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

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Frank L. Lewis

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13. 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.

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ARO Grant DAAD19-99-1-0137
"Neural Network Control of DoD and Industrial Motion Systems"

PI: F. L. Lewis

Prepared: Saturday, March 01, 2003

Table of Contents

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:

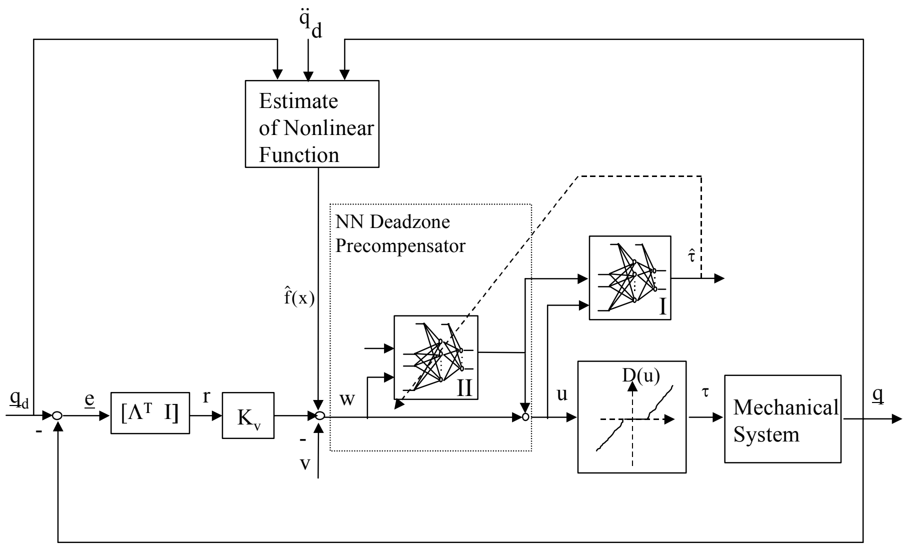
- develop neural network (NN) compensators for industrial actuator nonlinearities
- develop high-level NN architectures for control
- implement NN controllers on actual devices
- develop and implement rule-based discrete event (DE) supervisory controllers.

Summary of Results

Intelligent Control of DoD and Industrial Motion Systems

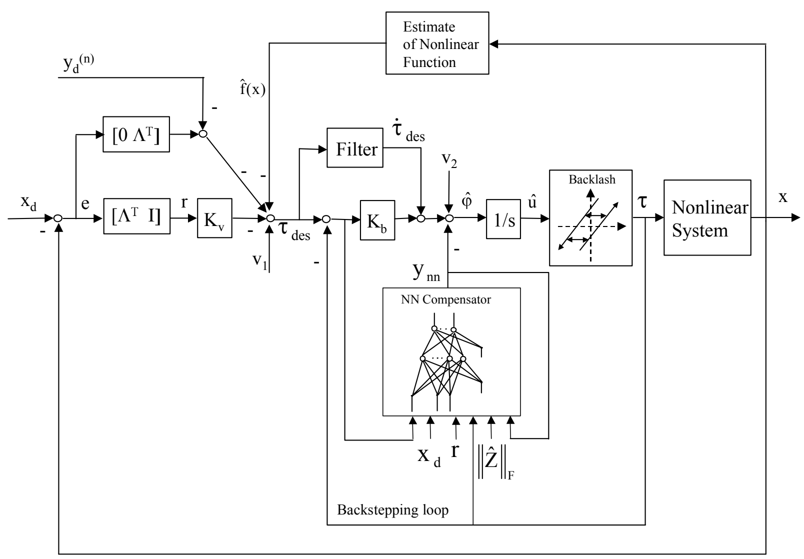
Under this ARO funding, a new family of neural net (NN) controllers was designed for compensation of nonlinearities in industrial and DoD system actuators. The key feature of these controllers is that the NN appears in the *feedforward loop*, whereas other NN controllers whose stability has been guaranteed 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.



Tracking controller with NN Deadzone Compensation

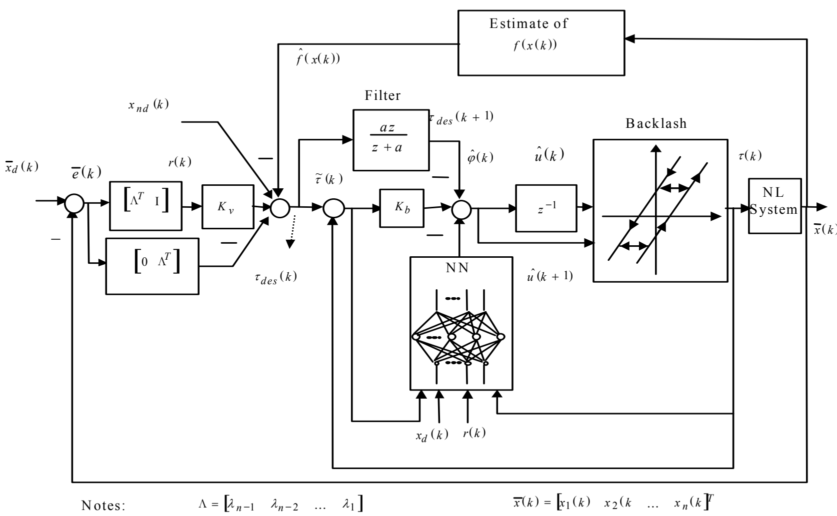
Backlash Control. In the case of backlash, we developed a NN controller based on *dynamic inversion,* which has popularly been used for aircraft control. Rigorous proofs of stability were used to derive tuning laws and a topology that guarantees closed-loop system performance. The controller is shown in the figure. A patent was applied for this work.



Tracking controller with NN backlash compensation

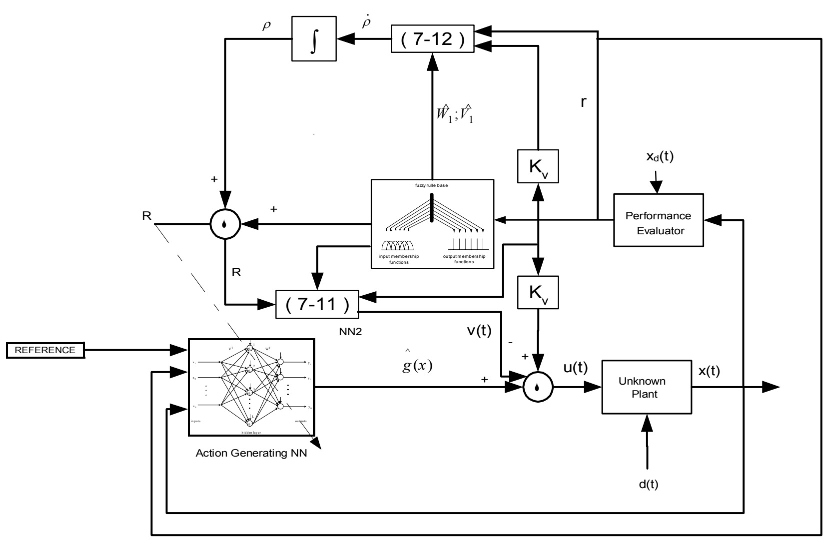
Discrete-Time Backlash Control. Since actual controllers are implemented on digital computers, discrete-time algorithms for deadzone and backlash NN control were also developed. Providing rigorous stability proofs for discrete-time systems is very difficult, since the Lyapunov function derivative is 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



Adaptive Critic Controller with Fuzzy critic and Neural Network action generator 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.

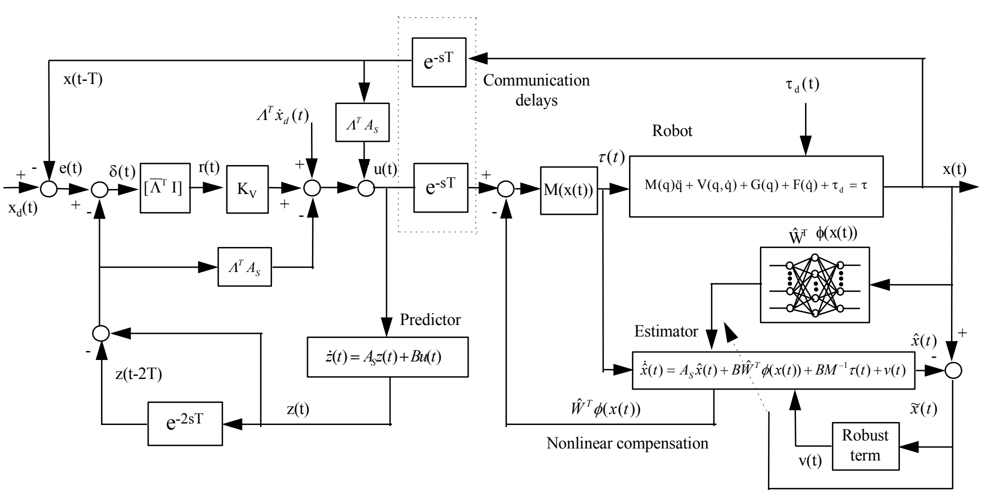
It was shown that a large class of nonlinear systems can be supervised by the adaptive critic control system shown in the figure. This system does not require knowledge of the system dynamics or disturbances. Both the fuzzy critic and the NN controller are tuned in such a way that the system has guaranteed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

$$R = \hat{W}_1^T \cdot \mu(\hat{V}_1^T r) + \rho,$$

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 ρ 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.

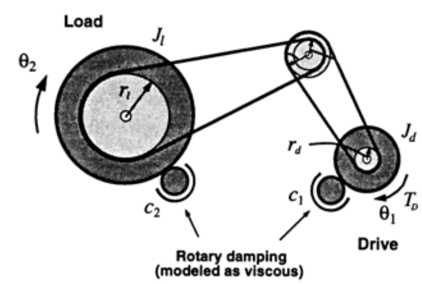


NN time delay compensator for telerobotic system

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



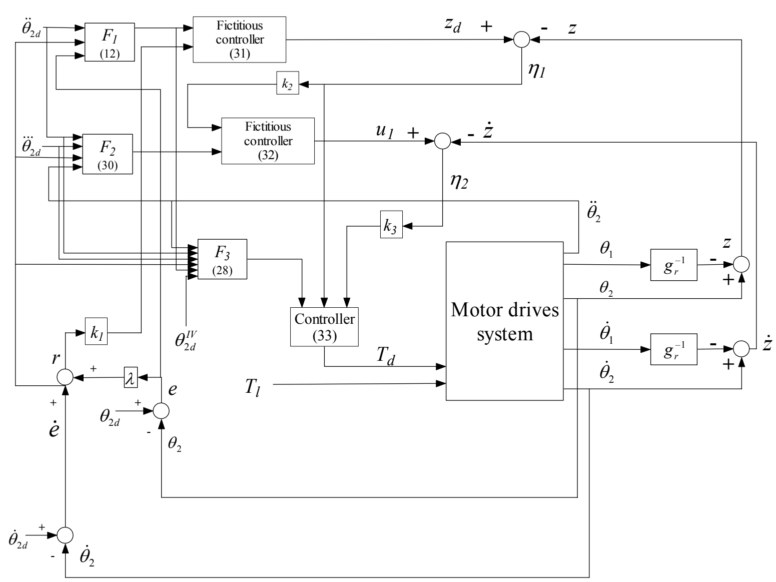
Coupled Motor Drives System

$$\hat{F}_1 = \hat{W}_1^T \Phi_1$$

with $\hat{W}_1$ the NN weights and Φ_1 the activation functions. The weights are tuned according to

$$\dot{\hat{W}}_1 = \Gamma \Phi \xi^T - m\Gamma \|\xi\| \hat{W}_1$$

with parameters defined in the papers. This is an adaptive law for nonlinearly parametrized systems using a form of σ-modification. Our approach shows in a rigorous mathematical fashion that these tuning laws provide both stability and guaranteed robust performance.



Backstepping Controller with three neural networks.

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.

Fig. 19 GUI for UTA Internet-Based Remote Site Control 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.

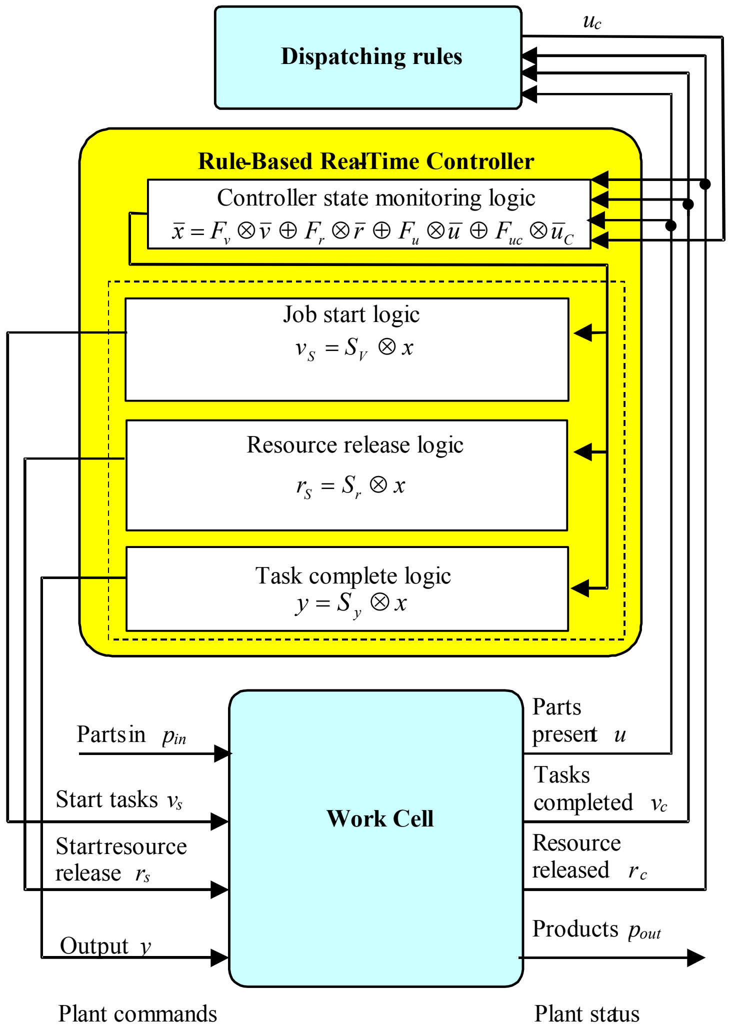
The DE supervisory control structure is shown in the figure, which also contains the equations. These equations are performed over a nonstandard logical algebra where matrix multiplies signify logical ‘and’ operations, and matrix additions signify logical ‘or’ operations. In the figure we have depicted 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.



Discrete Event Supervisory Controller based on matrices

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.

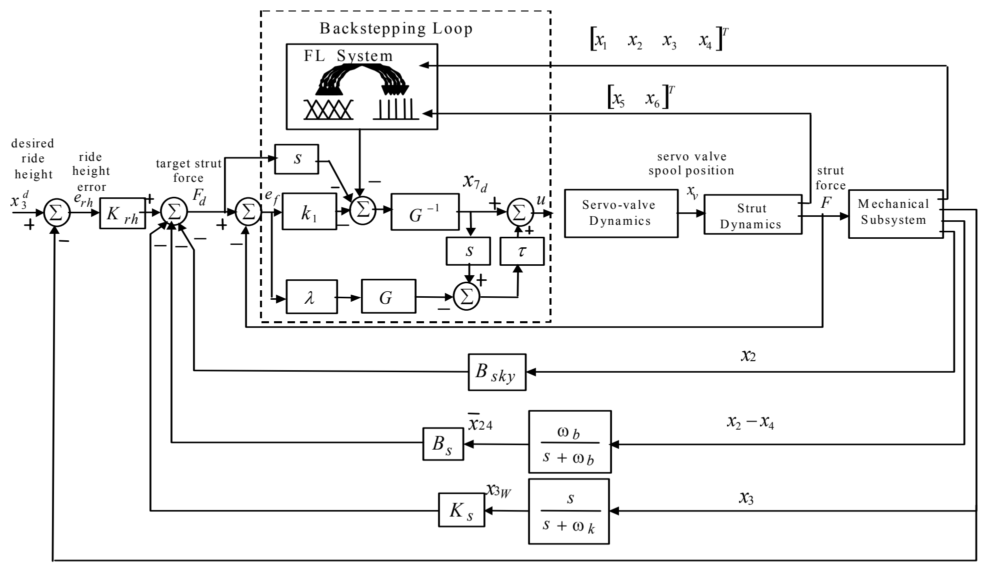
Technology Transfer

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

1. U.S. Army ARO Small Business Innovation Research (SBIR) Contract, Phase 11: "Nonlinear/Fuzzy Logic Control for Scout Active Suspension and Steering," with Davis Technologies Int., 12 mo. subcontract for $34,000.
2. U.S. Navy ONR Small Business Innovation Research (SBIR) Contract, Phase 1: "Neural Network Control of Nonlinear Systems Using Multiple Models," with Intelligent Automation, Inc., 6 mo. contract for $22,998.
3. NASA Small Business Innovation Research (SBIR) Contract, Phase I: "MEMS Wire Testing for Aging Aircraft," Williams Pyro, Inc., 6 mo. contract for $14,500, Jan. 2002.

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.



Backstepping fuzzy logic controller for the quarter-vehicle suspension system

Also active were two industry contracts:

1. Bell Helicopter, “Laser-Assisted Automated Machine Tool Verification System,” contract for $128,000, 1999-2000.
2. Andrew Corp, " Satellite Tracking Antenna Controller Design," contract for $65,700, Apr. 2000.

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

1. F.L. Lewis, S. Jagannathan, and A. Yesildirek, *Neural Network Control of Robot Manipulators and Nonlinear Systems,* Taylor and Francis, London, 1999.
2. G. Tao and F.L. Lewis editors, *Adaptive Control of Nonsmooth Dynamic Systems*, Springer-Verlag, London, 2001.
3. F.L. Lewis, J. Campos, and R. Selmic, *Neuro-Fuzzy Control of Industrial Systems with Actuator Nonlinearities*, Society of Industrial and Applied Mathematics Press, Philadelphia, 2002.

Book Chapters

1. R.R. Selmic and F.L. Lewis, "Neural Network Approximation of Piecewise Continuous Functions: Application to Friction Compensation," in Soft Computing and Intelligent Control Systems: Theory and Applications, Chap. 20, pp. 491-517, ed. N.K. Sinha and M.M. Gupta, Academic Press, London, 2000.
2. R.R. Selmic and F.L. Lewis, "Deadzone Compensation in Motion Control Systems Using Augmented Multilayer Neural Networks," in *Adaptive Control of Nonsmooth Dynamic Systems*, ed. G. Tao and F.L. Lewis, Springer-Verlag, Berlin, 2001.
3. J. Campos and F.L. Lewis, "Neural Control Systems," Encyclopedia of Life Support Systems, ed. H. Unbehauen, chapter 6.43.24, Eolss Publishers, to appear 2002.

Journal Special Issues

1. K.S. Narendra and F.L. Lewis ed., "Special Issue on Neural Network Feedback Control, Automatica, Aug. 2001.

Journal Papers

1. R. Selmic and F.L. Lewis, "Neural Network Approximation of Piecewise Continuous Functions: Application to Friction Compensation," in Soft Computing and Intelligent Control Systems: Theory and Applications, Chap. 20, pp. 491-517, ed. S. Tzafestas, 1999.
2. 2. Y. Kim and F.L. Lewis, "Neural network output feedback control of robot manipulators, "IEEE Trans. Robotics and Automation, vol. 4, pp. 301-309, Apr. 1999.
3. C. Kwan, A, Yesildirek, and F.L. Lewis, "Robust force/motion control of constrained robotsusing neural networks," J. Robotic Systems, vol. 16, no. 12, pp. 697-714, Dec. 1999.
4. Y. Kim and F.L. Lewis, "Reinforcement adaptive learning neural network based friction compensator for high speed and precision," IEEE Trans. Control Systems technology, vol. 8, no. 1, pp. 118-126, Jan. 2000.
5. R. Selmic and F.L. Lewis, "Deadzone compensation in motion control systems using neural networks," IEEE Trans. Automatic Control, vol. 45, no. 4, pp. 602-613, Apr. 2000.
6. Y. Kim and F.L. Lewis, "Optimal design of CMAC neural network controller for Robot Manipulators," IEEE Trans. Systems, Man, and Cybernetics, vol. 30, no. 1, pp. 22-31, Feb 2000.
7. R. Selmic and F.L. Lewis, "Backlash compensation in nonlinear systems using dynamic inversion by neural networks," Asian J. Control, vol. 2, no. 2, pp. 76-87, June 2000.

8. Y. Kim and F.L. Lewis, "Intelligent optimal control of robotic manipulators using neural networks," Automatica, vol. 36, no. 9, pp. 1355-1364, Sept. 2000.
9. J.-Q. Huang, F.L. Lewis, and K. Liu, "A neural net predictive control for telerobots with time delay," J. Intelligent and Robotic Systems, vol. 29, pp. 1-25, Jan. 2000.
10. C. Kwan and F.L. Lewis, "Robust backstepping control of induction motors using neural networks, IEEE Trans. Neural Networks, vol. 11, no. 5, pp. 1178-1187, Sept. 2000.
11. C. Kwan and F.L. Lewis, "Robust backstepping control of nonlinear systems using neural networks, IEEE Trans. Systems, Man, Cybernetics, to appear.
12. S. Jagannathan, M.W. Vandegrift, and F.L. Lewis, "Adaptive fuzzy logic control of discrete-time dynamical systems," Automatica, vol. 36, no. 2, pp. 229-241, Feb. 2000.
13. A. Gurel, S. Bogdan, and F.L. Lewis, "Matrix approach to deadlock-free dispatching in multi-class finite buffer flowlines," IEEE Trans. Automatic Control, vol. 45, no. 11, pp. 2086-2090, Nov. 2000.
14. F.L. Lewis, B.G. Horne, and C.T. Abdallah, "Computational complexity of determining resource loops in reentrant flow lines," IEEE Trans. Systems, Man, and Cybernetics, vol. 30, no. 2, pp. 222-229, 2000.
15. B. Harris, D. Cook, and F.L. Lewis, "Automatically generating plans for manufacturing," J. Intelligent Systems, vol. 10, no. 3, pp. 279-319, 2000.
16. Yesildirek and F.L. Lewis, "Adaptive feedback linearization using efficient neural networks," Journal of Intelligent & Robotic Systems, vol. 31, pp. 253-281, 2001.
17. Kwan, D.M. Dawson, and F.L. Lewis, "Robust adaptive control of robots using neural network: global stability," Asian J. Control, vol. 3, no. 2, pp. 111-121, June 2001.
18. R.R. Selmic and F.L. Lewis, "Neural net backlash compensation with Hebbian tuning using dynamic inversion," Automatica, vol. 37, no. 8, pp. 1269-1277, Aug. 2001.
19. R.R. Selmic and F.L. Lewis, "Neural network approximation of piecewise continuous functions: application to friction compensation," IEEE Trans. Neural Networks, pp. 745-751, vol. 13, no. 3, May 2002.

Refereed and Published Conference Papers

1. J. Campos and F.L. Lewis, "Deadzone compensation in discrete time using adaptive fuzzy logic control," IEEE Trans. Fuzzy Systems, vol. 7, no. 6, pp. 697-307, Dec. 1999.
2. J. Campos and F.L. Lewis, "Adaptive critic neural network for feedforward compensation, "Proc. American Control Conf., pp. 2813-2818, San Diego, June 1999.
3. J. Ezzine and F.L. Lewis, "Disturbance accommodating neurocontrol," Proc. IFAC World Congress, pp. 367-372, Beijing, June 1999.
4. R.R. Selmic and F.L. Lewis, "Backlash compensation in nonlinear systems using dynamic inversion by neural networks," Proc. IEEE Int. Conf. Control Applications, pp. 1163-1168,Hawaii, Aug. 1999.
5. F.L. Lewis, J. Campos, and R. Selmic, "On adaptive critic architectures in feedback control, "Proc. IEEE Conf. Decision and Control, pp. 1677-1684, Phoenix, Dec. 1999.

6. J. Campos and F.L. Lewis, "Deadzone compensation in discrete time using adaptive fuzzy logic," Proc. IEEE Conf. Decision and Control, pp. 2920-2926, Tampa, Dec. 1998.
7. J. Campos, L. Davis, F.L. Lewis, S. Ikenaga, S. Scully, and M. Evans, "Active suspension
8. control of ground vehicle heave and pitch motions," Proc. IEEE Mediterranean Conf. Control and Automation, pp. 222-233, Haifa, June 1999.
9. S. lkenaga, F.L. Lewis, L. Davis, J. Campos, M. Evans, and S. Scully, "Active suspension control using a novel strut and active filtered feedback," Proc. IEEE Conf. Control Applics., pp. 1502-1508, Hawaii, Aug. 1999.
10. S. Ikenaga, F.L. Lewis, J. Campos, and L. Davis, "Active suspension control of ground vehicle based on full-vehicle model," 70th Shock and Vibration Symposium, Albuquerque, Nov. 1999.
11. J. Campos, F.L. Lewis, and R. Selmic "Backlash compensation in discrete time nonlinear systems using dynamic inversion by neural networks," Proc. IEEE Int. Conf. on Robotics and Automation, pp. 1289-1295, San Francisco, CA, April 2000.
12. J. Campos, R. Selmic, and F.L. Lewis, "Backlash compensation in nonlinear systems by dynamic inversion using neural networks," Proc. IASTED Int. Conf. Control and Appl., pp. 223-229, Cancun, May 2000.
13. R.R. Selmic and F.L. Lewis, "Neural net backlash compensation with Hebbian tuning by dynamic inversion," Proc IEEE Conf. Decision and Control, Sydney, paper WeA12-1, Dec. 2000.
14. J. Campos and F.L. Lewis, "Backlash compensation with filtered prediction in discrete time nonlinear systems by dynamic inversion using neural networks," Proc IEEE Conf. Decision and Control, Sydney, paper ThM12-2, Dec. 2000.
15. J. Campos, F.L. Lewis, L. Davis, and S. Ikenaga, "Backstepping based fuzzy logic control of active vehicle suspension systems," Proc. American Control Conf., pp. 4030-4035, Chicago, June 2000.
16. S. Ikenaga, F.L. Lewis, J. Campos, and L. Davis, "Active suspension control of ground vehicle based on full-vehicle model," Proc. American Control Conf., pp. 4019-4024, Chicago, June 2000.
17. S. Ikenaga, F.L. Lewis, J. Campos, and L. Davis, "Active suspension control of ground vehicle based on full-vehicle model," Proc. American Control Conf. Chicago, June 2000.
18. B. Borovic, O. Kuljaca, and F.L. Lewis, "Neural net underwater vehicle dynamic positioning control," Proc. Med. Conf. Control and Automation, paper MED01-066, Dubrovink, June 2001.
19. G. Galan, S. Jagannathan, and F.L. Lewis, "A one-layer neural network controller with input preprocessing for autonomous underwater vehicles," Proc. IFAC Symposium on System Structure and Control, paper 119, Prague, Aug. 2001.
20. Y.H. Kim and F.L. Lewis, "Reinforcement adaptive fuzzy control for a class of nonlinear uncertain systems," Proc. IFAC Conf. New Technol. Comp. Control, Hong Kong, Nov, 2001.

21. R.R. Selmic, and F.L. Lewis, "Multimodel neural networks identification and failure detection of nonlinear systems," Proc. IEEE Conf. Decision and Control, pp. 3128-3133, Orlando, Dec. 2001.

22. O. Kuljaca, N. Swamy, F.L. Lewis, and C. M. Kwan, "Design and implementation of industrial neural network controller using backstepping," Proc. IEEE Conf. Decision and Control, pp. 2709-2714, Orlando, Dec. 2001.

23. Y.H. Kim, F.L. Lewis, and C. Kwan, "Reinforcement adaptive fuzzy control for a class of nonlinear dynamical systems," Proc. IFAC Conf. New Technol. for Computer Control, Hong Kong, Nov. 2001.

24. J. Mireles and F.L. Lewis, "Matrix constructions for implementation of a deadlock avoidance in discrete event supervisors," Proc. Int. Symposium on Robotics And Automation, Toluca, Mexico, Sept. 2002.

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.

2. J. Campos, Intelligent Control of Complex Mechanical Systems, May 2000.

   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.

3. S. Ikenaga, Real Time Digital Controller for Active Suspension Control of Ground Vehicles, May 2000.

4. B. Harris, Improving the Efficiency and Applicability of Machine Planning: Applications in Manufacturing Scheduling and Routing, May 2002. Co-advised with Prof. Diane Cook, CSE Dept.

5. J. Mireles, *Matrix-Based Intelligent Discrete Event Control for Flexible Manufacturing Systems*, August 2002.

   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

1. Murad Abu-Khalaf, "Intelligent Tracking of Geostationary Satellite Systems," Master's Thesis, Sept. 2000.

2. Chanitnan Khanthapanit, "Internet Based Control," Master's Thesis, May 2002.

   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.
2. UTA LERR Laboratory Equipment Funds, “Lab Equipment for Capstone Design Course in Control Engineering,” $35,000, June-Aug. 2001.

F. Lewis Awards

The following awards resulted from the ARO work at least in part.

1. Ft. Worth Business Press, Who's Who in Manufacturing, Top 200 Leaders, 1999- pres.
2. ARRI Sponsored Research Award, 1999.
3. UTA University-Wide Outstanding Research Achievement Award, March 2000.
4. ARRI Patent Award, 2000.
5. Elected to the New York Academy of Sciences, June 2000.
6. Selected as Distinguished Speaker, 10^{th} Anniversary Ceremony of Engineering Faculty, Chinese University of Hong Kong, Nov. 2001.
7. Finalist, STARTech Dallas Business Plan Competition, March 2002.

Inventions

Patents

1. A. Yesildirek and F.L. Lewis, "Method for feedback linearization of neural networks and neural network incorporating same," U.S. Patent 5,943,660, Patent Awarded 24 August 1999. (For work during writing of the ARO proposal)
2. S. Jagannathan and F.L. Lewis, "Discrete-time tuning of neural network controllers for nonlinear dynamical systems," U.S. Patent 6,064,997, Patent Awarded 16 May 2000.
3. F.L. Lewis, D.A. Tacconi, Ayla Gurel, and O.C. Pastravanu, "Method and Apparatus for Testing and Controlling a Flexible Manufacturing System," U.S. Patent 6,185,469, awarded 6 Feb. 2001.

Patents Applied For

1. R.R. Selmic and F.L. Lewis, "Backlash Compensation Using Neural Networks," Patent applied for, SN 09/553,601, The Univ. Texas at Arlington, Mar 2000.
2. J. Campos and F.L. Lewis, "Method for Backlash Compensation Using Discrete-Time Neural Networks," disclosure of invention, The Univ. Texas at Arlington, Jun 2000.