Improving the Pointing Accuracy of Direct-Fire Weapons

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Status of Linear, Fixed-Point Controllers

Advantages

The great advantage of linear, fixed-point controllers is that they have a long history of reliable service. These controllers, especially Proportional, Integral, Derivative (PID) controllers, have been in widespread use for many decades. In a recent 50th Anniversary Issue of the Transactions of the American Society of Mechanical Engineers, the landmark result selected for the featured article [1] of the issue was a summary of the original Ziegler-Nichols paper [2] providing an approach for determining optimal settings for PID controllers. This paper provided control engineers with formulas which applied results from open and closed-loop observations to calculate appropriate settings for proportional, integral and derivative control action in the forward path of a feedback control system. These simple observations and reliable adjustments of control parameters have been widely used for the last five decades to control a wide variety of systems, including control of pointing accuracy of direct-fire weapons. In addition to the great body of experience and practical knowledge available to assist design enngineers in solving prototyping and implementation issues, the production, maintenance, and repair of linear, fixed-point controllers, especially PID controllers, is well-understood. The successor of the PID as a linear, fixed-point controller, the linear multivariable controller [3], has also recently (in the last two decades) gained popularity as a more accurate methodology for controlling complex systems.

Disadvantages

The biggest problem with the PID controller is that closed-form solutions of the behavior of the system are only good for single-loop control of a simple, linear process. More complex systems (like fire control of tanks and artillery systems) actually have many feedback loops which are subject to nonlinear constraints. Linear multivariable control theory has been developed to address the complexity issue but lack the intuitive appeal of the PID adjustments made so papular by Ziegler-Nichols and closed-form results are still restricted to linear systems. Another fundamental problem with linear, fixed-point controllers is the difficulty (high cost) in identifying the structure and parameter values of the models for the process being controlled. The problem which H-infinity control was proposed to solve [4] was the design of feedback controllers in the presence of nonparametric or unstructured uncertainty. Success in this endeavor will enlarge the region around the fixed point in which the controller provides satisfactory response. However, these results presuppose (and thus designed controlled systems require) linear conditions for the analysis to be accurate. This leads to application of two different control methodologies in developing practical control systems: (1) switching control is used to position the control system "close enough" to the equilibrium point and (2) feedback control is used for precision control to maintain the accuracy of the linear assumptions. Thus, the most problematic difficulty with linear, fixed-point controllers is the fact that physical systems are actually highly nonlinear and a linear control algorithm cannot adequately handle nonlinear effects encountered as the performance envelope is pushed.

Example

We have been involved in the analysis and design of an alternative approach for design and implementation of feedback control systems, the Multiple-Agent Hybrid Control Architecture (MAHCA) technology [5, 6, 7, 8]. An early experiment in the development of this technology was analysis of a single-agent architecture for control of a test fixture which features a highly nonlinear environment for control of the angular position of the tip of a flexible metal rod [9]. The rod is about a meter long and a centimeter in diameter and is fixed at one end into the edge of a rotating metal disk about 30 centimeters in diameter and about 6 centimeters thick. The intent is to approximate the problem of pointing the tip of a direct-fire weapon instead of the breech, taking into account the fact that the barrel bends as the round travels through the rifling or is subjected to disturbances as the vehicle moves over terrain.

The flexible beam model has a flexure mode at about 8 hertz and a saturation nonlinearity which restricts allowable control action. Without a shaping filter to eliminate the bending mode, simulation studies show that a conventional PID controller is utterly incapable of controlling the beam. Even with a shaping filter, our simulations show a conventional PID controller still cannot accurately point the tip of the flexible beam since it can only achieve a limit cycle of oscillating about the new commanded angular position. On the other hand, a simulation of our single-agent controller indicates the ability of the hybrid systems approach (introduced in the next section) to improve the pointing accuracy of the test fixture. Our study indicates, as expected with a step change in commanded angular position, there is a large error between the commanded position and actual position of the tip of the rod at time $t = 0$. However, the single-agent controller drives the error signal asymptotically to zero within a short time (see Figure 1). Moreover, a phase plot of the single-agent controller

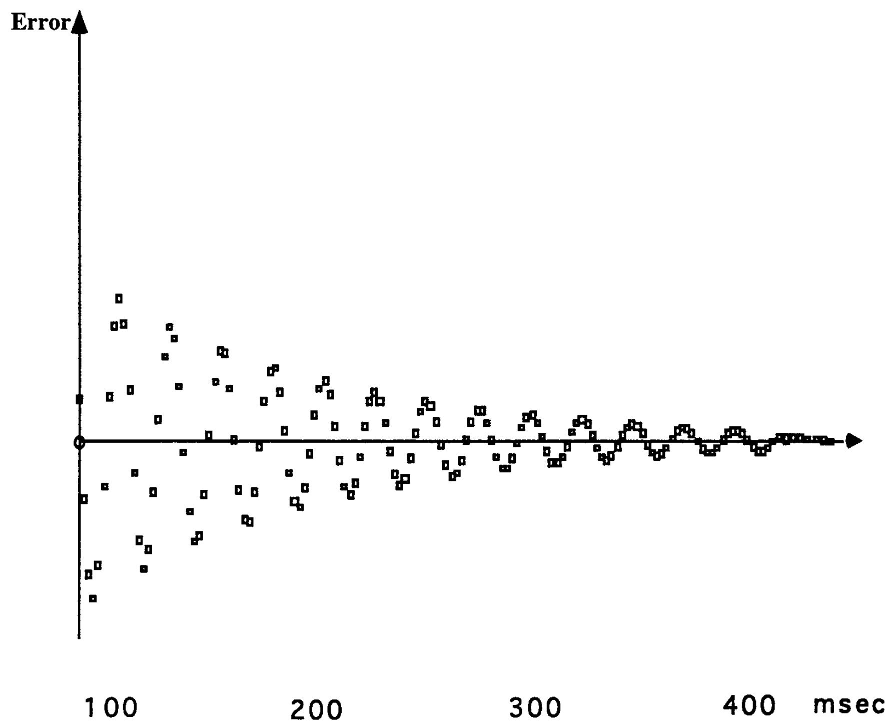

Figure 1: Error Signal of Step Response of Change in Angular Position

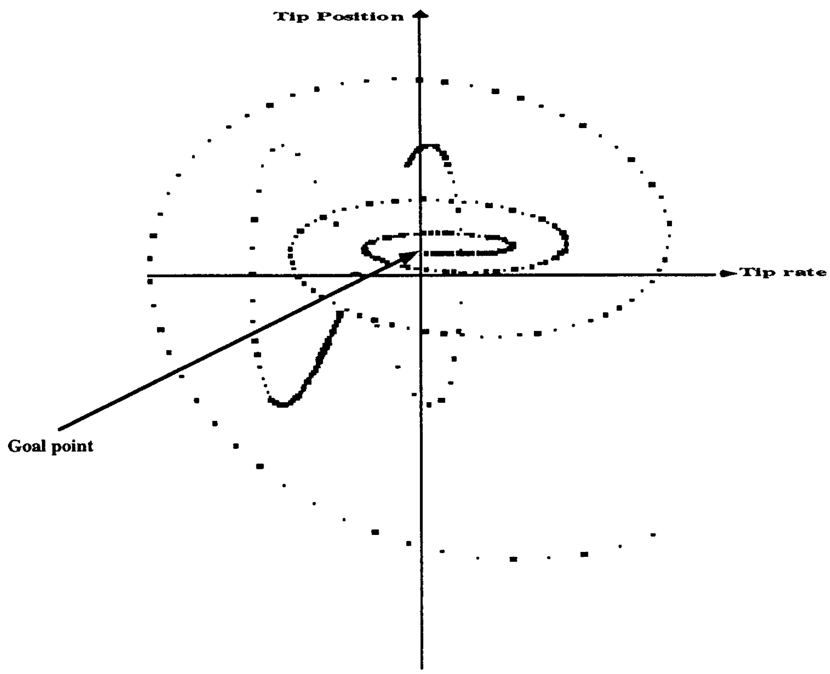

Figure 2: Phase Plot of Test Fixture

(see Figure 2) clearly shows two regions of attraction of the nonlinear system and the ability of the single-agent controller to asymptotically move to the goal point (desired angular position).

Scope of Proposed Research

The previous study has resulted in successful creation of simulation programs for single-agent control of the test fixture and creation of the initial version of the prototype demonstration. Work remains in interfacing the single-agent controller into the test fixture. We propose to expand the previous study to encompass the formulation and development of a tool for the generation of formal hybrid models for Vehicle Management and Control Systems. We propose a distributed control architecture for the dynamic integration and communication of interacting processes using intelligent control agents cooperating via a logic communication network. This architecture, termed Multiple Agent Hybrid Control Architecture (MAHCA), is based on our recent advancements in hybrid systems theory and applications. This approach provides for the flexible interoperability of distributed, real-time information systems by generating, in real-time, control programs which comply with logical and evolutionary specifications. We maintain that the network of interacting computer systems already implemented in the Abrams tank is a hybrid system, that is, a system described by an amalgamation of logical and evolution representations. We propose to expand the hybrid systems results achieved thus far and investigate the issues of scalability, dynamic integration, and verification as they apply to interoperability of components of a crew-served weapons system.

A simulation for the development and testing of a hybrid system must flawlessly blend incompatible models of, for example, the continuous navigation and guidance sensors, the discrete display events, and knowledge-based advisor systems. While mature models exist for continuous and discrete dynamic systems, the integration of these models is poorly understood. For knowledge-based systems, there are no currently available formal procedures for their modeling and simulation. Thus, a need exists for formal principles and procedures for specifying and constructing consistent, logically-valid hybrid system models.

To address this need, our research will develop: 1) a robust integration theory, 2) an architecture for the generation of hybrid models, and 3) a prototype tool based on this architecture.

Kohn and Nerode developed MAHCA, or the multiple agent hybrid control architecture. Kohn-Nerode-James have been extending MAHCA to areas, such as computer aided manufacturing, traffic control, distributed cost-benefit analysis, wireless communications systems, distributed control of military assets, and distributed simulation [10]. Each new application area presents new intellectual modeling and mathematical challenges.

The initial object of the proposed integration theory is a result known as the *Kohn-Nerode Theorem* (1991) that states that in every hybrid system a logically coherent and robust integration between its continuous and discrete elements can only be achieved if the following continuity conditions are satisfied: 1) The behavior trajectories of the system must continuously depend on the requirements, 2) Every trajectory of discrete variables (generated by a discrete component) in the behavior is a collection of sampling points of a continuous trajectory generated by constructing a continuous component, by a formal interpolation procedure, whose output coincides with the discrete component at sampling times, and 3) The map from the requirements space to behavior space is continuous with respect to the induced product topology.

The importance of this theorem for our purposes resides in the following three observations:

1) We have developed and implemented *effective computational schemas* for evaluating the premises of the theorem. Thus, we have effective tests to determine whether or not a hybrid model is consistent, and if not, which elements or constraints are responsible for the inconsistency.

2) It provides a *unified complete representation* of hybrid systems which allows for the evaluation of fundamental global qualitative performance measures such as stability, goal reachability, observability, and controllability.

3) This theorem allows us to consider a hybrid model as a device with two types of degrees of freedom: *physical degrees of freedom*, as in conventional

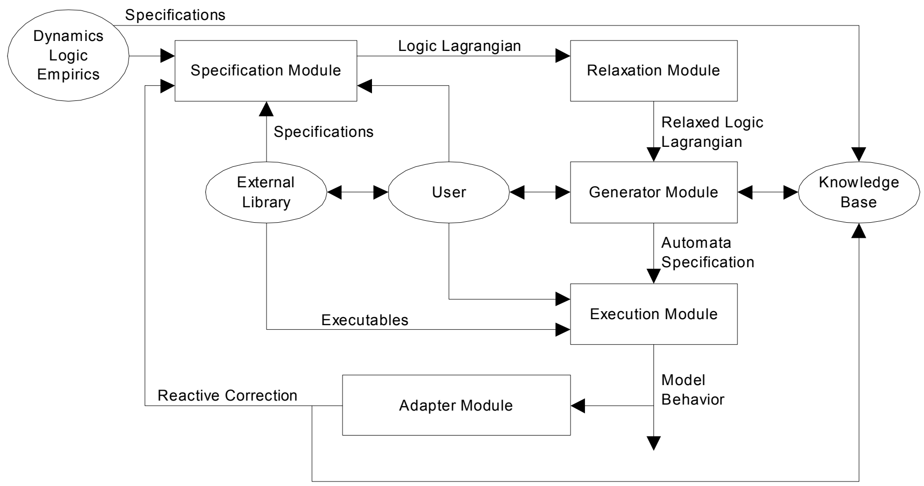

Figure 3: Architecture of Hybrid Model Generator

physical systems, and *logical degrees of freedom*.

Our proposed architecture, shown in Figure 3, is based on our research and development in hybrid systems. This architecture has the capability to generate code for the execution of hybrid models from a set of, possibly incomplete, equational specifications. A prototype tool, based on our architecture and customized for the domain of vehicle management systems, will be developed. It will use deductive capabilities to generate executable hybrid system models that are consistent, complete, and sound with respect to the physical, logical, and computational principles, that satisfy behavioral requirements, and maintain consistency under unavoidable knowledge uncertainty. The next section overviews the principles on which our proposed architecture is based.

Hybrid Model Generator Architecture

Knowledge Base

The central mechanism of our proposed architecture is *formal deductive inferencing* over an equational domain. The objects in this domain are hybrid models which are represented by two composite items: an *evolution operator* and a *knowledge specification set*. An evolution operator is a set of coupled differential and difference equations, possibly with algebraic side constraints. A knowledge specification set is a set of discrete specifications stated by a chained set of rules. For a hybrid model, both its evolution operator and knowledge specification set are encoded in the knowledge base of the architecture via equational clauses of the Horn type. This commonality facilitates the generation of an executable for the model. In our proposed architecture, the generic aspects of the domain and the system-dependent elements associated with a given hybrid system are encoded in the *knowledge base*.

Specification and Relaxation Modules

The *specification module* takes the equational specifications of the system under study and constructs a faithful variational functional, the *logic Lagrangian*. In our theory, the behavior of each hybrid system is characterized via an optimization criterion called the *relaxed logic Lagrangian* of the model. Our theory provides for a formal symbolic procedure to transform a set of specifications of a hybrid system into the corresponding relaxed logic Lagrangian which is implemented in our proposed architecture by the *relaxation module*. The input to this module is the logic Lagrangian which is a functional capturing the specifications associated with the hybrid model. The central objectives of the relaxation of the logic Lagrangian are to incorporate model uncertainty and to provide formal, effective requirements from which an executable specification can be extracted. These requirements are transformed into a single requirement, the minimization of the relaxed logic Lagrangian.

Generator Module

In our proposed architecture, the specification of the automaton associated with a given hybrid model is constructed by the *generator module*. We have postulated and tested in several prototypes a construction procedure for an executable of a hybrid model on the basis of a relax. This executable is a *locally finite non-deterministic automaton*. Each state of an automaton associated with a hybrid model contains a finite set of equational relations. Each edge, which indicates state transition from a source to a destination state, is labeled by one of a finite set of *inference operators*. An inference operator transforms the equational relations in the source state associated with the edge into the set of equational relations associated with the destination state. Each automaton that represents a hybrid model has three sets of distinguished state: *initial states*, *terminal states* and *interior states*. Each of the initial states contains a set of behavioral specifications of the model. Each of the terminal states contains behavior values. The interior states represent intermediate inference steps in the generation of the behavior.

Execution Module

The automaton specification is expressed in a generic equational form that completely characterizes its state transition dynamics. To execute this specification, valid state paths from initial to terminal states must be carried out. Our theory provides an *automata decomposition procedure*, based on the Kohn-Nerode theorem, for traversing these paths. This procedure has linear complexity on the number of states of the paths. In the proposed architecture, the *execution module* carries out this task.

Adapter Module

The behavior of a hybrid system must satisfy the requirements and specifications as encoded in the knowledge base. The relations that characterize this satisfaction are explicitly expressed in the *model behavior output*. If one or more of these relations have a truth value of false, it indicates that the generated behavior does not logically follow from the stated specifications. This situation requires corrective actions both in the knowledge base and to the logic Lagrangian of the hybrid model. In our theory, we have incorporated a general *commutator reactivity principle* for generating correcting directives for offending clauses in the knowledge base and modification directives for the specification module for correcting the logic Lagrangian of the model. In our proposed architecture, the commutator reactivity principle is implemented by the *adapter module*.

External Library

There are many commercial tools that implement portions of the tasks in the development and execution of hybrid models. We propose to provide mechanisms for incorporating these tools by writing specification terms for the declarative semantics of each external tool module, and incorporating them in the logic Lagrangian of the model so that at execution time the corresponding modules are used as appropriate.

Ongoing Research and Development

We have developed a common framework for the representation of the components of hybrid models. This framework is implemented in the equational syntax and semantics of our equational clauses for encoding and reasoning about hybrid systems.

We have developed a prototype of a *deductive inferencer* over equational clause domains, termed an *Equational Reactive Inferencer (ERI)*. It is the basis of the generator, adapter, and execution modules in our architecture. We have shown that the proof system implemented by ERI is *sound and complete over equational domains*. The proof strategy behind ERI is automata generation and execution.

We have implemented several application prototypes which incorporate elements of our proposed architecture [10]. These include an intelligent controller for a transport aircraft in the vicinity of a congested airport, an autonomous rendezvous system for space vehicles, and an intelligent controller for space robots. We are currently developing a prototype of an intelligent vehicle-highway control system which includes incident detection. This effort includes the development of a continuous wave model of the freeway and a discrete optimal routing algorithm. Finally, we have had considerable experience in the Space Shuttle avionics system (a highly integrated hybrid system) including simulations, and system analysis and design.

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