REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	31-March-1996	Final Progress Report 6/1/91-12/31/95

4. TITLE AND SUBTITLE

Rapid Prototyping of Nonlinear Controller Designs

5. FUNDING NUMBERS

DAAL03-91-G-0171

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARO 28835.13-MA

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

In this funding period we have begun a large activity in developing software for nonlinear control systems design. The software is being evaluated and tested on numerous practical control systems design problems. We have also continued our activity in adaptive control of nonlinear systems, both adaptive regulation and adaptive tracking, as well as sliding mode control of nonlinear systems. We also began a project on the use of saturation functions for stabilizing systems which either had finite escape time or for which the presence of actuator constraints actually made the linearizing control laws difficult to implement.

14. SUBJECT TERMS

tools for nonlinear control, adaptive tracking control, sliding mode control, saturation functions, virtual prototyping tools

15. NUMBER IF PAGES

11

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

ARO Grant Number DAAL-91-G0171
Rapid Prototyping of Nonlinear Controller Designs
June 1, 1991 - Dec. 31, 1995
Final Tehnical Report

S.Shankar Sastry

1 Summary of Research Findings

In this funding period we have begun a large activity in developing software for nonlinear control systems design. The software is being evaluated and tested on numerous practical control systems design problems. We have also continued our activity in adaptive control of nonlinear systems, both adaptive regulation and adaptive tracking, as well as sliding mode control of nonlinear systems. We also began a project on the use of saturation functions for stabilizing systems which either had finite escape time or for which the presence of actuator constraints actually made the linearizing control laws difficult to implement.

Six students supported on this grant finished their Ph.D.s in this period, R. Kadiyala, A. Teel, A. K. Pradeep, L. Bushnell, C. Coleman, and S. Burgett (finished shortly after end of grant on AASERT supplement to this grant). The details of some of our work are as follows:

1. **CAD and Implementational Tools for Nonlinear Systems**

   One of the most important goals of this grant is to develop at least at conceptual level, user friendly tools for nonlinear control, which contain on the one hand recent advances in the theory, but on the other hand also take advantage of recent advances in workstations to provide graphical and symbolic visualization of simulations. Our software has incorporated graphical depiction of our control laws on Sun workstations. This, we believe, is essential to allow for rapid prototyping of new nonlinear and adaptive control laws. The systematic development of the software in C with a good user interface are current topics of research. What has begun as an off-line CAD tool design effort has, owing to the development of computer hardware, become an attractive option for real-time control: consequently, the real time aspects of the computations are our future priorities.

The toolbox (AP_LIN) contains modules to approximate systems by polynomial systems of arbitrary order and then to render them input-output or input-state linear with error terms of arbitrarily high order. The approximation of the full nonlinear system by a polynomial nonlinear system allows us to compute the control law numerically, as opposed to symbolically. Furthermore, since the package is a stand-alone package written in C, we have the ability to repeat computations in real time along the trajectory of the controlled system. The task of approximating a system and updating the control law accordingly is very similar to adaptive control.

Finally, we have a visualization tool called SYS_VIEW which allows one to view the stability regions of the control laws. The calculations for this purpose are carried out in parallel on multiple networked workstations and the results presented on a Silicon Graphics workstation.

2. Control of MIMO nonlinear systems

In this research, we (in a collaboration with M. Di Benedetto from the Università di Roma) studied two schemes for the adaptive tracking control of MIMO systems with parametric uncertainty in their dynamics. The first approach is an adaptive version of a static feedback law for tracking control based on some results on asymptotic model matching recently proposed by Di Benedetto. This scheme is based on new techniques for extending the so-called zero dynamics algorithm of Isidori and Byrnes to problems of stable model matching followed by their specialization to tracking. The second scheme is an adaptive version of a dynamic precompensation law of Descusse and Moog for linearization using dynamic state feedback. The later work with Godbole, produced new techniques for the approximate feedback linearization of MIMO nonlinear systems which were close to being singular.

3. **Sliding Mode Control of MIMO nonlinear systems**

   The problem of developing precise matching conditions for nonlinear systems which are not linearizable by static state feedback has proved to be a surprisingly hard nut to crack. In early work on the grant we encountered success in developing matching conditions for MIMO systems linearizable by static state feedback. The extension of these results to either dynamically decouplable MIMO systems or other more general systems is not yet complete.

   However, our earlier experiments with sliding mode control laws have enabled us to understand solutions to stabilization problems where it may be shown that the underlying control system cannot be stabilized by continuous, state feedback.

4. **Using Saturation to Stabilize Nonlinear Systems**

   For a large class of systems with polynomial nonlinearities, there is a problem of finite escape time and also the problem that the systems cannot be globally full-state linearized. In the dissertation work of Teel, he used saturation functions to stabilize such systems and also to stabilize systems which could not be linearized because of actuator constraints. These results represent solutions to several classical problems of stabilizing systems in the presence of a very common nonlinearity: saturation. Among the surprises, one can show that it is not completely obvious how to stabilize a *linear* system consisting of a chain of integrators when saturation is presented. Teel presented a methodology using nested sequences of saturation functions for this purpose.

5. **Virtual Prototyping Tools**

   In this research, Steve Burgett, who has a background in mechanical design, began thinking about problems in concurrent design of electromechanical systems. He was initially motivated by rapid prototyping concerns in Micro-Electro-Mechanical Systems (MEMS). Here the problem was to build integrated mechanisms sensors and actuators on a chip. While this research is very much in the news, in our laboratory we have moved away from the micro scale to the milli-scale. We have been working on integrated sensors, actuators and controllers for milli-robots for surgery in a project begun with Colonel (Dr.) Richard Satava, of Fort Ord, Monterey and ARPA. We have proceeded inductively to develop several prototypes of robots for endoscopic and laparoscopic surgery and are working towards the area of mobile surgical workstations for remote surgery to be performed (for instance, on the battlefield). These are reported on in several publications reported on in this grant and have become a large and important and high-profile direction of future research.

In this context, we began investigating the fundamental tenets of prototyping and came up with the sense that some of the most important prototyping ideas lay in the production line machine tools (a sort of meta-prototyping). To this end, we have developed software modules, MechEdit for simulating planar kinematic machines and Racer-X for laying out parts from a reduced (minimalist) part description. These packages are being interfaced to Pro-Engineer, a commercial CAD package on the suggestion of Drs. Kurt Fickie and Ben Cummings of ARL.

This project while extremely promising is still in a growth mode, though the software is available for free dissemination. It is called *Racer X* and is a virtual prototyping tool because of its reliance on state of the art simulation and visualization tools.

6. **Rapid Prototyping of Electromechanical Designs**

We have developed software that minimally demonstrates a design environment with integrated shape synthesis. It allows the design of a single flat part (2-D) through interactive editing of features, illegal regions, and global part properties. Features are specified by selecting a feature type and positioning it in the design with the mouse. Illegal regions, represented by polygons, are specified and modified interactively. A thick skeleton is generated that connects the features and avoids the illegal regions. The resulting design is rendered by extruding the part into the third dimension, and resembles a physical part that could be made by bending and welding bars, or by milling.

In addition to specifying local features (application features) we support global attributes for parts. Two such part attributes are spar width and illegal region clearance. The user can modify these attributes for the part via an on-screen slider, and see the part dynamically resynthesize. The algorithms are currently fast enough to resynthesize a reasonably complex part several times per second, thus when the user interactively drags a feature or edits an illegal region, the part appears to stretch.

We currently support a single application feature (holes) and two skeleton synthesis algorithms (Delaunay Triangulation and manual). A connectivity graph is computed without regard for illegal regions, then a path is planned around them for each edge in the graph. This planning is done by computing CSPACE (illegal regions are grown by half the spar width plus the clearance), and its visibility graph. Dijkstra's algorithm is then used to find the shortest path for each connectivity edge. The software is implemented entirely in C++, with the exception of the Forms and Numerical Recipes C source code libraries. We have also made progress in three areas: user interface, graph optimization, and constraint-based recomputation.

User interface: We now have centralized event processing, which regularizes and unifies the user interface. Modality is minimized. User-configurable key bindings are modeled after the user interface of GNU Emacs – bindings of keystrokes to program actions are no longer hardcoded. Assignment of keystrokes to actions is defined in an ASCII text file that is read at program startup. The result is that all user functions can be available at all times (except where it doesn't make sense). For example, view navigation with the mouse can be performed at any time by holding down the "Alt" key. Switching to navigation mode is no longer required. Further, the assignment of the "Alt" key to this behavior is not hardcoded, but is defined in the text file. In addition to the obvious advantage of user convenience, development effort is reduced because key-assignment collisions are eliminated: programmers do not define key-assignments in code, so conflicts do not arise. The syntax of the user key-assignment file is Lisp, and may be extended in a regular way in the future to support additional user options.

Skeleton Optimization: We have begun work on new skeleton-generating code that incorporates numerical optimization techniques. This is a fairly marked departure from the computational-geometry-inspired techniques we have previously implemented. These methods compliment the CG methods, and together provide a broad selection of skeleton forms. The present implementation incorporates a conjugate-gradient nonlinear numerical optimizer, and uses as a cost function the total length of the skeleton. The optimizer repositions certain of the nodes of the skeleton in order to drive the cost function to a local minimum. Given the proper starting topology (manually entered), the result is a Steiner tree of the feature nodes.

Object-Oriented Constraint System: Implementation of 3D user-interface components is traditionally fairly difficult because of the lack of interaction support in most toolkits. Most commercially available graphics toolkits have aimed at drawing pictures. Our application requires the interactive manipulation of models, so geometric modeling, interaction and drawing must be combined. We have developed a constraint-based subsystem which facilitates the development of geometric objects that allow modeling operations, user interaction, and correct rendering. The technique computes a correct order based on implied relationship graph, and then issues notifications for the geometric objects to recompute their internal state based on local inputs. The system allows both simple and aggregate objects.

7. **Trajectory Planning**

   One of the key elements of intelligent control design that is overlooked by most control theorists is the transfer of high level task descriptions into trajectory specification. This specification of trajectories is in turn made complicated by non-holonomic constraints. In this research we (Tilbury, Bushnell and Sastry) have been studying the generation of feasible trajectories for systems of wheeled bodies with nonholonomic constraints. This could represent a truck pulling several trailers. Initially, we studied the generation of trajectories for a kinematic model of multi-trailer vehicles, and subsequently trajectory generation for the full dynamic model next. This area of work is referred to as *non holonomic motion planning.*

8. **Intelligent Control of Hybrid Systems**

One of the major challenges in the design and prototyping of controller designs is the problem of aggregating continuous time dynamics and control with discrete event dynamics, arising from logical operations. This problem is particularly acute in the context of complex hierarchically organized control systems where at all but the lowest levels of the hierarchy the control is on models of a coarser granularity, then differential equations. Such problems arise, for example, in highway automation problems, problems of command and control and also more generically in flight control (with many modes of operation) and process control.

This is an ambitious project, and we are guided in our choice of problems by a number of detailed case studies of large, complex systems with multiple agents arising in intelligent vehicle highway systems, air traffic management systems, biological motor control. Key issues that have been addressed in this research are: *hybrid dynamics, multi-agent character, sensor data compression and actuator command expansion, verification, adaptation and learning.* However, after conversations with Drs. Linda Bushnell and Dr. Lou Piscitelle of the Army Natick laboratories, we have initiated a related project (under an AASERT grant awarded to support this grant), for the detailed study of control algorithms for dynamic simulations for human systems. In addition to this program having intrinsic scientific merit as one of the most challenging "open problems" of our times, it will be extremely useful for the Army to have realistic, dynamic simulators for simulating soldier gaiting, performance, etc., and also to use in more complex simulation and visualization packages for training.

We are developing a control design strategy for complex multibody systems, of the kind that are encountered in simulating humans. The difficulty of controlling multibody systems is derived from the inherent complexity of the differential equations as well as the many degrees of freedom present. Our effort has been directed toward designing a verifiable control methodology for these systems to overcome the limitations in current technology. The controlled multibody system is required to produce the desired behavior in a robust manner, that is, it must be able to recover from unexpected changes in the environment and react to external disturbances. The desired behavior need not be as specific as a desired trajectory; rather, it is our goal to develop controllers to satisfy more natural design criteria such as "move forward without falling over." Interactive simulation and design of the controlled system is an important aspect of our approach.

A good control design methodology for complex multibody systems will be useful in several areas. One application is dynamic animation. In dynamic animation, the motion is required to appear real and obey our intuitive understanding of the world. Simulating a controlled model of a physical system is one method of producing realistic simulations. This methodology can also be applied to the design of robots with multiple limbs that can be used in hazardous environments. Robots with multiple limbs are also able to traverse rough terrain that is difficult for wheeled vehicles. We have begun to develop our control methodology by investigating the control of planar dives. Given an initial state, the diver must execute a certain dive maneuver, which we have chosen to be a forward $1\frac{1}{2}$ somersault pike, and enter the water in a fully extended, vertical position. This problem is a difficult one because after the diver has left the board, his angular momentum is conserved, but is generally not zero, so the system has drift. While in the air, the diver can change the drift velocity by changing his moment of inertia (moving his arms and legs into the pike position). Since the diver is falling while executing the maneuver, there is a predetermined length of time in which the controls can act. In a paper with Lara Crawford, a controller for a 5 DOF planar model of the diver. In order to restrict the number of control choices, we based our controls on certain principles of biological motor control, using also models of artificial neural networks for learning and storing patterns. The controls are chosen from a biologically plausible family of Gaussian velocity profiles. The controller searches a parametrization of this control space to find a control that reduces an error measurement below a cutoff value. The error measurement we have chosen incorporates the final rotation angle, the final angles of the arms and legs, and a parameter measuring how soon the piked phase of the dive was completed (early completion is considered good diving style). We have begun to develop a more general biologically-inspired learning controller, which uses torques rather than velocities as controls, and apply it to the three-dimensional, 25 DOF diving system.

2 List of Manuscripts Submitted or Published

1. R. R. Kadiyala, "CAD Tools for Nonlinear Control," Proceedings of the IEEE Conference on Computer Aided Design, Napa, April 1992.

2. R. R. Kadiyala, "Sys_View: A Visualization Tool for viewing the regions of validity and attraction of nonlinear systems," ERL Memo No. M 92/21, March 1992.

3. A. Teel, "Global Stabilization and Restricted Tracking for Multiple Integrators with Bounded Controls," *Systems and Control Letters*, Vol. 18, 1992, No. 3, pp. 165-171.

4. A. Teel, "Error Based Adaptive Nonlinear control and regions of feasibility," *International Journal of Adaptive Control and Signal Processing*, Vol. 6. No. 4, 1992, pp. 319-327.

5. A. Teel, "Using Saturation to Stabilize a class of partially linear composite systems," Proceedings of the IFAC conference on Nonlinear Control Systems Design (NOLCOS), pp. 224-229.

6. G. Burgio, M. Di Benedetto and S. Sastry, "Adaptive Linearization by dynamic state feedback: a case study," Proceedings of the IFAC conference on Nonlinear Control Systems Design (NOLCOS), pp. 594-600.

7. R. Kadiyala, "Indirect Adaptive Control of Induction Motors," Proceedings of the IFAC conference on Nonlinear Control Systems Design (NOLCOS), 1991. pp. 144-150.

8. A. Teel, "Semi-global stabilization of minimum phase nonlinear systems in special normal forms," *Systems and Control Letters*, Vol. 19, N0. 3, pp. 187-192.

9. A. Teel, R. Murray and G. Walsh, "Nonholonomic Control Systems: from Steering to stabilization with sinusoids," *International Journal of Control*, Vol. 62, No. 4., 1995, pp. 849-870.

10. R. Kadiyala, "AP_LIN: a tool box for approximate linearization of nonlinear systems," IEEE Control Systems Magazine, 1993, also ERL Memo M 92/22.

11. M. Cohn, L. Crawford, J. Wendlandt and S. Sastry, "Surgical Applications of Milli-robots", *Journal of Robotic Systems*, Vol. 12, No. 6, 1995, pp. 401-416.

12. S. Sastry, M. Cohn and F. Tendick, "Millirobotics for Minimally Invasive telesurgery," *Journal of Robotics and Autonomous Systems*, Vol. 21, 1997, pp. 305-316.

13. S. Burgett, R. Bush, S. Sastry and C. Sequin, " Mechanical Design Synthesis for Sparse, Feature Based Input," *SPIE Workshop on Smart Structures*, San Diego, 1995, Vol. 2442, pp. 280-291.

14. S. Burgett, R. Bush, S. Sastry and C. Sequin, "Shape Synthesis from Sparse feature based input," Proceedings of the ASME Winter Annual Meeting, San Francisco, CA, November 1995.

15. S. Burgett, " Shape synthesis for assembly-centric design", doctoral dissertation, University of California, Berkeley CA 94720.

16. D. Godbole and S. Sastry, "Approximate Decoupling and Asymptotic trakcing for MIMO systems", *IEEE Transactions on Automatic Control*, Vol. AC-40, NO.3, March 1995, pp. 441-450.

17. L. Bushnell, D. Tilbury and S. Sastry, "Steering Three Input Nonholonomic Systems — the Firetruck Example," *International Journal of Robotics Research*, Vol. 14, No. 4, pp. 366-381, August 1995.

18. G. Walsh and S. Sastry, "On reorienting linked rigid bodies using internal motions", *IEEE Transactions on Robotics and Automation*, Vol. 11, 1995, pp. 139-146.

19. D. Tilbury and S. Sastry, "The Multisteering N-trailer system – a Case Study of Goursat Normal forms and Prolongations," *International Journal of Robust and Nonlinear Control*, Vol. 5, No. 4, pp. 343-364, July 1995.

20. L. Crawford and S. Sastry, "Biological Motor Control Approaches for a Planar Diver", *Proceedings of the IEEE International Conference on Decision and Control*, New Orleans, LA, December 1995.

21. L. Crawford and S. Sastry, "Learning Controllers for Complex Behavioral Systems," ERL Memo No. M 96/73, December 1996, in *Proceedings of the Neural Information Processing Conference*, Boulder, Co., Dec. 1996.

3 Scientific Personnel and Degrees awarded

1. R. Kadiyala — Research Assistant.
2. A. Teel — Research Assistant.
3. A. K. Pradeep — Research Assistant.
4. S. Burgett — Research Assistant.
5. L. Crawford — Research Assistant.
6. C. Coleman — Research Assistant.
7. L. Bushnell — Research Assistant.
8. S. Burgett — Research Assistant.
9. Prof. S. S. Sastry