach consumer use within this decade - related legislation has already passed in California. The most significant technical challenge associated with these vehicles is their integration in transportation environments with manned vehicles. Abnormal or incorrect manipulation of the manned vehicles by their human drivers creates a highly non-deterministic environment that is difficult to consider in the control algorithms for unmanned vehicles.

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1 Introduction

Advances in computing are enabling the development of unmanned vehicles deemed sufficiently safe for urban transportation. Ample evidence for this claim is evident from submissions to a number of autonomous vehicle competitions sponsored by the Defense Advanced Research Projects Agency (DARPA). These competitions culminated in the "DARPA Urban Challenge," in which autonomous vehicles were required to safely navigate a 60-mile urban course in fewer than 6 hours, obeying all traffic laws and navigating through traffic and obstacles while executing challenging tasks such as left turns onto roads with moderate to heavy traffic [7]. Google has begun development and testing of autonomous vehicles with approval from the California state legislature [8]. This development has set the stage for making self-driving cars available to consumers in three to ten years, and complete transition to driver-less cars anticipated by 2040 [9]. Forbes estimates that the U.S. autonomous vehicles market is worth $2 trillion a year in revenue.[10].

This rapid development brings about a need to understand how autonomous vehicles interact with each other in a large transportation network, as well as how manned and unmanned vehicles interact with each other. This project aimed to develop analytical models that can be used to gain this understanding. In this final report, we present our findings on existing work related to modeling of unmanned vehicle systems and present our preliminary reliability model for such systems.

2 Survey of Related Literature

Vehicular traffic can be modeled a various levels of abstraction. The state of a traffic system is given by the number of vehicles present in a section of the transportation network at a given time. The most basic models are microscopic discrete-event models such as those in Refs. [11], [12], [13], [14], and [15], which accurately describe traffic behavior at intersections or a single stretch of road or highway. When the roads are highly populated, these models suffer from state space explosion, complicating analysis. These models are useful for representation of individual intersections and roads and have been expanded to reflect human behavior.

Macroscopic models overcome this state space expansion by disregarding individual vehicles. They use only three variables to describe local behavior: density, average speed, and flow rate [16]. Examples of macroscopic Petri net and non-Petri net based traffic models can be found in Refs. [17], [18], [19], [20], [21], [22], [23].

Petri nets represent a powerful modeling formalism that has been successfully used in different application domains. A Petri net consists of places, transitions, arcs and tokens. Arcs serve as connections between places and transitions and tokens represent some aspect of the system - in this case vehicles in a traffic system. Places hold the tokens until they are passed via an arc through a transition based on a set of firing rules. Many different types of Petri nets have been developed and tailored to model specific applications. Ref. [24] defines a fluid stochastic Petri net, which allows for abstracting away from individual tokens and instead considering the flow of tokens. Ref. [25] presents colored fluid stochastic Petri nets, which add a way to distinguish types of markings in a system.

The preliminary model developed in the course of the project builds on the work of Ref. [16]. We would like to emphasize that our model is preliminary, and as such currently reflects many elements of the work upon which it is based. Future refinements to our model will substantially differentiate it from its predecessor. In the original model, the traffic system is modeled as a hybrid Petri net, with road sections modeled as continuous transitions and stop lights and intersections modeled as discrete transitions. Hybrid Petri nets allow for modeling both continuous and discrete elements of a system while preventing the state space explosion that would result from a purely discrete model. Roads are represented as a series of virtually-divided road sections that are described by the density $d(t)$ of cars at time t, their average speed $v(t)$, and the flow $f(t)$. The marking $m(t)$ of a place represents the number of cars present at time t, uniformly distributed along the length of the road section with an average speed $v(t)$. The modeled road sections have three different modes of operation, depending on the traffic conditions, i.e., density of vehicles. If a section has low density, vehicles will travel at the free speed (free flow), where out flow increases proportionally to the density. When the density is higher, the average speed will decrease, but the out flow will remain constant (constant flow). And lastly, when the density is very high, the out flow decreases due to congestion.

A continuous Petri net model of a single road section is represented in the original model with three places (p_1, p_2, p_3) and two transitions (t_{i-1}, t_i). The number of cars in a section is the marking of p_1. The flow of vehicles entering and leaving a section is dictated by t_{i-1} and t_i, respectively. Free-flow traffic is modeled by ignoring p_2 and p_3. Constant-flow traffic is modeled using p_3, which has a constant marking and imposes an upper bound on the flow of t_i. Lastly, when the density reaches the maximum, as a road section can hold a finite number of vehicles, p_2 is used to ensure $m[p_1] + m[p_2] =$ capacity of road section. The marking at p_2 represents the number of gaps in the section. To model a road, multiple sections are connected with transitions. Traffic lights are modeled as discrete events that can take one of three values: red, amber, or green. Each traffic light is modeled as a four-phase system, each represented by a place. The phases for an intersection of two roads R_1 and R_2 would be:

1. Phase 1: Green light for R_1 and Red light for R_2.
2. Phase 2: Amber to Red light for R_1 and Red light for R_2.
3. Phase 3: Red light for R_1 and Green light for R_2.
4. Phase 4: Red light for R_1 and Amber to Red light for R_2.

Phases 1 and 3 are when traffic is flowing on one of the two roads and phases 2 and 4 are the safety periods used to clear the intersection. This discrete Petri net has only one marking, so the system can be in only one state, with each phase being active when the corresponding place is marked. The road sections are joined to the intersection as follows. The flow through the intersection at any time is calculated by multiplying the flow of the continuous transition by the average velocity of the section. The velocity is dictated by the phase. The flow for R_1 during phase 1 is the same as the flow would be if there were no traffic light. During phase 2, the flow decreases linearly to zero and remains at zero for phases 3 and 4.

3 Proposed Model

The objective of this project was to model an intelligent transportation system populated by both manned and unmanned vehicles, to better understand how these vehicles would coexist. To say that autonomous vehicles would have the behavior of a perfect human driver would be a somewhat naïve statement. While an autonomous vehicle will obey all traffic laws and will never be driven by a driver who is intoxicated, drowsy, or texting/talking on the phone, it is still prone to failure. Firstly, computer sensor/control systems are not as adaptive as the human eye/ear/brain and to overcome this, an autonomous vehicle will need to rely heavily on broadcasted information about events such as road closures and construction, or traffic jams and accidents, and information on road and weather conditions. Dynamic traffic control, carried out with variable speed limits and dynamic lanes, also needs to be communicated to the autonomous vehicle. This broadcasted information will allow an autonomous vehicle to operate more similarly to a perfect human driver. Secondly, autonomous vehicle control lacks the ability to react in states of varying uncertainty, i.e., when the broadcasted data is corrupted or unavailable as a result of a failure of malicious attack. Our work aims to model and investigate the robustness of autonomous vehicles in the face of such non-determinism - the main contribution of the eventual result will be in modeling the behavior of autonomous vehicles in an intelligent (urban) transportation system. Additionally, the work will contribute to the understanding of the human-machine interactions in large cyber-physical systems. Fig. 1 places our work in the larger body of related research. The need for this type of research is outlined in the National Institute of Standards and Technology (NIST)[26].

3.1 Failure Ontology

Our goal is to achieve analytically and empirically verifiable guarantees for system-level reliability and survivability of an intelligent vehicle system. Existing literature, e.g., [27–30], focuses on models for mechanical operation of robots - to our knowledge, system-level performance has not been assessed from a non-functional point of view. System-level investigations such as [31] have centered on the development of control algorithms to increase robustness of connectivity. Unmanned (autonomous) vehicles have been justifiably scrutinized with regards to both functional and non-functional aspects. Examples include [32–35], where potential failures of unmanned ground vehicles were enumerated and classified.

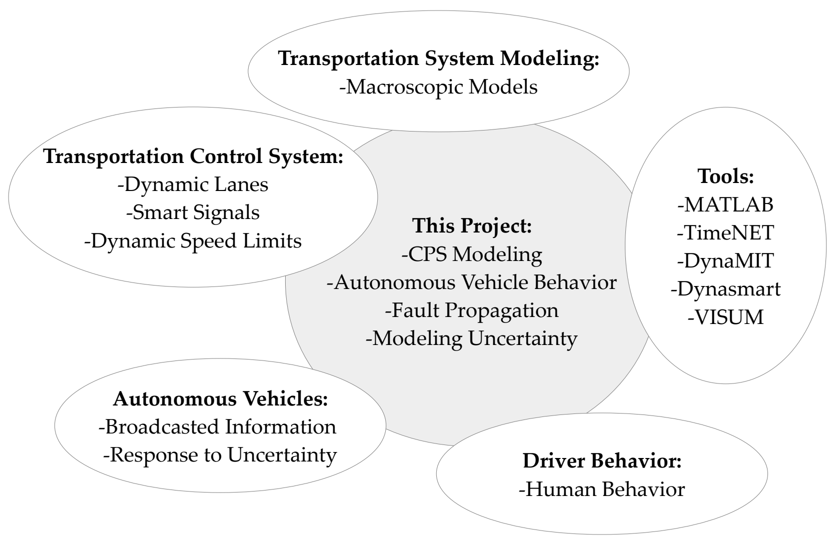

Fig. 1. Expected contributions and related topics.

The failure ontology considered in our modeling and analysis, presented in Figure 2, is based on [35]. This ontology, which will be refined in the course of the future work, especially with respect to failure severity (per Failure Mode, Effects, and Critically Analysis [36]), is crucial to study of the various aspects of dependability of an intelligent transportation system - a task that necessitates identification of all failure states of the system. These failures could be accidental (resulting from malfunction) or maliciously induced (as a result of a security breach). We are cognizant of the importance of assuring security and dependability; however, in this initial investigation, our approach is based on the *consequences* of failure, i.e, the tangible manifestation of a malfunction in system-level operation of the intelligent transportation system.

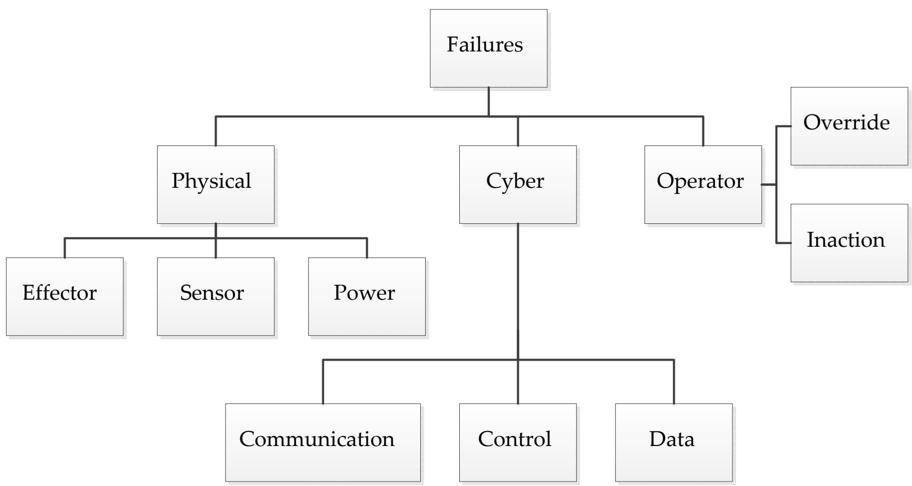

Fig. 2. Failure ontology for an intelligent transportation system.

3.2 Quantification and Modeling of Reliability

The overall reliability of an intelligent transportation system (independent of its human operators) is a function of the respective reliabilities of its elements, including both physical components, e.g., the hardware of individual modules comprising sensors, and actuators; and cyber components, e.g., control software and communication links. As such, we propose the Markov Imbedded Systems (MIS) technique [37] as the mathematical foundation for our proposed reliability model.

The MIS model requires identification of "Functional" and "Failed" states of the system, and computes the system reliability as the probability of being in one of the "Functional" states. The state of a system with n components can be represented by an n-dimensional binary vector, S, each element of which reflects the operational state (functional or failed) of one component. 2^n such vectors exist, reflecting all possible states. Let $\mathbf{\Pi_0}$ denote a vector of probabilities, where $Pr(Y_0 = S_i)$ is the probability of the system initially being in state S_i.

$$\mathbf{\Pi_0} = [Pr(Y_0 = S_0), Pr(Y_0 = S_1), \ldots, Pr(Y_0 = S_N)]^T \quad (1)$$

In a normal system, the initial state would be S_0, which represents a system with no component failures. A crude measure of robustness of the intelligent transportation system can be created by assuming an initial state that includes one or more failed components.

Furthermore, for a given component, l, the matrix Λ_l represents the state transition probabilities of the system as a function of l. In other words, each element $p_{ij}(l)$ in the matrix Λ_l represents the probability that the system will switch from state S_i to state S_j due to the failure of component l.

Finally, a vector $\mathbf{u}$ is defined, with length equal to the number of states, where each element has a value of '1' if the corresponding state is considered a "Functional" state for the system, and '0' otherwise. The overall reliability of the n-component system is expressed as $R = (\mathbf{\Pi_0})^T \left(\prod_{l=\mathbf{1}}^{n} \mathbf{\Lambda}_l\right) \mathbf{u}$. The model parameters are populated with data derived from laboratory/field testing and will be continually refined as research progresses. Technical reports from the DARPA grand challenge ([38], [39], [40], [41], and [42]) will be used to characterize the vehicle behavior. State space explosion is a legitimate concern, but safety-critical nature of an intelligent transportation system limits the number of states considered as "Functional," and as such, the vectors and matrices used in computation are expected to be sparse.

We have applied the MIS technique to modeling of the reliability of large and complex cyber-physical systems such as smart grids [43–46, 2, 1]. An intelligent transportation system shares several characteristics with these systems: it is complex, an underlying physical system (an unmanned vehicle) is intelligently and adaptively controlled using data collected from sensors, and failures cannot necessarily be considered independent. Cascading failures - a significant concern in any highly-interconnected system - have been a focus of our prior work and will be rigourously investigated in future extensions to this research.

3.3 Quantification and Modeling of Survivability

The MIS technique could potentially be used to capture multiple levels of functionality (non-terminal failures), resulting in a model for survivability of the an unmanned vehicle or intelligent transportation system. This would not be a prudent strategy, as it is prone to state space explosion. Reliability takes a binary view of the operation of the system, and as such, the number of states that positively contribute to the reliability are limited. In the case of survivability, states with degraded performance will have to be considered, leading to a considerable increase in computational complexity of the model. To overcome this challenge, we use a Petri net structure [47], where the system is decomposed into a hierarchical structure of components and subcomponents, each with a place representing the percentage of component/subcomponent failed - from no failures up to complete (catastrophic) system failure. Transition firing rules are set based on the specific subcomponent. The tokens represent some percentage of component failure. For an unmanned vehicle, the component level could be individual vehicles, the subcomponent level could be elements such as mobility or communication capability. The complexity of unmanned vehicle movement lends itself well to survivability representation, due to the vast number of locomotive methods. A single module of the vehicle could be damaged, eliminating ability to turn, but it could still be capable of forward movement.

4 Publications and Student Involvement

Five refereed conference publications [1–5] and related presentations resulted from this project. Two related journal publications are under final submission and will be submitted in the near future. One MS thesis [6] was completed in conjunction with work related to the project. One undergraduate student, two doctoral students (one funded by the project), and two MS students contributed to the research.

5 Conclusions

This report articulated the tasks carried out towards modeling failure propagation in intelligent transportation systems. Progress towards this goal was hampered by the unavailability of simulators capable of accurate representation of such systems. Development of a purpose-built simulator is underway and a near-term objective of research related to the funded project.

Acknowledgments

Financial support from the National University Transportation Center is gratefully acknowledged. This project leverages prior research funded by the US and Missouri Departments of Transportation, the US Department of Education, and the Intelligent Systems Center at the Missouri University of Science and Technology.

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