P.J. Antsaklis, "Hybrid and Supervisory Control Systems in Autonomous Underwater Vehicles," First International Workshop on A utonomous U nderwater V ehicles f o r S hallow W aters a nd C oastal Environments , pp. 135-139, Lafayette, Louisiana, February 17-19, 1998.

Hybrid and Supervisory Control Systems in Autonomous Underwater Vehicles

P.J. Antsaklis
Department of Electrical Engineering
University of Notre Dame, Notre Dame, IN 46556 USA
(219) 631-5792, (219) 631-4393 Fax
antsaklis.1@nd.edu

Abstract

This paper summarizes the main points of the presentation at the First International Workshop on Autonomous Underwater Vehicles for Shallow Waters and Coastal Environments in Lafayette, Louisiana, February 17-19, 1998. It also provides some useful references in hybrid and supervisory control systems.

Introduction

Autonomous Underwater Vehicles (AUV) are unmanned untethered underwater vehicles that rely on on-board computers and machine intelligence to execute a mission which consists of a sequence of preprogrammed instructions that are modifiable on-line based on information gathered by the vehicle sensors (see [1] and the references therein). Untethered underwater vehicles may be primarily cruising vehicles that are used for surveys, search, object delivery and object location, or hovering vehicles that hold station in the water column to perform their tasks that include detailed inspection and physical work on and around fixed objects. Cruising vehicles typically require only three degrees of control - longitudinal, yaw and pitch - while hovering vehicles require thrust to produce forces in three orthogonal directions and moments in yaw and sometimes pitch. AUV capabilities are of course heavily dependent on the quality and power of the hardware on-board the vessel. This is clearly evident since AUV operations are limited by the computing, sensing and actuating hardware resources available, and of course the length of the AUV operations is limited by its power source. The algorithms and the instructions given to the hardware for implementation are of course at least as important. Data need to be processed and translated into useful information and fed to decision making machines, which will issue the new set of instructions that will determine the behavior of the AUV. It is fair to say that the degree of autonomy of the AUV primarily depends on and is limited by the sophistication of its control system.

There exist several AUV control architectures designed for different vehicles and [1] provides a summary of their main characteristics (in [2] the AUV control architecture, developed in the University of Southwestern Louisiana in Lafayette, is described in more detail). The need for highly autonomous behavior in Autonomous Underwater Vehicles (AUV) makes intelligent control methodologies necessary and this point was highlighted in [3], but also throughout the NSF/ISR Workshop on 'Undersea Robotics and Intelligent Control', in Lisboa, Portugal, March 2-3, 1995. Intelligent control methodologies are appropriate for AUV and efforts towards this direction are being reported.

A look at the literature shows that the primary emphasis of the research community interested in the control of AUV has been on actually designing and building such systems for existing vehicles. That is the emphasis has been on applied research, rather on theoretical results. This is perhaps not surprising as a proof of concept that is based on currently available methodologies and hardware that works on simple missions is needed first, before more ambitious goals are attempted.

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However it should be pointed out that as the control architectures become more ambitious and sophisticated, it becomes apparent that better understanding of the underlying dynamics is needed if highly autonomous systems are to become a reality. This is the case in the control of any complex systems and it is of course true in the case of AUV. In intelligent control architectures there are interactions between discrete planning algorithms and continuous vehicle dynamics, for example, that make necessary the study of hybrid systems. This understanding has real practical consequences since, for instance, careless switching even between stable systems can lead to unstable behavior (contrary perhaps to popular belief) and the loss of subsystems or of the vehicle. Hybrid dynamics may also be of importance in more conventional approaches to nonlinear control. The complexity of the vehicle dynamics and of the environment, coupled with the needs for real time control and fast algorithms, also leads to the use of simpler models and hybrid control methodologies. Hybrid systems contain two distinct types of components, subsystems with continuous dynamics and subsystems with discrete event dynamics that interact with each other. Hybrid control systems are currently being studied intensively and several approaches for modeling analysis and synthesis have emerged. The study of hybrid control systems is interdisciplinary and the applications, in addition to AUV, also include land and space vehicles, chemical processes, manufacturing and communication systems.

Also important in intelligent control are discrete event dynamic systems. Discrete event systems (DES) models describe the behavior of systems with discrete dynamics. Such models are used to describe event-driven, often asynchronous behavior and model sequential and concurrent activities. They are useful in many application areas including concurrent distributed systems, integrated manufacturing, communication networks, and of course intelligent machines among others. Supervisory control methodologies for such systems (DES) are of interest in their own right. Supervisory controllers also provide higher level control in hybrid control systems.

Hybrid control systems

Hybrid systems arise from the interaction of discrete planning algorithms and continuous processes, and as such, they provide the basic framework and methodology for the analysis and synthesis of autonomous and intelligent systems. Such systems are important in a variety of contexts: Hybrid systems frequently arise from computer aided control of continuous processes in manufacturing, communication networks, autopilot design, computer synchronization, traffic control, and industrial process control, for example. Another important way in which hybrid systems arise is from the hierarchical organization of complex control systems. In these systems, a hierarchical organization helps manage complexity and higher levels in the hierarchy require less detailed models (discrete abstractions) of the functioning of the lower levels, necessitating the interaction of discrete and continuous components. Examples of such systems include flexible manufacturing and chemical process control systems, interconnected power systems, intelligent vehicle highway systems, air traffic management systems, computer communication networks. The study of hybrid control systems is essential in designing sequential supervisory controllers for continuous systems, and it is central in designing intelligent control systems with a high degree of autonomy. The investigation of hybrid systems is creating a new and fascinating discipline bridging control engineering, mathematics and computer science.

In the control area, very well known instances of a hybrid systems are sampled-data or digital control systems. If one also considers quantization of the continuous-valued variables or signals then the hybrid system contains not only continuous-valued variables that are driven by continuous and discrete times, but also discrete-valued signals as well. Another familiar example of a hybrid control system is a switching system where the dynamic behavior of interest can be adequately described by a finite (and small) number of dynamic models, that are typically sets of differential or

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difference equations, together with a set of rules for switching among these models. These switching rules are described by logic expressions or a discrete event system with a finite automaton or a Petri net representation. A familiar simple example of a practical hybrid control system is the heating and cooling system of a typical home. The furnace and air conditioner, along with the heat flow characteristics of the home, form a continuous-time system which is to be controlled. The thermostat is a simple asynchronous discrete event driven system which basically handles the symbols {too hot, too cold} and {normal}. The temperature of the room is translated into these representations in the thermostat and the thermostat's response is translated back to electrical currents which control the furnace, air conditioner, blower, etc.

There are several reasons for using hybrid models to represent dynamic behavior of interest. Reducing complexity was and still is an important reason for dealing with hybrid systems. This is accomplished in hybrid systems by incorporating models of dynamic processes at different levels of abstraction; for example the thermostat in the above example sees a very simple, but adequate for the task in hand, model of the complex heat flow dynamics. For another example, in order to avoid dealing directly with a set of nonlinear equations one may choose to work with sets of simpler equations (e.g. linear), and switch among these simpler models. This is a rather common approach in modeling physical phenomena. In control, switching among simpler dynamical systems has been used successfully in practice for many decades. Recent efforts in hybrid systems research along these lines typically concentrate on the analysis of the dynamic behaviors and aim to design controllers with guaranteed stability and performance. The advent of digital machines has made hybrid systems very common indeed. Whenever a digital device interacts with the continuous world the behavior involves hybrid phenomena that need to be analyzed and understood. Whenever the behavior of a computer program depends on values of continuous variables within that program (e.g. continuous time clocks) one needs hybrid system methodologies to guarantee correctness of the program; in fact the verification of such digital computer programs has been one of the main goals of several serious research efforts in hybrid systems literature.

A look in the literature clearly shows that there are many approaches to modeling, analysis and synthesis of hybrid systems. They can be characterized and described along several dimensions. In broad terms, approaches differ with respect to the emphasis on or the complexity of the continuous and discrete dynamics, and on whether they emphasize analysis and synthesis results or analysis only or simulation only. On one end of the spectrum there are approaches to hybrid systems that represent extensions of system theoretic ideas for systems (with continuous-valued variables and continuous time) that are described by ordinary differential equations to include discrete time and variables that exhibit jumps, or extend results to switching systems. Typically these approaches are able to deal with complex continuous dynamics and emphasize stability results. On the other end of the spectrum there are approaches to hybrid systems that are embedded in computer science models and methods, that represent extensions of verification methodologies from discrete systems to hybrid systems. Typically these approaches are able to deal with complex discrete dynamics described by finite automata and emphasize analysis results (verification) and simulation methodologies. There are additional methodologies spanning the rest of the spectrum that combine concepts from continuous control systems described by linear and nonlinear differential/difference equations, and from supervisory control of discrete event systems that are described by finite automata and Petri nets to derive, with varying success, analysis and synthesis results. Further information on hybrid systems research may be found in references [4]-[12] below.

There exist several software packages that may be used for simulation and verification of hybrid systems. In [13] a number of these packages were used and compared with each other in a case study of the two tanks benchmark problem. In [14] a hybrid simulation software package that was based on the programming language SHIFT was used to generate a simulation environment of the coordinated operation of multiple AUV. In that study the operation of 6 Phoenix AUV was simulated. Each AUV was described by a 6 dof model and the vehicles were in an underwater environment where 3 fixed transponders placed at appropriate locations were used for acoustic navigation.

Supervisory Control of Discrete Event Systems

Discrete event system theory is important in intelligent control, as it can be used for example to study planning the different control tasks. Discrete event systems are of course important in their own right and they have been studied using many approaches. They are also very useful in connection to hybrid systems. Recently, an efficient methodology for supervisory controller synthesis for DES was developed using Petri nets [15]-[20]. The approach uses the concept of place invariants of the net to design control supervisors that enforce linear inequality constraints on the marking and firing vectors of the net. The methodology can handle uncontrollable and unobservable transitions. The problem of deadlock has also been addressed. The control supervisors involve only places, that are equal in number to the number of constraints, and arcs that connect to the transitions of the plant Petri net. The approach is simple and transparent and it can be used in real time in control reconfiguration.

In the hostile environment where many AUV are expected to operate, such fast reconfigurable control algorithms may provide the necessary capabilities to help accomplish demanding missions. The control system, at the loss of one or more of its sensors and of one or more of its actuators will be able to reconfigure itself on-line, so that the AUV (if this is of course possible at all by its structural characteristics) will still be able to accomplish its goal or part of it successfully.

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