Publication list of Danil V. Prokhorov

Total 68 publications including 11 journal papers, 45 conference papers, 9 book chapters and technical reports, and 3 patents.

1. D. Prokhorov, "Backpropagation Through Time and Derivative Adaptive Critics: A Common Framework for Comparison," in J. Si, A. Barto, W. Powell, and D. Wunsch (Eds.), *Learning and Approximate Dynamic Programming*, Wiley, 2004.
2. D. Prokhorov, U.S. Patent No. 6682122, "Supplemental Sun Visor System for Automotive Vehicle", 2004.
3. D. Filev, D. Prokhorov, L. Feldkamp, M. Lixing, and T. Larsson, U.S. Patent No. 6701193, "Method for Adaptively Controlling Paint System", 2004 (also derivative patents for Europe and several European countries).
4. L. Feldkamp, D. Prokhorov, and C. Eagen, "Multiple-Start Directed Search for Improved NN Solution," in *Proceedings of IJCNN 2004*, Budapest, Hungary, July 2004.

   We propose a new technique to improve the confidence in results of repeated neural network training runs under the practical constraint of a fixed computational budget. Our technique is applicable to problems for which there is a correlation between results early in the training process and results near the end of training. Targeting well-studied training problems, the technique may be most valuable when the computational time required for thorough training makes impractical performing a large number of differently initialized training sessions.

5. V. Red'ko, D. Prokhorov, and M. Burtsev, "Theory of Functional Systems, Adaptive Critics and Neural Networks," in *Proceedings of IJCNN 2004*, Budapest, Hungary, July 2004.

   We propose a general scheme of intelligent adaptive control system based on the Petr K. Anokhin's theory of functional systems. This scheme is aimed at controlling adaptive purposeful behavior of an animat (a simulated animal) that has several natural needs (e.g., energy replenishment, reproduction). The control system consists of a set of hierarchically linked functional systems and enables predictive and goal-directed behavior. Each functional system includes a neural network based adaptive critic design. We also discuss schemes of prognosis, decision making, action selection and learning that occur in the functional systems and in the whole control system of the animat.

6. N. Barabanov and D. Prokhorov, "A New Method for Stability Analysis of Nonlinear Discrete-Time Systems," *IEEE Trans. Automatic Control*, December 2003.

   We address the problem of global Lyapunov stability of discrete-time systems with known coefficients. We develop a method for reduction of dissipativity domain effectively testing if the system has a convex Lyapunov function. Our implementation is immediately applicable to differentiable systems with bounded nonlinearities, but the method proposed is more general and applicable to non-differentiable systems with bounded right-hand sides. Our main application emphasis is on stability analysis of recurrent neural networks. We illustrate how to use our approach with examples.

7. I. Tyukin, C. Van Leeuwen, and D. Prokhorov, "Parameter Estimation of Sigmoid Superpositions: Dynamical System Approach," *Neural Computation*, Vol. 15, October 2003, pp. 2419-2455.

   Superposition of sigmoid function over a finite time interval is shown to be equivalent to the linear combination of the solutions of a linearly parameterized system of logistic differential equations. Due to the linearity with respect to the parameters of the system, it is possible to design an effective procedure for parameter adjustment. Stability properties of this procedure are analyzed.

8. I. Tyukin, D. Prokhorov, and C. Van Leeuwen, "Finite Form Realization of Adaptive Algorithms," *Proceedings of European Control Conference (ECC) 2003*, Cambridge, UK, September 2003.

We suggest a new method to design adaptation algorithms that guarantee improved performance and are applicable for a class of plants with nonconvex parameterization. The main idea of the method is, first, to augment the tuning error (possibly using uncertainty-dependent signals) of the known adaptive schemes in such a way that the desired characteristics of the adaptive system are guaranteed. Then we search for realization of the proposed schemes in an integral-differential form similar to the PI (proportional-integral) rules. Such adaptation schemes in the paper are called adaptive algorithms in *finite forms*. For this new description, dependence on neither state derivatives, nor unknown parameters is required. Sufficient conditions for existence of new finite form realizations of adaptive algorithms are proposed.

9. L. A. Feldkamp, D. V. Prokhorov, and T. M. Feldkamp, "Simple and Conditioned Adaptive Behavior from a Fixed Neural Network," *Neural Networks*, Vol. 16, July 2003, pp. 683-689.

We illustrate the ability of a fixed-weight neural network, trained with Kalman filter methods, to perform tasks that are usually entrusted to an explicitly adaptive system. Following a simple example, we demonstrate that such a network can be trained to exhibit input-output behavior that depends on which of two conditioning tasks was performed a substantial number of time steps in the past. This behavior can also be made to survive an intervening interference task.

10. L. A. Feldkamp, D. V. Prokhorov, and T. M. Feldkamp, "Conditioned Adaptive Behavior from a Fixed Neural Network," *Proceedings of IJCNN 2003*, Portland, OR July 2003 (earlier version appeared in *Proceedings of the Eleventh Yale Workshop on Adaptive and Learning Systems*, New Haven, CT, pp. 78-83, 2001).

This paper is a condensed version of [9].

11. L. A. Feldkamp and D. V. Prokhorov, "Recurrent Neural Networks for State Estimation," *Proceedings of the Twelve Yale Workshop on Adaptive and Learning Systems*, New Haven, CT, 2003.

We explore the use of recurrent neural networks (RNN) for state estimation, performing the same role as adaptive systems such as Kalman filters or particle filters. We demonstrate that RNN can combine available information from measurements with an implicit representation of state evolution to produce state estimates that are competitive with those produced by modern filter techniques.

12. D. Prokhorov, "Optimal Neurocontrollers for Discretized Distributed Parameter Systems," in *Proc. of ACC*, Denver, CO, June 2003.

We propose to use the framework of backpropagation through time (BPTT) to create optimal feedback neurocontrollers for distributed parameter systems (DPS). DPS are systems distributed in space while evolving in time. Unlike the lumped parameter systems, DPS are represented by a set of partial differential equations in the state space. Our neurocontrollers obtained for discretized DPS in the infinite-horizon regulator setting are applicable to a broad set of initial states (an envelope of initial state profiles). We compare our technique and results with another approach to synthesizing optimal DPS neurocontrollers introduced by Balakrishnan et al.

13. I. Tyukin, D. Prokhorov, V. Terekhov, "Adaptive Control with Nonconvex Parameterization," *IEEE Trans. Automatic Control*, April 2003, pp. 554-567.

This paper deals with the problem of non-convex parameterization in adaptive control for a class of nonlinear dynamic systems. New algorithms for stable adaptive control are introduced. Sufficient conditions for achieving control objectives of adaptive control with new algorithms are investigated. Simulation examples are presented for illustration.

14. L. A. Feldkamp, D. V. Prokhorov, and T. M. Feldkamp. Nonlinear Kalman Filter for Tire Pressure Estimation. Internal Technical Report, Ford Research and Advanced Engineering, 2003.

We present a new method for estimating tire pressure. It uses joint estimation of states and parameters, using the ``derivative-free" formulation for nonlinear Kalman filters recently reported by Norgaard, Poulsen, and Ravn (NPR). The proposed method is fundamentally simpler than that of Umeno et al. (Toyota R&D) and appears to produce substantially better results.

15. N. Barabanov and D. Prokhorov, "Two Alternative Stability Criteria for Discrete-Time RMLP," in *Proc. of Control and Decision Conference (CDC)*, Las Vegas, NV, December 2002.

Two criteria for analysis of global asymptotic stability of recurrent multilayered perceptrons (RMLP) are presented in the unperturbed setting. Both criteria are in the form of LMI. They differ by their strength and computational complexity.

16. I. Tyukin, C. Van Leeuwen, D. Prokhorov, V. Terekhov, "On a Problem of Time-Varying Learning Rate Influence on the Adaptive System Dynamics," in *Proc. of Control and Decision Conference (CDC)*, Las Vegas, NV, December 2002.

We consider a special class of nonlinear adaptive systems with full-state feedback and time-varying learning or adaptation rate. For the given class of systems we introduce sufficient conditions which guarantee boundedness of system trajectories and an additional assumption to guarantee asymptotic reaching of the control goal. These conditions extend the certainty-equivalence or attainability condition for gradient adaptive rules.

17. Prokhorov, D., Feldkamp, L., and I. Tyukin, "Adaptive Behavior with Fixed Weights in Recurrent Neural Networks: An Overview," *Proc. of International Joint Conference on Neural Networks (IJCNN), WCCI'02,* Honolulu, Hawaii, May 2002, pp. 2018-2022.

In this paper we review recent results on adaptive behavior attained with fixed-weight recurrent neural networks (meta-learning). We argue that such behavior is a natural consequence of prior training.

18. L. A. Feldkamp, T. M. Feldkamp, and D. V. Prokhorov, "Recurrent Network Training with the nprKF: Joint Estimation," *Proceedings of IJCNN 2002*, May 2002.

We present a method for training recurrent networks with the joint estimation of states and parameters, using the "derivative-free" formulation for nonlinear Kalman filters by Norgaard, Poulsen, and Ravn (NPR). Our approach is consistent with that described by Williams for the extended Kalman filter (EKF). We have extended the treatment to handle multistream training and propose ways of making the required computation more efficient.

19. N. Barabanov and D. Prokhorov, "Stability Analysis of Discrete-Time Recurrent Neural Networks," *IEEE Trans. on Neural Networks*, March 2002.

We address the problem of global Lyapunov stability of discrete-time recurrent neural networks (RNN) in the unforced (unperturbed) setting. It is assumed that network weights are fixed to some values, for example, those attained after training. Based on classical results of the theory of absolute stability, we propose a new approach for stability analysis of RNN with sector-type monotone nonlinearities and nonzero biases. We devise a simple state space transformation to convert the original RNN equations to a form suitable for our stability analysis (without compositions of nonlinearities). We then write appropriate linear matrix inequalities (LMI) to be solved to determine whether the system under study is globally exponentially stable. Unlike previous treatments, our approach readily permits us to account for nonzero biases usually present in RNN for improved approximation capabilities. We show how recent results of others on stability analysis of RNN can be interpreted as special cases within our approach. We illustrate how to use our approach with examples. Though illustrated on stability analysis of recurrent multilayer perceptrons, the approach proposed can also be applied to other forms of time-lagged RNN.

20. I. Y. Tyukin, V. A. Terekhov, and D. V. Prokhorov, On the applicability conditions for the algorithms of adaptive control in nonconvex problems, *Automation and Remote Control*, Vol. 63, No. 2, February 2002, pp. 262-279.

Solution of the problem of adaptive control of nonlinear plants with nonconvex-in-control-parameters functions of the right sides of their state equations was presented. Conditions for existence of the auxiliary functions for designing the adaptive control algorithms were formulated. For the adaptive systems using the introduced adaptation algorithms, theorems of attainability of the control goals were proved. The theoretical propositions were supported by computer simulation.

21. A. Petrosian, D. Prokhorov, W. Lajara-Nanson, and B. Schiffer, Recurrent Neural Network Based Approach for Early Recognition of Alzheimer's disease in EEG, *Clinical Neurophysiology*, Vol.112/8, 2001, pp. 1378-1387.

Objective: We explored the ability of specifically designed and trained recurrent neural networks (RNNs), combined with wavelet preprocessing, to discriminate between the EEGs of patients with mild Alzheimer's disease (AD) and their age-matched control subjects. Methods: 2-min. recordings of resting eyes-closed continuous EEGs (as well as their wavelet-filtered subbands) obtained from parieto-occipital channels of ten early AD patients and ten healthy controls were input into RNNs for training and testing purposes. The RNNs were chosen because they can implement extremely nonlinear decision boundaries and possess memory of the state which is crucial for the considered task. Results: The best training/testing results were achieved using a three-layer RNN on left parietal channel level 4 high-pass wavelet subbands. When trained on three AD and three control recordings, the resulting RNN tested well on all remaining controls and five out of seven AD patients. This represented a significantly better than chance performance of about 80% sensitivity at 100% specificity. Conclusion: The suggested combined wavelet/RNN approach may be useful in analyzing long term continuous EEGs for early recognition of AD. This approach should be extended on larger patient populations before its clinical diagnostic value can be established. Further lines of investigation might also require that EEGs be recorded from patients engaged in certain mental (cognitive) activities.

22. T. M. Feldkamp, D. V. Prokhorov, L. A. Feldkamp, and K. Marko, U.S. Patent No. 6292738, "Method for Adaptive Detection of Engine Misfire", 2001.

23. L. A. Feldkamp, T. M. Feldkamp, and D. V. Prokhorov, Network Training with the nprKF, *Proceedings of IJCNN 2001*, July 2001, pp. 109-114.

We present the training of feedforward and recurrent networks based on a more accurate treatment of the Kalman filter as applied to nonlinear systems.

24. D. V. Prokhorov, L. A. Feldkamp, and T. M. Feldkamp, A New Approach to Cluster Weighted Modeling, *Proceedings of IJCNN 2001*, July 2001.

This paper is a condensed version of [31].

25. L. A. Feldkamp, D. V. Prokhorov, and T. M. Feldkamp, Cluster Weighted Modeling with Multiclusters, *Proceedings of IJCNN 2001*, July 2001.

Cluster-Weighted Modeling (CWM) was recently proposed by Neil Gershenfeld for density estimation in joint input-output space. In the base CWM algorithm there is a single output cluster for each input cluster. We extend the base CWM to the structure in which multiple output clusters are associated with the same input cluster. We call this CWM with multiclusters and illustrate it with an example. This is a companion paper to [24].

26. I. Y. Tyukin and D. V. Prokhorov, Adaptive Idle Speed Control of an Internal Combustion Engine, *Proceedings of the 5th Symposium on Nonlinear Control Systems (NOLCOS)*, St.Petersburg, Russia, July 2001, pp. 504-505.

This paper is a condensed version of [30].

27. N. E. Barabanov and D. V. Prokhorov, Global Stability Analysis of Discrete-Time Recurrent Neural Networks, *Proceedings of American Control Conference (ACC)*, June 2001.

This paper is a condensed version of [19].

28. D. Prokhorov, G. Puskorius, and L. Feldkamp, "Dynamical Neural Networks for Control," in J. Kolen and S. Kremer (Eds.) *A Field Guide to Dynamic Recurrent Networks*, IEEE Press, 2001.

We discuss in this chapter the application of dynamical neural networks to control. We describe our approach to training of such networks and summarize our experience accumulated through extensive computer simulations and experimentation with time-lagged recurrent networks used as components of a control system. In the past we have experimented with both real control systems and simulations thereof. In this chapter, for the sake of reproducibility, we adopt the setting of neurocontrol systems developed and tested in simulation. We provide two examples to illustrate our approach.

29. L. Feldkamp, T. Feldkamp, and D. Prokhorov, "An Approach to Adaptive Classification," in S. Haykin (Ed.) *Intelligent Signal Processing*, IEEE Press, 2001.

We present an on-line learning system that is capable of analyzing an input-output data sequence to construct a sequence of binary classifications, without being provided correct class information as part of the training process. The system employs a combination of supervised and unsupervised learning techniques to form two or more behavior models. By examining these models for consistency with the sequence of observed data, an estimate of the class at each time step may be constructed. The learning system has been formulated by considering the general characteristics of the automotive misfire detection problem. The present paper, however, concentrates on the general aspects of the approach and uses synthetic problems as illustrative examples.

30. I. Tyukin, D. Prokhorov. Adaptive Idle Speed Control. Internal Technical Report, Ford Research Laboratory, 2001.

We propose new adaptive controllers for the idle speed control problem of the 1.6L internal combustion engine model. The controllers are developed for direct and indirect control based on the theory of adaptive control on manifolds. The original mathematical model of the engine is approximated by a third order nonlinear system obviating the need to deal with variable time delay while enabling analytical design of sufficiently accurate controllers. We increase the realism of our simulations by permitting some uncertainty on the plant parameters, additive noise on measured variables and partial state information. We demonstrate that our controllers work well in simulations.

31. D. Prokhorov, L. Feldkamp, T. Feldkamp. Cluster Weighted Modeling: Performance Enhancements. Internal Technical Report, Ford Research Laboratory, 2001.

We discuss a novel approach to joint density estimation called cluster-weighted modeling (CWM). The base approach was originally proposed by Neil Gershenfeld. We describe several innovations to the base CWM. Among them, two major innovations stand out. The first enables the CWM to work with continuous streams of data. The second addresses the commonplace problem of local minima which can be encountered during CWM parameter adjustment process. Our approach to mitigate this problem is quite elaborate, but it represents a principled way of improving efficacy of the parameter adjustment process. We illustrate CWM and our performance

enhancements with four examples. We conclude with a few thoughts on possible applications of CWM and a summary of our experience with it.

32. V. Terekhov, I. Tyukin, D. Prokhorov, "Adaptive Control on Manifolds with RBF neural nets," in *Proc. of Control and Decision Conference (CDC)*, Sydney, Australia, December 2000.

We propose a new method of adaptive control on manifolds for non-linear plants in the full-state feedback case using radial basis function (RBF) neural networks. We introduce a procedure for synthesis of adaptation algorithms based on associated performance criteria. We analyze applicability of the algorithms developed for a quadratic performance criterion.

33. L. Feldkamp, T. Feldkamp, D. Prokhorov, "Adaptive Classification," in *Proc. of the IEEE Symp. on Adaptive Systems for Signal Processing, Communications, and Control*, Lake Louise, Canada, October 2000, pp. 52-57.

This paper is a condensed version of [29].

34. Eaton, P., Prokhorov, D., and D. Wunsch, "Neurocontroller Alternatives for “Fuzzy” Ball-and-Beam Systems with Nonlinear, Nonuniform Friction," *IEEE Trans. on Neural Networks*, March 2000, pp. 423-435.

The ball-and-beam problem is a benchmark for testing control algorithms. In the World Congress On Neural Networks, 1994, Prof. Lotfi Zadeh proposed a twist to the problem, which, he suggested, would require a fuzzy logic controller. This experiment uses a beam, partially covered with a sticky substance, increasing the difficulty of predicting the ball’s motion. We complicated this problem even more by not using any information concerning the ball’s velocity. Although it is common to use the first differences of the ball’s consecutive positions as a measure of velocity and explicit input to the controller, we preferred to exploit recurrent neural networks, inputting only consecutive positions instead. We have used truncated backpropagation through time with the Node-Decoupled Extended Kalman Filter (NDEKF) algorithm to update the weights in the networks. Our best neurocontroller uses a form of approximate dynamic programming called an adaptive critic design. A hierarchy of such designs exists. Our system uses Dual Heuristic Programming (DHP), an upper-level design. To our best knowledge, our results are the first use of DHP to control a physical system. It is also the first system we know of to respond to Zadeh’s challenge. We do not claim this neural network control algorithm is the best approach to this problem, nor do we claim it is better than a fuzzy controller. It is instead a contribution to the scientific dialogue about the boundary between the two overlapping disciplines.

35. A. Petrosian, D. Prokhorov, R. Homan, R. Dasheiff, D. Wunsch, "Recurrent Neural Network Based Prediction of Epileptic Seizures in Intra- and Extracranial EEG," *Neurocomputing*, Vol. 30, pp. 201-218.

Predicting the onset of epileptic seizure is an important and difficult biomedical problem, which has attracted substantial attention of the intelligent computing community over the past two decades. We apply recurrent neural networks (RNN) combined with signal wavelet decomposition to the problem. We input raw EEG and its wavelet-decomposed subbands into RNN training/testing, as opposed to specific signal features extracted from EEG. To the best of our knowledge this approach has never been attempted before. The data used included both scalp and intracranial EEG recordings obtained from two epileptic patients. We demonstrate that the existence of a “preictal” stage (immediately preceding seizure) of some minutes duration is quite feasible.

36. N. Barabanov and D. Prokhorov, Stability Analysis of Recurrent Neural Networks. Internal Technical Report, Ford Research Laboratory, November 1999.

37. D. Prokhorov and L. Feldkamp, Application of SVM to Lyapunov Function Approximation, *Proc. of the 1999 International Joint Conference on Neural Networks*, Washington, DC, July 1999.

This paper proposes a novel technique to approximate Lyapunov functions for discrete time autonomous systems using a special form of Support Vector Machine (SVM). We assume that a Lyapunov function can be accurately approximated by a polynomial of arbitrary degree on a finite set of points from trajectories of the closed-loop system. We transform the original problem of linearly constrained quadratic optimization into an equivalent dual problem. For computational tractability, we apply an iterative decomposition of the dual problem. We illustrate our technique on two examples.

38. Saad, E., Prokhorov, D., and D. Wunsch, "Comparative Study of Stock Trend Prediction Using Time Delay, Recurrent and Probabilistic Neural Networks," *IEEE Trans. on Neural Networks*, Vol. 9, No. 6, November 1998, pp. 1456-1470.

Three networks are compared for low false alarm stock trend predictions. Short-term trends, particularly attractive for neural network analysis, can be used profitably in scenarios such as option trading, but only with significant risk. Therefore, we focus on limiting false alarms, which improves the risk/reward ratio by preventing losses. To predict stock trends, we exploit Time Delay, Recurrent, and Probabilistic Neural Networks (TDNN, RNN and PNN, respectively), utilizing conjugate gradient and multi-stream extended Kalman filter training for TDNN and RNN. We also discuss different predictability analysis techniques and perform an analysis of predictability based on a history of daily closing price. Our results indicate that all the networks are feasible, the primary preference being one of convenience.

39. Prokhorov, D., and L. Feldkamp. "Analyzing for Lyapunov Stability with Adaptive Critics." In *Proc. of the IEEE Conf. on Systems, Man, and Cybernetics*, San Diego, CA, October 1998, pp. 1658-1661.

We propose an approach to analyze trained neurocontrollers numerically for achieving Lyapunov stability of the closed-loop system. Our approach is based on training an adaptive critic to approximate a Lyapunov function. The trained critic is analyzed numerically to establish regions of stability of the closed-loop system. A simple example illustrates our approach. Our setting is the most relevant for neurocontrollers, but conclusions are applicable to other forms of controllers as well.

40. Prokhorov, D., and L. Feldkamp. "Bayesian Regularization in Extended Kalman Filter Training of Neural Networks." In *Proc. of the 10th Yale Workshop on Adaptive Systems*, Yale University, New Haven, CT, 1998, pp. 77-82.

This paper discusses the incorporation of Bayesian regularization into the training of neural networks with updates based on the extended Kalman filter. We propose several alternatives and illustrate one of them on two examples.

41. L. Feldkamp, D. Prokhorov, C. Eagen, F. Yuan. Enhanced Multi-Stream Kalman Filter Training for Recurrent Networks. In J. Suykens and J. Vandewalle (Eds.) *Nonlinear Modeling: Advanced Black-Box Techniques*, pp. 29-53, Kluwer Academic Publishers, 1998.

We present a framework for the training of time-lagged recurrent networks that has been used for a wide variety of both abstract problems and practical applications. Our method is based on rigorous computation of dynamic derivatives, using various forms of backpropagation through time (BPTT), a second-order weight update scheme that uses the extended Kalman filter, and data delivery mechanics designed for sequential weight updates with broad coverage of the available data. We extend our previous discussions of this framework by discussing various alternative forms of BPTT. In addition, we consider explicitly the issue of dealing with and optimizing network initial states. We discuss the initial state problem from the standpoint of making time-series predictions.

42. Feldkamp, L., and D. Prokhorov. "Phased Backpropagation: A Hybrid of Temporal Backpropagation and Backpropagation Through Time." In *Proceedings of World Congress on Computational Intelligence*, Anchorage, Alaska, May 1998.

We present a synthesis of backpropagation through time (BPTT) and temporal backpropagation (TB) that permits the efficiency of TB in dealing with delay lines to be combined with the generality of BPTT with respect to arbitrary discrete-time network structures. We express our formulation in terms of an ordered network, subsuming less general network architectures such as time-delay networks and recurrent multiplayer perceptrons. The resulting formulation can also be combined with derivative adaptive critics, thereby providing a further unification of techniques for training dynamic networks.

43. James, J., Marko, K., Feldkamp, L., Puskorius, G., Prokhorov, D., Feldkamp, T., Sun, P., Jesion, G., Baker, R. Application of Recurrent Neural Networks to Misfire Detection. Internal Technical Report, Ford Research Laboratory, December 1997.

44. Prokhorov, D., and D. Wunsch. "Convergence of Critic-based Training." In *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics (SMC'97)*, Orlando, FL, October, 1997.

45. Feldkamp, L., and Prokhorov, D. "Observations on the Practical Use of Derivative Adaptive Critics." In *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics (SMC'97)*, Orlando, FL, October, 1997, pp. 3061-3066.

By studying adaptive critic designs (ACD) from the standpoint of practical use in training neural networks, we expect to establish the types of problems for which ACD might be preferable to more established methods. To restrict the scope, we have chosen to concentrate on applying ACD, specifically derivative critics, to the training of recurrent networks. This is actually less restrictive than it may appear; many problems, including controller training, can be posed as optimizing some or all of the weights of a recurrent network. An immediate benefit of this focus has been to clarify the relationship between the derivatives that result from backpropagation through time (BPTT) and the quantities that derivative critics are expected to deliver. At the same time, many questions have been raised, such as that of the critic representation that best balances accuracy against the number of time steps required for adaptation. Because our formulation permits BPTT and derivative critics to be used together or separately, we expect that experience with a variety of problems will further clarify the various tradeoffs and suggest situations in which critics may be used to particular advantage.

46. Feldkamp, L., Puskorius, G., and D. Prokhorov. "Unified Formulation for Training Recurrent Networks with Derivative Adaptive Critics." In *Proceedings of the IEEE/INNS International Joint Conference on Neural Networks (ICNN'97)*, Houston, TX, pp. 2268-2272, June 1997.

47. Prokhorov, D., and L. Feldkamp. "Primitive Adaptive Critics." In *Proceedings of the IEEE/INNS International Joint Conference on Neural Networks (ICNN'97)*, Houston, TX, pp. 2263-2267, June 1997, pp. 2263-2267.

We propose a simple framework for critic-based training of recurrent neural networks and feedback controllers. We term the critics that are used *primitive adaptive critics*, since we represent them with the simplest possible architecture (bias weight only). We derive this framework from two main premises. The first of these is a natural similarity between a form of approximate dynamic programming, called Dual Heuristic Programming (DHP), and backpropagation through time (BPTT), as we will discuss. The second premise is our emphasis on a development of a truly on-line critic-based training procedure competitive in performance and computational cost to truncated BPTT. Three examples illustrate the main features of the framework proposed.

48. Zaman, R., Prokhorov, D., and D. Wunsch. "Adaptive Critic Design in Learning to Play Game of Go." In *Proceedings of the IEEE/INNS International Joint Conference on Neural Networks (ICNN'97)*, Houston, TX, June 1997.
49. Prokhorov, D., and D. Wunsch. "Advanced Adaptive Critic Designs," in *Proceedings of the World Congress on Neural Networks (WCNN'96)*, San Diego, CA, pp. 83-87, September 1996.
50. Marko, K., James, J., Feldkamp, T., Puskorius, G., Feldkamp, L., and D. Prokhorov. "Training Recurrent Neural Networks for Classification: Realization of Automotive Engine Diagnostics." In *Proceedings of the World Congress on Neural Networks (WCNN-96)*, San Diego, CA, pp. 845-850, September 1996.
51. Prokhorov, D., and D. Wunsch. Adaptive Critic Designs, *IEEE Trans. on Neural Networks*, Vol. 8, No. 5, September 1997, pp. 997-1007. (Earlier version of this paper appeared in *Computational Intelligence: A Dynamic System Perspective*, IEEE Press, 1995, pp.98-107.)
52. Visnevski, N., and D. Prokhorov. "Control of a Nonlinear Multivariable System with Adaptive Critic Designs," in *Intelligent Engineering Systems Through Artificial Neural Networks 6 (Proc. Conf. Artificial Neural Networks in Engineering)*, C. Dagli et. al., Eds. NY: ASME Press, 1996, pp. 559-565.
53. Eaton, P., Prokhorov, D., and D. Wunsch. "Neurocontrollers for Ball-and-Beam Systems," in *Intelligent Engineering Systems Through Artificial Neural Networks 6 (Proc. Conf. Artificial Neural Networks in Engineering)*, C. Dagli et. al., Eds. NY: ASME Press, 1996, pp. 551-557.
54. Petrosian, A., Homan, R., Prokhorov, D., and D. Wunsch. "Classification of Epileptic EEG using Neural Networks and Wavelet Transform." In *SPIE Proc*., Vol. 2825, pp. 834-843, August 1996.
55. Saad, E., Prokhorov, D., and D. Wunsch. Advanced Neural Network Training Methods for Low False Alarm Stock Trend Prediction. In *Proceedings of the IEEE International Conference on Neural Networks (ICNN'96)*, Washington, DC, pp. 2021-2026, June 1996.
56. Prokhorov, D., Santiago, R., and D. Wunsch. "Adaptive Critic Designs: A Case Study For Neurocontrol." *Neural Networks*, vol. 8, no. 9, pp. 1367-1372, 1995.
57. Prokhorov, D. "A Globalized Dual Heuristic Programming and Its Application To Neurocontrol." In *Proceedings of the World Congress on Neural Networks (WCNN'95)*, Washington, DC, pp. II-40-43, July 1995.
58. Tan H., Prokhorov D., Wunsch D., Conservative Thirty Calendar Day Stock Prediction Using a Probabilistic Neural Network, in *Proc. of the IEEE Conf. "Computational Intelligence for Financial Engineering"*, April 1995, N.Y. (extension of this work with addition of Time Delayed Neural Network appeared in *Proc. of WCNN'95*, pp. II-44-47).
59. Prokhorov D., A Lyapunov Machine for Stability Analysis of Nonlinear Systems, *Proc. of the 1st World Congress on Computational Intelligence*, Orlando, June/July 1994.
60. Prokhorov, D., and D. Wunsch. A Threshold-Polynomial Neural Network. In *Proceedings of the World Congress on Neural Networks (WCNN'94)*, San Diego, CA, June 1994.
61. Timofeev A., Prokhorov D., Neural Networks with Adaptive Architecture and their Applications, *Proc. of Institute for Informatics and Automation/ISPE Conf. on CAD/CAM "Robotics and Factories of the Future"*, St. Petersburg (Russia), May 1993.
62. Timofeev A., Prokhorov D., Neural Network Processing Systems in Recognition and Control Problems, in *Proc. of the 1st RNNS/IEEE Symp. on Neuroinformatics and Neurocomputers*, Rostov-on-Don , Russia, October 1992.
63. Timofeev A., Prokhorov D., A Neural Network-like Recognition System, in *Proc. of the 12th World Computer Congress (IFIP Congress'92)*, Madrid (Spain), September 1992.

64. Timofeev A., Prokhorov D., Construction Principles and Training Algorithms for Neural Network Processing Systems in Recognition and Control Problems, in *Proc. of the International Conf. on Bionic Modeling BIOMOD'92*, St. Petersburg (Russia), June 1992.
65. Prokhorov D., Fedyushin B., A Propulsive System for an Interplanetary Vehicle, in *Proc. of the Student Research Conf., Moscow Institute of Aviation Technology*, April 1991 (in Russian).
66. Prokhorov D., Fedyushin B., Launch Vehicles for Very Fast Space Flights, in *Proc. of the International Student Research Conf.*, Moscow Aviation Institute, April 1990.
67. Prokhorov D., Solid-Fuel Jet Engines for Rocket Models and their Design, *Proc. of Korolev Conf.* (Amateur Section), Moscow, January 1989 (in Russian).
68. Prokhorov D., Lexachenko T., Designing Rocket Models, *Proc. of the Student Research Conf. "Challenges in Aerospace Engineering"*, Kazan', November 1985 (in Russian).