Form PTO-1595 (Rev. 07/05)
OMB No. 0651-0027 (exp. 6/30/2008)

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6,904,422

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CONFIRMATORY INSTRUMENT

Title of Invention: ***Adaptive Control System Having Direct Output Feedback and Related Apparatuses and Methods***

Inventor(s): Anthony J. Calise; Naira Hovakimyan; Moshe Idan

Patent No. : Patent No. 6,904,422, issued on June 7, 2005

Contractor : Georgia Tech Research Corporation, Project No. E-16-P13

Contract No.: **F49620-98-1-0437**

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ADAPTIVE CONTROL SYSTEM HAVING DIRECT OUTPUT FEEDBACK AND RELATED APPARATUSES AND METHODS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority benefits of U.S. provisional application No. 60/208,101 filed May 27, 2000 naming Anthony J. Calise, Naira Hovakimyan, and Hungu Lee as inventors.

STATEMENT OF GOVERNMENT RIGHTS IN THE INVENTION

This invention was funded in part by the Air Force Office of Scientific Research (AFOSR) under Grant No. F4960-01-1-0024. The United States Government therefore has certain rights in the invention.

FIELD OF THE INVENTION

The invention is directed to a system, apparatuses and methods for adaptively controlling a plant such as an aircraft, automobile, robot, or other controlled system.

BACKGROUND OF THE INVENTION

Research in adaptive output feedback control of uncertain nonlinear dynamic systems is motivated by the many emerging applications that employ novel actuation devices for active control of flexible structures, fluid flows and combustion processes. These include such devices as piezoelectric films, and synthetic jets, which are typically nonlinearly coupled to the dynamics of the processes they are intended to control. Modeling for these applications vary from having accurate low frequency models in the case of structural control problems, to having no reasonable set of model equations in the case of active control of flows and combustion processes. Regardless of the extent of the model accuracy that may be present, an important aspect in any control design is the effect of parametric uncertainty and unmodeled dynamics. While it can be said the issue of parametric uncertainty is addressed within the context of adaptive control, very little can be said regarding robustness of the adaptive process to unmodeled internal process dynamics.

Synthesis approaches to adaptive output feedback control typically make use of state estimation, and therefore require that the dimension of the plant is known. Some approaches further restrict the output to have full relative degree, or restrict the uncertainties in the plant to be an unknown function of the output variables. It would be desirable to remove all these restrictions by adopting a direct output feedback approach that does not rely on state estimation. One of the immediate consequences of such an approach would be that the dimension of the controlled plant need not be known. Consequently, the resulting system would be applicable to plants having both parametric uncertainty and unmodeled dynamics. Furthermore, it would be desirable to produce a control system that is not only robust to unmodeled dynamics, but also learns to interact with and control these dynamics.

Output feedback control of full relative degree systems was introduced by Esfandiari and Khalil, 1992, "Output feedback stabilization of fully linearizable systems," *International Journal of Control*, 56(5):1007–1037. In their publication the authors formulated a control methodology that involves a high gain observer for the reconstruction of the unavailable states. A solution to the output feedback stabilization problem for systems in which nonlinearities depend only upon the available measurement, was given by Praly, L. and Jiang, Z. (1993), "Stabilization by output feedback for systems with iss inverse dynamics," *System & Control Letters*, 21:19–33. Krstic, M., Kanellakopoulos, I., and Kokotovic, P. (1995), *Nonlinear and Adaptive Control Design*, John Wiley & Sons, Inc. New York and Marino, R. and Tomei, P. (1995). *Nonlinear Control Design: Geometric, Adaptive, & Robust*. Prentice Hall, Inc., presented backstepping-based approaches to adaptive output feedback control of uncertain systems, linear with respect to unknown parameters. An extension of these methods due to Jiang can be found in Jiang, Z. (1999), A combined backstepping and small-gain approach to adaptive output feedback control. *Automatica*, 35:1131–1139.

For adaptive observer design, the condition of linear dependence upon unknown parameters has been relaxed by introducing a neural network (NN) in the observer structure of Kim, Y. and Lewis, F. (1998), *High Level Feedback Control with Neural Networks*, World Scientific, N.J. Adaptive output feedback control using a high gain observer and radial basis function neural networks (NNs) has also been proposed by Seshagiri, S. and Khalil, H. (2000), "Output feedback control of nonlinear systems using {RBF} neural networks," *IEEE Transactions on Neural Networks*, 11(1):69–79 for nonlinear systems, represented by input-output models. Another method that involves design of an adaptive observer using function approximators and backstepping control can be found in Choi, J. and Farrell, J. (2000), "Observer-based backstepping control using on-line approximation," *Proceedings of the American Control Conference*, pages 3646–3650. However, this result is limited to systems that can be transformed to output feedback form, i.e., in which nonlinearities depend upon measurement only.

The state estimation based adaptive output feedback control design procedure in the Kim and Lewis 1998 publication is developed for systems of the form:

$$\ddot{x}=f(x)+g(x)\delta_c \tag{1}$$

$$y=x \quad \dim x=\dim y=\dim u, \tag{2}$$

which implies that the relative degree of y is 2. In Hovakimyan, N., Nardi, F., Calise, A., and Lee, H. (1999), "Adaptive output feedback control of a class of nonlinear systems using neural networks," *International Journal of Control* that methodology is extended to full vector relative degree MIMO systems, non-affine in control, assuming each of the outputs has relative degree less or equal to 2:

$$\ddot{x}=f(x, \delta_c) \tag{3}$$

$$y=h(x) \quad \dim y=\dim u\leq\dim x. \tag{4}$$

These restrictions are related to the form of the observer used in the design procedure. Constructing a suitable observer for a highly nonlinear and uncertain plant is not an obvious task in general. Therefore, a solution to adaptive output feedback control problem that avoids state estimation is highly desirable.

SUMMARY OF THE INVENTION

The adaptive control system (ACS) and method of this invention uses direct adaptive output feedback to control a plant. The system can comprise a linear controller (LC) and an adaptive element (AE). The linear controller can be used