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CONTRACT/GRANT NUMBER: DAAD 19-99-1-0137

REPORT TITLE: Neural Network Control of DoD and Industrial Motion Systems

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SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Frank L. Lewis

Enclosure 3
**REPORT DOCUMENTATION PAGE**

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<td>The University of Texas at Arlington</td>
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**SUPPLEMENTARY NOTES**

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

**ABSTRACT (Maximum 200 words)**

Actuator deadzones, backlash, and saturation impose severe performance limitations in industrial and DoD systems. Modern Battle Information Systems need improved dynamic decision-making control systems to avoid NP-complexity problems and properly assign resources. The goals of this grant were to develop neural network (NN) compensators for industrial actuator nonlinearities, to develop high-level NN architectures for control, to implement NN controllers on actual devices, and to design and implement discrete event decision controllers. A family of NN and fuzzy logic (FL) controllers was developed for deadzones and backlash. Rigorous analytical techniques were given for design of NN controllers for actuator compensation that guarantee stability. High-level NN adaptive critic controllers were designed. Intelligent controllers were implemented on industrial testbeds. We designed a remote site control system allowing monitoring and control of systems over the internet. A supervisory controller was designed based on matrices that allows for fast changing of goals and priorities. Matching funding has allowed us to work with small companies and transfer the ARO technology to them. Three patents were awarded. Two books were published and numerous journal papers. Numerous students graduated and received many awards.

**SUBJECT TERMS**

- DoD and industrial control systems
- Robot workcell control
- Neural network and fuzzy logic control
- Discrete event control

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"Neural Network Control of DoD and Industrial Motion Systems"

PI:  F. L. Lewis  
Prepared:  Saturday, March 01, 2003

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Statement of Problem Studied

Today's industrial and DoD motion systems are increasingly complex and yet have tighter performance specifications. Tanks must point their gun barrels quickly with no residual vibration, off-road vehicles must travel over rugged terrain at speeds of 60 mph with low rms vibration and power transferred to the load, precision positioning tables for VLSI manufacturing must move quickly to precise locations. Limitations to all these objectives are set by vibratory modes, system delays, and actuator deadzones, backlash, friction, and saturation.

Such systems are characterized by complex nonlinear dynamics and actuators with deadzones, backlash, and saturation. The control problems associated with such systems are not easy, as they do not satisfy most of the assumptions made in the controls literature. Therefore, most existing control algorithms do not work well. New classes of nonlinear feedback control systems are needed.

Modern battlespace systems require increased speed and dynamical responsiveness, novel deployable sensor systems, greater information for Military Leaders and JFACC, and faster information assimilation connections for warfighters and weapons platforms. This requires intelligent, dynamically reconfigurable high-level control systems for decision-making and supervision. New information protocols and control architectures are needed for decision-making control systems.

The goals of this grant are to:

- develop neural network (NN) compensators for industrial actuator nonlinearities
- develop high-level NN architectures for control
- implement NN controllers on actual devices
- develop and implement rule-based discrete event (DE) supervisory controllers.

Summary of Results

Intelligent Control of DoD and Industrial Motion Systems

Under this ARO funding, a new family of neural net (NN) controllers was designed for compensation of nonlinearities in industrial and DoD system actuators. The key feature of these controllers is that the NN appears in the feedforward loop, whereas other NN controllers whose stability has been guaranteed have generally used NN in the feedback loop. This presents a problem for application of rigorous stability proof techniques.

Deadzone Control. The key to overcoming the difficulty for the case of deadzone was found to be using two NN, one of which acts as a sort of observer that evaluates the performance of the action generating NN. The topology of this controller is shown in the figure.
Backlash Control. In the case of backlash, we developed a NN controller based on dynamic inversion, which has popularly been used for aircraft control. Rigorous proofs of stability were used to derive tuning laws and a topology that guarantees closed-loop system performance. The controller is shown in the figure. A patent was applied for this work.

Discrete-Time Backlash Control. Since actual controllers are implemented on digital computers, discrete-time algorithms for deadzone and backlash NN control were also developed. Providing rigorous stability proofs for discrete-time systems is very difficult, since the Lyapunov function derivative is quadratic in the first difference. We base our proofs on a single Lyapunov function that weights the estimation error, the tracking error, and the NN weight estimation error.
These proofs are extremely complex and may require completion of the squares on three or more separate occasions. A patent was filed on this discrete-time approach for backlash control. The discrete-time backlash controller is shown in the figure. The NN controller significantly improves the motion speed and precision, effectively compensating for the backlash. It is based on a discrete-time version of dynamic inversion.

Discrete-time neural network backlash controller

Adaptive Critic Controller Using Fuzzy Supervision of Neural Network. Most neurocontroller designs have relied on the function approximation property of NN. It would be desirable to use more advanced learning and intelligent features of NN in controls design. A particularly intriguing higher-level topology is the adaptive critic, which emulates some decision-making and evaluation abilities of the human. Adaptive Critics hold promise of...
applications in high-level decision systems such as battlefield management. In the usual adaptive critic architecture there are two neural networks (NN), one of which (the critic) evaluates system performance and tunes the other (the action generating network), which in turn provides the control input signal for the system being controlled.

The effectiveness of fuzzy logic (FL) systems in classification, discrimination, and decision-making is well documented. This makes fuzzy logic systems a natural candidate for higher-level control components such as the adaptive critic evaluator. Therefore, we designed an adaptive critic controller with a FL critic and a NN action generating network.

It was shown that a large class of nonlinear systems can be supervised by the adaptive critic control system shown in the figure. This system does not require knowledge of the system dynamics or disturbances. Both the fuzzy critic and the NN controller are tuned in such a way that the system has guaranteed stability and guaranteed robust tracking of user-input command trajectories. The fuzzy logic critic signal is of the form

\[ R = \hat{W}_1^T \cdot \mu(V_1^T r) + \rho, \]

where \( \mu(.) \) are the membership functions, and the MF offsets and spreads \( \hat{V}_1 \) as well as the control representative values \( \hat{W}_1 \) are tuned on-line using modified backpropagation tuning with an e-mod term. It is shown that \( \rho \) is a dynamic term, that is, the critic requires a memory as shown in the figure by the integrator.

In this hierarchical controller design, the FL critic plays the role of a long term memory and the NN action generator plays the role of a short term memory. This is clearly seen in the proof where it comes out that the FL system must be tuned more slowly than the NN.

**Control of Teleoperated Systems with Time Delay.** A NN controller was developed for a class of telerobotic systems with constant time delays caused by a communications channel. The control structure is essentially a Smith predictor extended to the nonlinear case by using a NN control inner loop at the slave station. Stability is guaranteed for any value of system delay. See the figure.
Implementation of Intelligent Controllers

We implemented a backstepping NN controller on the coupled motor drive system shown in the figure. This flexible joint system appears in DoD motion and vehicle drive train systems and in industrial motors and machine tools. It has dual dynamics to the tank gun barrel studied in an SBIR contract, and similar techniques can be used to design an intelligent controller.

In the coupled motor drives system, neither the motor dynamics nor the flexible belt coupling characteristics are known. An intelligent controller is needed to learn the unknown dynamics, system parameters, and disturbances and to adapt as these change. Using a specialized energy function, we used modified Lyapunov techniques to derive the intelligent controller shown in the figure. There are three NN used in this backstepping controller, one to learn the load dynamics, one to learn the coupling dynamics, and one to learn the drive dynamics. The NN are indicated as the ‘fictitious controllers’ and the ‘controller’. Each NN has the form

\[ \hat{F}_i = \hat{W}_i^T \Phi_i \]

with \( \hat{W}_i \) the NN weights and \( \Phi_i \) the activation functions. The weights are tuned according to

\[ \dot{\hat{W}}_i = \Gamma \Phi_i \xi^T - m \Gamma \|z\| \hat{W}_i \]

with parameters defined in the papers. This is an adaptive law for nonlinearly parametrized systems using a form of \( \sigma \)-modification. Our approach shows in a rigorous mathematical fashion that these tuning laws provide both stability and guaranteed robust performance.
**Internet-Based Control.** Under SBIR and ARO funding, we have built a remote site monitoring and control system that uses the internet. We have controlled our lab equipment at UTA remotely from Europe and elsewhere. We are not talking about the usual java-based systems that allow the user to adjust a few control parameters. Using our system one can fully configure and even rewrite the controller from a remote location. The NN and FL controllers designed under this ARO sponsorship can be fully implemented over the internet. The GUI shown allows the user to change the controller and view the remote system on a camera. It displays any selected signals from the controlled remote system.

**Discrete Event (DE) Supervisory Controllers**

The receipt of an ARO DURIP grant:

U.S. Army Research Office Grant DAAD19-00-1-0037, "Supervisory and Motion Control for DoD and Industrial Dynamical Systems," PI, equipment grant for $75,000, March 2000.

allowed us to add a new thrust to this ARO work in Discrete Event (DE) System Control.

DE systems are decision-making systems that include DoD battlefield systems with numerous battle platforms, fighters, sensors, and decision-making levels; or manufacturing workcells with several machines, robot manipulators, conveyors, and numerous sensors. Complex DE systems can be difficult to schedule. Improper assignment of shared resources (e.g. radars, gun platforms, machines, or robots) can result in blocking phenomena or in a situation known as deadlock, where further activity is stopped until human invasive intervention sorts out the impasse.

In DE systems, there may be problems of complexity, since certain types of DE systems are known to be NP-hard. We have shown (journal paper [11]) that proper selection of communications protocols and information flow structures yields a structure that is polynomial, allowing for improved computing speed with the appropriate assignment of computing resources.

We developed a new formulation of DE supervisors that is based on matrices. A patent was received for this new design. The matrix formulation allows fast design of DE supervisors based on computer science planning techniques. It is also possible to use the manufacturing Bill of Materials (BOM) or assembly trees to generate the DE supervisory control matrices.

The DE supervisory control structure is shown in the figure, which also contains the equations. These equations are performed over a nonstandard logical algebra where matrix multiplies signify logical ‘and’ operations, and matrix additions signify logical ‘or’ operations. In the figure we have depicted a multi-resource manufacturing workcell, though an identical structure holds for a multi-agent battlefield situation.

Note that the DE controller functions exactly as a standard feedback controller, though over a nonstandard algebra. It senses the status of the workcell in terms of jobs complete and resources idle. It performs computations to determine which jobs to initiate next, and which resources are next to be set idle.

A key feature of our approach is the specific presence of a Conflict Resolution Input which is computed on a higher level. This CR input is selected according to performance
objectives assigned by management, including target priority, maximum job throughput, maximum resource utilization, fulfillment of due dates, etc. It must also be selected to avoid deadlock and blocking. This CR input effectively allows for on-line real-time optimization of logical decision-making systems.

We are going to examine the ramifications of this for generating battlefield information flow controllers.

**Implementation of DE Controller on Actual Workcell.** We implemented the DE controller on an actual manufacturing workcell consisting of three robots, three conveyors, and several simulated machines. We have programmed the robots via RS 232 ports to allow simultaneous coordination and control of all three from one computer using LabVIEW. We are currently implementing our matrix-based DE supervisory controller to allow fast programming of the workcell by setting up the requisite matrices in LabVIEW.

A major challenge lies in determining the appropriate selection of sensors to provide the correct information to the DE supervisor. We are discussing now the notion of a virtual sensor that is composed of a group of individual sensors. Techniques of sensor fusion may be necessary.

**Technology Transfer**

Three patents have been received for this ARO work, and two more patents were applied for on ARO work on backlash compensation. Two books were published based on the ARO work. One text is is based on the PhD thesis research of R. Selmic and J. Campos. The second book is an edited volume on intelligent control of industrial systems.

Several SBIR contracts were active during the period of this grant.


This matching money allowed the ARO technology to be transferred to these small companies. The fuzzy logic controller shown in the figure was designed for force control of a vehicle active suspension system.

Also active were two industry contracts:


These allowed our intelligent control technology to be transferred to major local companies.

**List of Publications**

Copies of publications are forwarded under separate cover through standard channels.
Books

Book Chapters

Journal Special Issues

Journal Papers


**Refereed and Published Conference Papers**


Scientific Personnel Supported During the Grant and Awards

PhD Students
1. R. Selmic, Neurocontrol of Industrial Motion Systems with Actuator Nonlinearities, May 2000.
   
   This research won the UTA ARRI Best Paper Award in 1997 and the IEEE Ft. Worth Section Graduate Student Paper First Place Award in 1999.

   
   This research won the UTA ARRI Best Paper Award in 1998 and the IEEE Ft. Worth Section Graduate Student Paper Second Place Award in 1999. Campos won the “Outstanding UTA International Student Award,” 2000.


   
   Mireles won the Best Presentation Award at the UTA Graduate Research Symposium in 2000, and the ARRI Student Paper Award in 2002.

6. O. Kuljaca, PhD, High-Level Neural Network and Fuzzy Logic Control, completed in May 2003.

Masters Students

   
   This thesis won the UTA ARRI Best Paper Award in 2002.
Matching Funding Received
1. UTA Centennial Funds Grant, "Equipment for Web-Based Virtual Controls Teaching Lab," PI, 1 year grant for $50,000.

F. Lewis Awards
The following awards resulted from the ARO work at least in part.
2. ARRI Sponsored Research Award, 1999.
3. UTA University-Wide Outstanding Research Achievement Award, March 2000.
6. Selected as Distinguished Speaker, 10th Anniversary Ceremony of Engineering Faculty, Chinese University of Hong Kong, Nov. 2001.

Inventions
Patents

Patents Applied For