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14. ABSTRACT

The goal of this project is to develop theoretical frameworks and computational tools for synthesis of provably correct control and communication strategies for teams of autonomous vehicles from specifications given in rich, human-like language. Central to our approach are finite abstractions, which allow for the use of (adapted) temporal logics as specification languages, tools from formal verification resembling model checking for analysis and control, and techniques inspired from synchronization in concurrency theory for synthesis of communication strategies.

We believe that we accomplished the initial objectives of the project. Specifically, we developed abstraction and control strategy for discrete-time affine systems, techniques for MDP control from PLTL and PCTL formulas, a top-down approach for distributed synthesis of control and communication strategies, and several applications to robot motion planning and control.

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YIP FORMAL SYNTHESIS OF CONTROL AND COMMUNICATION STRATEGIES FOR TEAMS OF UNMANNES VEHICLES

FA9550-09-1-0209

Calin Belta, Boston University

02-20-2011

Abstract

The goal of this project is to develop theoretical frameworks and computational tools for synthesis of provably correct control and communication strategies for teams of autonomous vehicles from specifications given in rich, human-like language. Central to our approach are finite abstractions, which allow for the use of (adapted) temporal logics as specification languages, tools from formal verification resembling model checking for analysis and control, and techniques inspired from synchronization in concurrency theory for synthesis of communication strategies.

We believe that we accomplished the initial objectives of the project. Specifically, we developed (1) an abstraction and control strategy for a Piecewise Affine (PWA) system from a specification given as an LTL formula over linear predicates in the states of the system; (2) a formula-guided refinement technique for PWA systems; (3) a technique to control a Markov Decision Process (MDP) from a specification given as a Probabilistic Computation Tree Logic (PCTL) formula with experimental validation in our Robotic Indoor Environment (RIDE); (4) a technique to control a MDP from a specification given as a Linear Temporal Logic (LTL) formula with specific application to a robot motion planning and control under uncertainty; and (5) a framework for automatic synthesis of control and communication strategies for a robotic team from a global specification given as a Regular Expression (RE) over a set of environmental service requests with experimental validation in our Robotic Urban-Like Environment (RULE).

Accomplishments

(1) A Symbolic Approach to Controlling Piecewise Affine Systems: In [2,3], we developed a computational framework for automatic synthesis of a feedback control strategy for a piecewise affine (PWA) system from a specification given as a Linear Temporal Logic (LTL) formula over an arbitrary set of linear predicates in its state variables. Our approach consists of two main steps. First, by defining appropriate partitions for its state and input spaces, we construct a finite abstraction of the PWA system in the form of a control transition system. Second, by leveraging ideas and techniques from Rabin games and LTL model checking, we develop an algorithm to generate a control strategy for the finite abstraction. While provably correct and robust to small perturbations in both state measurements and applied inputs, the overall procedure is conservative and expensive. It is important to note that PWA systems are quite general, since they can approximate nonlinear dynamics (such as aircraft dynamics) with arbitrary

accuracy. In addition, there exist several computation tools for the identification of such models from input-output experimental data.

(2) Formal Analysis of Piecewise Affine Systems through Formula-Guided Refinement: In [3], we presented a computational framework for identifying a set of initial states from which all trajectories of a piecewise affine (PWA) system satisfy a Linear Temporal Logic (LTL) formula over a set of linear predicates in its state variables. Our approach is based on the construction and refinement of finite abstractions of infinite systems (i.e. systems where states can take infinitely many values). We derive conditions guaranteeing the equivalence of an infinite system and its finite abstraction with respect to a specific temporal logic formula and propose methods aimed at the construction of such formula-equivalent abstractions. We show that the proposed procedure can be implemented using polyhedral operations and analysis of finite graphs. While provably correct, the overall method is conservative and expensive. The proposed algorithms have been implemented as a software tool that is available for download. Illustrative examples for the PWA models of two gene networks are included.

Both tools described above were implemented as user-friendly packages available for download at our website hyness.bu.edu/software. It is important to note that PWA systems are quite general, since they can approximate nonlinear dynamics (such as aircraft dynamics) with arbitrary accuracy. In addition, there exist several computation tools for the identification of such models from input-output experimental data.

(3) PCTL Control for MDP with Applications to Motion Planning and Control: In [4,5,6], we presented a computational framework for automatic deployment of a robot from a temporal logic specification over a set of properties of interest satisfied at the regions of a partitioned environment. We assumed that, during the motion of the robot in the environment, the current region can be precisely determined, while due to sensor and actuation noise, the outcome of a control action can only be predicted probabilistically. Under these assumptions, the deployment problem translates to generating a control strategy for a Markov Decision Process (MDP) from a temporal logic formula. We proposed an algorithm inspired from probabilistic Computation Tree Logic (pCTL) model checking to find a control strategy that maximizes the probability of satisfying the specification. We illustrated our method with simulation and experimental results in our Robotic InDoor Environment (RIDE).

To illustrate the developed computational approach, consider the configuration of RIDE given in Fig. 1 and explained in its caption. Consider the following two motion specifications: **Specification 1**: ``Reach *Destination* by driving through either only *Safe* regions or through *Relatively safe* regions only if *Medical Supply* is available at such regions," and **Specification 2**: ``Reach *Destination* by driving through *Safe* or *Relatively safe* regions only." Specifications 1 and 2 translate naturally to the PCTL formulas ϕ_1 and ϕ_2, respectively, where

$$\phi_1 \ : \ \mathcal{P}_{max=?}\left[(\mathbf{S} \vee (\mathbf{R} \wedge \mathbf{M}))\,\mathcal{U}\,\mathbf{D}\right]$$
$$\phi_2 \ : \ \mathcal{P}_{max=?}\left[(\mathbf{S} \vee \mathbf{R})\,\mathcal{U}\,\mathbf{D}\right]$$

Assuming that the robot is initially at R1, we find the control strategies maximizing the probabilities of satisfying the above specifications. The maximum probabilities for Specifications 1 and 2 are 0.227 and 0.674, respectively. To confirm these predicted probabilities, we performed 500 simulation and 35 experimental runs for each of the optimal control strategies. The simulations showed that the probabilities of satisfying ϕ_1 and ϕ_2 were 0.260 and 0.642, respectively. From the experimental trials, we inferred that the probabilities of satisfying ϕ_1 and ϕ_2 were 0.229 and 0.629, respectively. By using the chi-square and Fisher's exact statistical tests, we concluded that the frequency of trials satisfying the specifications in the experiment matched the simulation data with a minimum certainty of 0.95

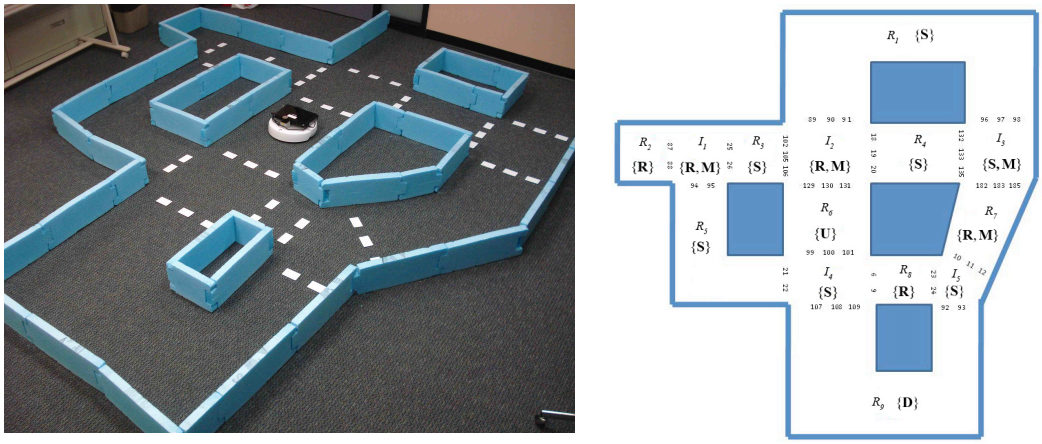

Figure 1: Left: The Robotic InDoor Environment (RIDE): an iCreate mobile platform equipped with a laptop, a laser range finder, and RFID reader moves autonomously through the corridors and intersection of an indoor-like environment, whose topology can be easily reconfigured by moving the foam walls. Right: schematic representation of the environment shown on the left. Each region has a unique identifier (R1,…, R9 for roads and I1,…, I5 for intersections, respectively). The properties satisfied at the regions are shown between curly brackets inside the regions: **S** = *Safe*, **R** = *Relatively safe*, **U** = *Unsafe*, **M** = *Medical supply*, and **D** = *Destination*.

(4) LTL Control for MDP with Applications to Motion Planning and Control in Uncertain Environments: In [7,8], we developed a method to generate a robot control strategy that maximizes the probability to accomplish a task. The task was given as a Linear Temporal Logic (LTL) formula over a set of properties that can be satisfied at the regions of a partitioned environment. We assumed that the probabilities with which the properties were satisfied at the regions were known, and the robot could determine the truth value of a proposition only at the current region. Motivated by several results on partitioned-based abstractions, we assumed that the motion was performed on a graph. To account for noisy sensors and actuators, we assumed that a control action enabled several transitions with known probabilities. We showed that this problem can be reduced to the problem of generating a control policy for a Markov Decision Process (MDP) such that the probability of satisfying an LTL formula over its states is maximized. We provided a complete solution for the latter problem that build on existing results from probabilistic model checking.

(5) A Hierarchical Approach to Automatic Deployment of Robotic Teams with Communication Constraints: In [9,10,11,12,13,14], we considered the following problem: GIVEN (1) a set of service requests occurring at known locations in an environment, (2) a set of temporal and logical constraints on how the requests need to be serviced, (3) a team of robots and their capacities to service the requests individually or through collaboration, FIND robot control and communication strategies guaranteeing the correct servicing of the requests. Our approach is hierarchical. At the top level, we check whether the specification, which is a regular expression over the requests, is distributable among the robots given their service and cooperation capabilities; if the answer is positive, we generate individual specifications in the form of finite state automata, and interaction rules in the form of synchronizations on shared requests. At the bottom level, we check whether the local specifications and the synchronizations can be implemented given the motion and communication constraints of the robots; if the answer is positive, we generate robot motion and communication plans, which are then mapped to control and communication strategies.

To illustrate the method, we present a case study in the Robotic Urban-Like Environment. Assume that two robots (cars), labeled as C1 and C2, are available for deployment in the city with the topology as shown in Fig. 2. Assume that the set of service requests that can occur in the environment is {H1, H2, L1, L2, L3}, where Li, i=1,2,3 are "light" requests, which require only one robot, and therefore should be serviced in parallel, while H1,2 are "heavy", and require the cooperation of the two robots. Assume that C1 can service L1 and C2 can service L2 and L3, i.e., the set of requests is distributed as {L1, H1, H2}, {L2, L3, H1, H2} between the two agents. Assume that the requests occur at the parking lots as given by the relation {(P1,H1), (P1,L1), (P2, H1), (P2, L2), (P3, L3), (P4, H2), (P5, H2)}.

Consider the following specification: "First service H1, then both L1 and L2 in an arbitrary order, then H2, and finally both L1 and L3 in an arbitrary order." The specification translates to the following Regular Expression: H1 (L1 L2 + L2 L1) H2 (L1 L3 + L3 L1). By applying the method developed in [4], we find that this global specification is distributable modulo language equivalence and synchronous product. The local task specifications for car C1 and C2 are H1 L1 H2 L1 and H1 L2 H2 L3, respectively. By assuming that C1 and C2 start in R1l and R2l respectively, the two so called motion and service (MS) plans are given by R1l I1 R6r P1 H1 P1 L1 R6r I4 R8l P5 H2 R8l I3 R4l I2 R3r P2 L1 and R2l I2 R3r P2 H1 P2 L2 R3r I1 R5r I4 R8l P5 H2 R8l R8r I4 R6l P3 L3, respectively. In the above strings, a region (road, intersection, or parking spot) label means that the car should visit the corresponding region. A service request following a region label means that the car should service the request at the region. The cars should synchronize on shared requests. The above MS plans are then mapped to control and communication strategies through the use of motion primitives, service primitives, communication primitives, and interrupts. The actual deployment of the robots in the RULE is shown in the that can be downloaded from hyness.bu.edu/rule/.

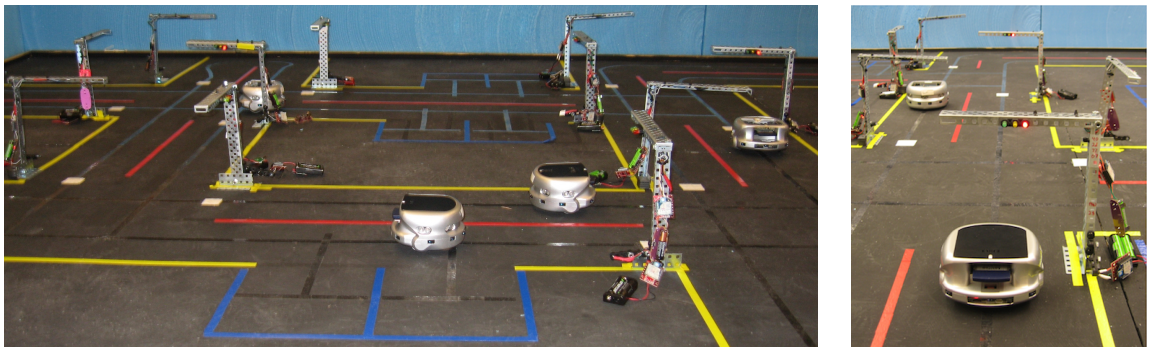

Figure 2. Left: Robotic Urban-Like Environment (RULE): Khepera III car-like robots move autonomously on streets while staying in their lanes, obeying traffic rules, and avoiding collisions. Right: A robot waiting at a traffic light.

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Publications

1. Jana Tumova, Boyan Yordanov, Calin Belta, Ivana Cerna, Jiri Barnat, A Symbolic Approach to Controlling Piecewise Affine Systems, IEEE Conference on Decision and Control (CDC), Atlanta, GA, 2010.

2. B. Yordanov, J. Tumova, C. Belta, I. Cerna, J. Barnat, Temporal Logic Control of Discrete-Time Piecewise Affine Systems, IEEE Transactions on Automatic Control, 2012 (in print)

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4. M. Lahijanian, J. Wasniewski, S. B. Andersson, and C. Belta, Motion Planning and Control from Temporal Logic Specifications with Probabilistic Satisfaction Guarantees, IEEE International Conference on Robotics and Automation (ICRA), Anchorage, Alaska, USA, 2010

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11. Y. Chen, X. C. Ding, A. Stefanescu, and C. Belta, A Formal Approach to Deployment of Robotic Teams in an Urban-Like Environment, Springer Tracts in Advanced Robotics, Springer-Verlag, Berlin, 2011 (to appear)

12. Yushan Chen, Xu Chu Ding, Calin Belta, Synthesis of Distributed Control and Communication Schemes from Global LTL Specifications, CDC 2011, Orlando, FL, 2011

13. Y. Chen, X. C. Ding, A. Stefanescu, and C. Belta, A Formal Approach to Deployment of Robotic Teams in an Urban-Like Environment, 10th International Symposium on Distributed Autonomous Robotics Systems (DARS), Lausanne, Switzerland, 2010 (Best student paper award)

14. Y. Chen, A. Stefanescu, and C. Belta, A Hierarchical Approach to Automatic Deployment of Robotic Teams with Communication Constraints, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Taipei, Taiwan, 2010

Honors & Awards Received

Best Student Paper Award for the paper "Y. Chen, X. C . Ding, A. Stefanescu, and C. Belta, A Formal Approach to Deployment of Robotic Teams in an Urban-Like Environment", (student: Yushan Chen), 10th Int. Symp. on Distributed Autonomous Robotic Sys, Lausanne, Switzerland, 2010.

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Transitions

The MDP control strategy developed as part of this project was the starting point for a collaboration with the United Technologies Research Center on the development of provably safe control strategies for unmanned aerial vehicles.