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This report describes recent progress in the development of PRET, a computer program that automates the process of system identification. Given hypotheses, observations, and specifications, PRET constructs an ordinary differential equation model of a target system with no other inputs or intervention from its user. The core of the program is a set of traditional system identification (SID) methods. A layer of artificial intelligence (AI) techniques built around this core automates the high-level stages of the identification process that are normally performed by a human expert.

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Automatic Construction of Accurate Models of Physical Systems

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1 Summary

System identification (SID) is the task of deducing the internal dynamics of a black-box system solely from observations of its outputs. This is an essential first step in a variety of engineering problems; most traditional control-theoretic methods, for example, require an accurate ordinary differential equation (ODE) model. Accuracy is not the only requirement, however; for efficiency reasons, engineers work hard to construct *minimal* models — ODEs that ignore unimportant detail and capture only the behavior that is important for the task at hand. This tandem of accuracy and abstraction is a subtle and difficult part of an engineer's training and practice.

The computer program PRET, the topic of this report, automates the process described in the previous paragraph by building an artificial intelligence (AI) layer around a set of traditional system identification techniques. This AI layer executes many of the high-level parts of the SID process that are normally performed by a human expert, intelligently assessing the task at hand and then reasoning from that information to automatically choose, invoke, and interpret the results of appropriate lower-level techniques. These tactics guide PRET quickly and accurately to the minimal ODE that accounts for the important behavior of the system.

The ultimate goal of this project is to build a tool that can automatically construct models of high-dimensional, nonlinear, black-box systems, drawn from any domain that admits ODE models. The objective of this project is to effectively automate existing SID techniques, not invent new ones; even so, this is an extremely ambitious goal, as nonlinear system identification is a state-of-the-art research area. As an automated tool that accomplishes this, PRET will be of obvious practical importance in science and engineering: as a corroborator of existing models and designs, as a medium within which to instruct newcomers, and as an intelligent assistant, whose aid will allow more time and creative thought to be devoted to other demanding tasks.

2 FY98 Progress

One of the core technical challenges in this project is to choose and orchestrate appropriate reasoning levels and techniques for each stage of the modeling task. This year, we have completed the construction of a specialized first-order logic system that performs this task effectively and efficiently. This custom logic system uses SLD resolution and a mathematical domain theory that ranges from trigonometry through calculus to nonlinear dynamics in order to automatically generate and test ODEs against a set of observations. The reasoning processes that PRET uses in the course of the modeling process, like those used by human experts, are mostly qualitative and highly heterogeneous. The logic system is designed to take maximum advantage of this; it uses declarative meta control to adapt dynamically to the current state of the theorem prover, thereby assuring that the cheapest and most appropriate (i.e., most likely to yield useful information) form of reasoning is used at all times. A "sparse" truth-maintenance system (STMS) adds to this efficiency, letting the logic system save and reuse information that is useful in the context of PRET's particular reasoning task — information that would be lost in a garden-variety theorem prover. Finally, static abstraction levels enforce the minimality constraint, assuring that PRET does no more work than necessary to model the target system.

Another important and difficult part of this project is the choice of the internal representation. We chose ODEs as PRET's target models because they are both general and powerful, but we have recently begun to suspect that they are not necessarily the best internal representation. After thinking hard about this issue over the last year, we have decided to retrofit PRET to use *bond graphs* — a generalized representation of a network of power relationships that is a common and powerful tool in an expert control theorist's arsenal — as the primary internal representation. The important notion that the same ODE may model different systems in different domains is captured naturally in bond graphs; their inherent abstraction brings out similarities and analogies — e.g., that springs and capacitors can play analogous roles in ODE models of mechanical and electronic systems. This feature should make it easy to add intelligence to PRET's model generator, which currently enumerates models in an unintelligent (and exponentially) complex manner. Bond-graph properties also induce a neat and obvious structure for the syntax and semantics for sensor/actuator specification — another hard and important problem on our remaining to-do list.

We have also made progress on variety of other fronts. Among other things, the graphical user interface (GUI) is now functional, and we added a variety of domain rules to the rulebase, as inspired (and demanded) by new examples. Implementing automated I/O interactions with the real world, however, continues to give us trouble; the problems involved are much more difficult than we had anticipated. This is not completely surprising, as we are proposing to automate one of the harder branches of nonlinear control theory in this section of the project: automatically determining what kinds of tests one can perform on a system, what kinds of results one can obtain, and what conclusions one may draw from them.

3 Accomplishments

Of the eleven[1] action items for the time remaining on this contract that were listed on pp 4—5 of our FY97 report, we have finished five and made significant progress on five, as summarized below.

- The logic system that forms PRET's core, which uses SLD resolution, static abstraction levels, dynamic meta control, constraint propagation, and a "sparse" truth-maintenance system (STMS) — a significant innovation — to build and check ODE models, is now complete and case-hardened.

  In FY98, Reinhard Stolle, the author of this logic system, defended his Ph.D., received offers for two tenure-track jobs and a variety of postdoc positions, and published two papers, one in the highly prestigious — and competitive — National Conference on AI (AAAI). His paper on the dynamic meta control system is in review at *Knowledge and Information Systems*, and a companion paper on the STMS is in preparation. He will be taking a postdoc at Stanford in January 1999.

- PRET's graphical user interface has been completed and tested.

  Apollo Hogan, who designed and implemented that GUI and worked closely with Stolle on the meta control and STMS systems, is a co-author on the *Knowledge and Information*

[1] There were actually twelve bullets on that list, but one of those tasks — augmentation of the rule base — is by definition ongoing.

Systems paper listed above. In August 1998, he will be entering the Ph.D. program at Berkeley in set-theoretic topology.

- We spent a great deal of time thinking about and redesigning PRET's internal representation to use bond graphs instead of ODEs; this adaptation, which has not yet been implemented, will have sweeping positive effects on the remaining action items, as detailed in section 5 of this report.

4 Transitions

PRET has now been developed to the point where outsiders can use it, but only with significant assistance from one of us. Interactions with application analysts have given us useful insights and suggestions (e.g., the GUI) and have forced us to augment, polish and bomb-proof the code. Three key example applications, in particular, have driven and will continue to drive PRET's development:

- A radio-controlled car used in a soccer-playing robot system by Dinesh Pai's group at the University of British Columbia
- An eyeglass lens cutting machine in David Trumper's lab at MIT
- A model of a ship-mounted crane constructed by Randall Tagg at the University of Colorado at Denver

PRET's results on the R/C car are complete; see our FY97 report and the accompanying quadchart materials. The lens-cutting machine and the on-ship crane are new endeavors this year. The crane, in particular, has obvious and significant naval applications — positioning and stabilizing a load swinging from a deck-mounted crane in rough seas is a difficult control problem, and an accurate ODE model of the crane-ship-load system is essential to its solution.

Our interactions with human experts have exposed a variety of subtle and difficult AI issues. For example, one analyst intuitively and immediately rejected a model that matched his spec perfectly — because it did not match some of his *implicit* knowledge about the system. Frames of reference in which to reason have also caused some difficulties: PRET is not equipped to choose the "best" reference frame for a given problem — a choice that is a large part of an engineering or science education, and that is simply too hard to automate.

PRET is still at the stage where interactions like this are far more useful to us than to our users. We hope to begin changing that this year, and we have some preliminary evidence that we will indeed be able to do so. In the past, the goal of these exercises has been to duplicate (and thereby verify) a model found by a human analyst; in the case described in the previous paragraph, however, PRET's model was actually *better*, which suggests that we can indeed make useful contributions to the modeling art.

We have also collaborated with the Information Technology group at NIST/NOAA in Boulder in order to develop an AI-adapted global optimization tool that combines qualitative reasoning and local numerical methods; see the *Annals of Mathematics and Artificial Intelligence* paper listed below.

5 Plans for next year

This work plan is designed to cover the next 12 months, but the contract ends on 31 March 1999, and we will not finish all of these items by then. Primary personnel for this period include one Ph.D. student (Matt Easley) and the PI; Stolle has agreed to stay on as a postdoc for the fall semester in order to help us finish some of the tasks listed under item 1 below.

1. **Bond graphs**:
   - Retool PRET to use bond graphs as an internal representation
   - Begin working out how to exploit this representation to improve the model generator
   - Test the power of these improvements by implementing a new domain: mechatronics
   - Begin working out how best to structure the syntax, semantics, and representation of the information that PRET receives about the sensors and sends to the actuators
   - Begin automating PRET's output interactions
   - Easley will defend his Ph.D. proposal

2. **Examples**
   - Build and test a simple mechanical system with input/output capabilities — probably a spring-mass oscillator on an air track
   - Continue working with David Trumper's group at MIT, who are performing system identification on a commercial eyeglass lens-cutting machine, and attempt to reproduce their results automatically
   - Continue working with Randall Tagg at the University of Colorado at Denver, applying PRET to the on-ship crane mockup in his lab

3. **Rulebase:** (ongoing)
   - Continue adding rules as PRET is tested on more examples in different domains

6 Publications on This Project

All are full-length, refereed papers.

- E. Bradley, A. O'Gallagher, and J. Rogers, "Global Solutions for Nonlinear Systems using Qualitative Reasoning," *Annals of Mathematics and Artificial Intelligence* (1998)

- E. Bradley and M. Easley, "Reasoning About Sensor Data for Automated System Identification," *Intelligent Data Analysis: An International Journal*, vol. 2 no. 2, Elsevier Science (1998) HTTP://WWW.ELSEVIER.COM/LOCATE/IDA *[Published electronically and archived on CD; neither format includes page numbers]*

- R. Stolle and E. Bradley, "Multimodal Reasoning about Physical Systems" *National Conference on Artificial Intelligence (AAAI)*, Madison WI; July *1998 [Expanded version of the paper listed below]*

- R. Stolle and E. Bradley, "Multimodal Reasoning about Physical Systems," *AAAI Spring Symposium on Multimodal Reasoning*; Stanford CA; March 1998