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Modeling and Supervisory Control of Mobile Robots: A Case of a Sumo Robot

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Abstract: This paper presents a methodology for modeling and controlling autonomous mobile robots and illustrates this approach using a sumo robot problem. The free behavior of the robot and its control specifications are modeled by finite state machines, and the supervisory control theory of discrete event systems is used to obtain the logical behavior of the robot in closed-loop. We also present a proposal for implementing the control structure obtained by the presented approach.

Keywords: Discrete Event Systems, Supervisory Control, Monolithic Approach, Mobile Robotics, Microcontrollers.

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1. INTRODUCTION

Obtaining the control logic for mobile robots can be a complex activity that requires the use of formal methods to guarantee the fulfillment of the control specifications. The Supervisory Control Theory (SCT) (Ramadge and Wonham, 1989) is a formal approach suitable for this purpose. In this framework, the plant to be controlled is modeled as a Discrete Event System (DES), and using controllable languages and finite state automata, a minimally restrictive and nonblocking control logic is obtained (Cassandras and Lafortune, 2008).

In (Wang *et al*., 2005; 2005b) the authors present the design, modeling, and supervisory control of a mobile robot based on a signed real measure of its discrete-event behavior. Thus, the robot plant model is built upon experimental results derived from a specific scenario and the supervisor is synthesized using a language-measure-based quantitative approach. The resultant supervisor is the same as the conventionally designed by means of the SCT. Jayasiri *et al*. (2009; 2011) suggest an alternative of using the theory of fuzzy DES where decisions are made using fuzzy logic. In (Sales *et al*., 2012) is proposed a visual navigation for autonomous vehicles that is based on finite state machines. Lopes *et al*. (2016) proposed and demonstrated the use of SCT for formally developing controllers in swarm robotics. Using a series of case studies, they illustrated how to formally model the capabilities of robots and their desired behavior (specifications). Supervisors were derived from these models and the code for controlling the robots was automatically generated by a tool named Nadzoru. Systematic experiments with up to 40 e-pucks and up to 600 Kilobots confirmed the correctness of the implementation code.

The SCT has been gradually used for flexible manufacturing systems, communication protocols, and process control. A major obstacle in the use of SCT is the combinatorial explosion of states that occurs in the solution of complex problems. Furthermore, difficulties in the implementation of control logic, especially in microcontrollers, due to their memory constraints, have hampered the adoption of SCT for industrial applications.

This work aims to explore the constraints between subsystems in modeling in order to reduce the number of states in the global system and thereby make feasible the implementation of the control logic in real controllers. Furthermore, are presented a proposal for implementing the control structure obtained by the presented approach. For validation, are proposed a systematic procedure for modeling, controller synthesis, and implementation of the control logic for a mobile sumo robot competition.

The major contributions of this paper are: through a successful case study, propose a manner to modeling plants, exploring physical restrictions in order to reduce the number of states of the global system; the proposition of an operational structure to implement a DES in real controllers.

2. SUPERVISORY CONTROL OF DES

This section is dedicated to reviewing the basic concepts of the supervisory control theory (Ramadge and Wonham, 1989), which is the basis for this paper.

A Discrete Event System (DES) is a discrete-state, event-driven system, that is, its state evolution depends entirely on the occurrence of asynchronous discrete events over time. It can be modeled by a deterministic automaton, a five-tuple $G=(Q,\Sigma,\delta, q_0,Q_m)$, where Q is the set of states, Σ is the alphabet or finite set of events associated with the transitions in G, $\delta: Q\times\Sigma\rightarrow Q$, is the transition function, $q_0 \in Q$ is the initial state and $Q_m \subset Q$ is a set of marked states.

In general, δ is a partial function, to be defined only for a set of events $\Sigma(q)$ occurring at q and δ can also be naturally extended to strings of events denoted by $\delta(q,s\sigma) =\delta(\delta(q,s),\sigma)$.

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The automaton G can be interpreted as a device that starts in state q_0 and generates a sequence of events following the *automaton.*

The *generated language* by G is defined as $L(G) = \{s : s \in \Sigma^* \wedge \delta(q_0,s)$ is defined$\}$ and *marked language* by G as $L_m(G) = \{s : s \in \Sigma^* \wedge \delta(q_0,s) \in Q_m\}$. In Ramadge-Wonham's model, a DES of *generated language L* (partial sequences) and *marked language Lm* (completed tasks) can be represented by a generator G such that $L(G) = L$ and $L_m(G) = L_m$.

The control of the DES is the switching of the control inputs, depending on the past behavior of the system, called closed-loop behavior. This concept leads to the distinction of the system to be controlled (Plant) and control agent (Supervisor), thus distinguishing the physically possible behavior of the system and the constraints linked to unwanted behaviors.

In order to associate control structures to a DES, the alphabet Σ is partitioned into a set of controllable events Σ_c that can be inhibited by the controller, and a set of uncontrollable events Σ_u over which the control agent has no influence (Ramadge and Wonham, 1989).

The supervisory control theory aims to synthesize a minimally restrictive and nonblocking controllable language. An automaton S that recognizes this language implements the required supervision. The control action of S, defined for each state of the automaton, is to disable in the plant G events that may not occur in S after a sequence of observed events. The automaton obtained from the synchronous composition of S and G, that is, $S||G$, represents the closed-loop behavior. In fact, in synchronous composition, only those transitions allowed in both the system G and the supervisor S are enabled.

It is said that a supervisor S is nonblocking for the plant G if from every state of the plant in closed-loop, one marked state can be achieved, which means that a task can be completed.

3. DES MODELING WITH RESTRICTIONS ON THE PLANT

One of the biggest problems faced in the modeling of DES using state machines is the explosion of states. Techniques that minimize or solve this problem are the current challenge for researchers.

In supervisory control theory, typically a complex system is divided into smaller subsystems for modeling. Each subsystem is modeled such that all possible sequences are represented, without worrying about the behavior of the other subsystems.

As a modeling alternative, aiming to reduce the explosion of states, this paper attempts to explore restrictions where a subsystem interferes with another system. Note that this proposal is not equivalent to a simple additional specification restricting the problem.

The presentation of this paper will be done with the assist of a small problem in mobile robotics. The robot for this study has two strip sensors s_1 and s_2 as shown in Figure 1.

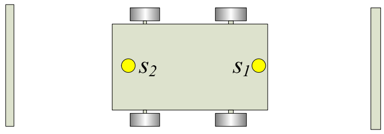
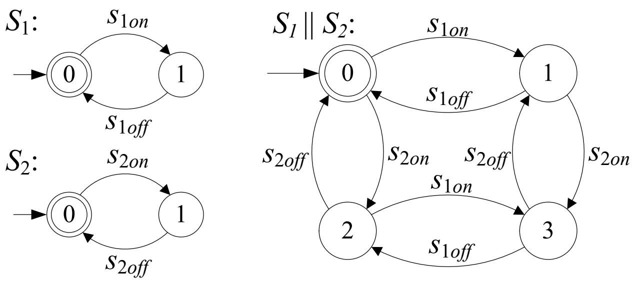


Figure 1. Basic robot to study.

The mobility is restricted to two directions of motion, forward and backward. The movement is limited by two strips placed at the ends of the paths, which are detected by sensors s_1 and s_2, respectively.

Traditional modeling of two sensors would be as shown in Figure 2(a) and the model of the synchronous composition of these two sensors is shown in Figure 2(b), where all events are uncontrollable.



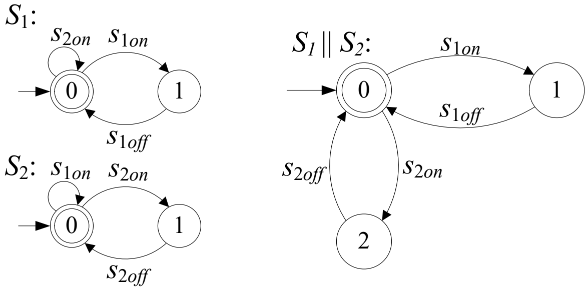
(a) (b)

Fig. 2. Plant Model for S_1 and S_2. (a) Traditional Modeling of sensors S_1 and S_2. (b) Synchronous composition of S_1 and S_2.

It can be observed that it is not physically possible to reach state 3 in this application, since the two sensors cannot be connected simultaneously.

To remove this state, following a supervisory control theory, a specification could be formulated, but this would not be feasible since all the events involved are uncontrollable and thus, cannot be prevented from happening by the supervisor.

In order to solve this problem, is proposed to adopt a model that restricts the behavior of each subsystem according to the behavior of the others. Thus, it is proposed a new model for the sensors s_1 and s_2 as shown in Figure 3(a).



(a) (b)

Fig. 3. Plant Models. (a) Restrictive Modeling of sensors S_1 and S_2. (b) Synchronous product of S_1 and S_2.