WORKSHOP TITLE

RISE-Based Robust and Adaptive Control of Nonlinear Systems

WORKSHOP ORGANIZERS AND PRESENTERS (see below for bios)

W. E. Dixon – University of Florida
Parag Patre – University of Florida

CONTACT INFORMATION: For more information about the workshop, please contact:

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WORKSHOP DURATION: One day (8 hours)

WORKSHOP ABSTRACT AND OBJECTIVES

In recent years, a new intelligent nonlinear control method has emerged that can identify and compensate for a broad class of disturbances. This method is coined RISE because the structure of the controller is a PI element with an additional **Robust Integral of the Sign of the Error** element. Advantages of the RISE method are that it is non-model based and yields asymptotic tracking despite a general class of smooth disturbances. The workshop will describe the basic structure of the RISE method. Details will be provided pertaining to how the closed-loop error system dynamics can be segregated into different classes that facilitate the definition of non-traditional Lyapunov function. The method will be extended to higher dimensional systems. Details will also be provided that describe how the method can be combined with other feedforward techniques (model-based and non-model-based) to yield improved performance with modular and composite adaptation. The implicit learning capability of the RISE method will be exploited to develop an optimal controller using the HJB optimization scheme. Experimental results are provided to illustrate the potential for improved performance. Other recent applications of the method will also be presented including artificial muscle stimulation, image-based state estimation, aircraft control. The workshop will conclude with a discussion of example applications, experimental results, open technical problems, and future research directions. The desired outcome of the workshop is to provide a detailed exposition of the methods such that the audience appreciates the advantages and limitations of the various methods for different classes of practical engineering applications.

WORKSHOP AUDIENCE

The expected audience includes engineers, scientists, graduate students, and academics. The workshop will be self-contained so that it is suitable for systems and control researchers and practitioners who may not have prior familiarity with the concepts as well as to those with some background in the field. The workshop assumes the audience has an introductory understanding of Lyapunov-based design and analysis methods.

ORGANIZATIONAL DETAILS

1. Attendees will be given hardcopies of the presentation slides and will be provided electronic copies as well.

2. The organizers and presenters will use electronic projection in PowerPoint or PDF format. We will provide our own computers, but we require the use of an LCD projector. The ability to make extemporaneous comments on a chalkboard or a dry-erase board would also be helpful, though not essential.

3. Two coffee breaks are planned in addition to a lunch break.

WORKSHOP SUMMARY

The workshop begins with a discussion on the philosophical motivation that improved performance and new enabling technologies may be realized by maintaining the complete nonlinear model of the systems in their control design. With this motivation, the RISE method will be introduced and applied to yield several results in areas such as implicit learning, standard adaptive, neural networks, modular adaptation, composite adaptation, optimal control, and input uncertainty. All work will use Lyapunov methods for design and stability of controllers. Each section will include motivation for the development of a particular method, a mathematical exposition of the method, examples of engineering applications of the method, and open problems that motivate future research on the topic. Specific details about each topic are discussed below.

Implicit Learning and Friction Identification: Modeling and compensation for friction effects has been a topic of considerable mainstream interest in motion control research. This interest is spawned from the fact that modeling nonlinear friction effects is a theoretically challenging problem, and compensating for the effects of friction in a controller has practical ramifications. If the friction effects in the system can be accurately modeled, there is an improved potential to design controllers that can cancel the effects; whereas, excessive steady-state tracking errors, oscillations, and limit cycles can result from controllers that do not accurately compensate for friction. In this section of the workshop, we will describe the implicit learning capabilities of the RISE controller and how they can be used for friction control problems. Specifically, a RISE-based tracking controller will be developed for a general Euler-Lagrange system that contains a new continuously differentiable friction model with uncertain nonlinear parameterizable terms. To achieve the tracking result, the RISE feedback compensation strategy will be used to identify the friction effects online, assuming exact model knowledge of the remaining dynamics. Experimental results will be provided to illustrate the tracking and friction identification performance of the RISE controller for such applications.

Adaptive and Neural Network-Based Control: The control of systems with uncertain nonlinear dynamics has been a decades long mainstream area of focus. The general trend for previous control strategies developed for uncertain nonlinear systems is that the more unstructured the system uncertainty, the more control effort (i.e., high gain or high frequency feedback) is required to cope with the uncertainty, and the resulting stability and performance of the system is diminished (e.g., uniformly ultimately bounded stability). This section will illustrate how the amalgamation of an adaptive model-based feedforward term (for linearly parameterized uncertainty) with the RISE feedback term (for additive bounded disturbances) can be used to yield an asymptotic tracking result for Euler-Lagrange systems that have mixed unstructured and structured uncertainty. Experimental results will be provided that illustrate a reduced root mean squared tracking error with reduced control effort.

The use of a neural network (NN) as a feedforward control element to compensate for nonlinear system uncertainties has been investigated for over a decade. Typical NN-based controllers yield uniformly ultimately bounded (UUB) stability results due to residual functional reconstruction inaccuracies and an inability to compensate for some system disturbances. Several researchers have proposed discontinuous feedback controllers (e.g., variable structure or sliding mode controllers) to reject the residual errors and yield asymptotic results. This section describes how RISE feedback term can be incorporated with a NN-based feedforward term to achieve semi-global asymptotic tracking. To achieve this result, the typical stability analysis for the RISE method will be modified to enable the incorporation of the NN-based feedforward terms, and a projection algorithm will be developed to guarantee bounded NN weight estimates. Experimental results will be presented to demonstrate the performance of the proposed controller.

Modular Adaptive Control: In this section, a novel adaptive nonlinear control design will be presented which achieves modularity between the controller and the adaptive update law. Modularity between the controller/update law designs provides flexibility in the selection of different update laws that could potentially be easier to implement or used to obtain faster parameter convergence and/or better tracking performance. For a general class of linear-in-the-parameters (LP) uncertain multi-input multi-output systems subject to additive bounded non-LP disturbances, the developed controller will use a model-based feedforward adaptive term in conjunction with the RISE feedback term. Modularity in the adaptive feedforward term will be made possible by considering a generic form of the adaptive update law and its corresponding parameter estimate. This generic form of the update law will be used to develop a new closed-loop error system and stability analysis that does not depend on nonlinear damping to yield the modular adaptive control result. The result will then be extended by considering uncertain dynamic systems that are not necessarily LP, and have additive non-LP bounded disturbances. A multilayer neural network (NN) structure will be used in the non-LP extension as a feedforward element to compensate for the non-LP dynamics in conjunction with the RISE feedback term. A NN-based controller will be developed with modularity in NN weight tuning laws and the control law. An extension will be provided that describes how the control development for the general class of systems can be applied to a class of dynamic systems modeled by Euler-Lagrange formulation. Experimental results on a two-link robot will be provided to illustrate the concept.

Composite Adaptation: In a typical adaptive update law, the rate of adaptation is generally a function of the state feedback error. Ideally, the adaptive update law would also include some feedback of the parameter estimation error. The desire to include some measurable form of the parameter estimation error in the adaptation law resulted in the development of composite adaptive update laws that are functions of a prediction error and the state feedback. In all previous composite adaptive controllers, the formulation of the prediction error is predicated on the critical assumption that the system uncertainty is linear in the uncertain parameters (LP uncertainty). The presence of additive disturbances that are not LP would destroy the prediction error formulation and stability analysis arguments in previous results. A new prediction error formulation will be constructed through the use of the RISE technique. The contribution of this design and associated stability analysis is that the prediction error can be developed even with disturbances that do not satisfy the LP assumption. A composite adaptive controller will be developed for a general MIMO system with mixed structured (i.e., LP) and unstructured uncertainties. A Lyapunov-based stability analysis will be used to derive sufficient gain conditions under which the proposed controller yields semi-global asymptotic tracking. Experimental results will be presented to illustrate the approach.

Optimal Control: A Hamilton-Jacobi-Bellman optimization scheme will be used along with a RISE feedback structure to minimize a quadratic performance index while the generalized coordinates of a nonlinear Euler-Lagrange system asymptotically track a desired time-varying trajectory despite general uncertainty in the dynamics, such as additive bounded disturbances and parametric uncertainty. Motivated by recent previous results that use a neural network structure to approximate the dynamics (i.e., the state space model is approximated with a residual function reconstruction error), the result will use the implicit learning capabilities of the RISE control structure to learn the dynamics asymptotically. Specifically, a Lyapunov stability analysis will be performed to show that the RISE feedback term asymptotically identifies the unknown dynamics, yielding semi-global asymptotic tracking. In addition, it will be shown that the system converges to a state space system that has a quadratic performance index which has been optimized by an additional control element. Simulation results will be presented to demonstrate the performance of the developed controller.

Input Uncertainty: In this section, a RISE-based control structure will be shown to achieve asymptotic output tracking control of a model reference system, where the plant dynamics include a bounded additive disturbance (e.g., potential disturbances include: gravity, inertial coupling, nonlinear gust modeling, etc.). This represents application of the RISE method to a multi-input multi-output (MIMO) aircraft system containing a non-vanishing, non-LP disturbance, where the control input is multiplied by a column-deficient matrix containing parametric uncertainty. To achieve the result, the typical RISE control structure and closed-loop error system development will be first modified by including a constant feedforward estimate of the input uncertainty along with a novel robust control term, which will be designed to compensate for the resulting inversion error. Motivated by the desire to develop an adaptive controller, the robust control design will be then extended to an ADI-based method, where a Lyapunov-based adaptive law will be utilized to compensate for the parametric uncertainty in the input matrix. Asymptotic tracking results will be proven via a Lyapunov stability analysis, and high fidelity numerical simulations will be provided to show the performance of the proposed control designs.

RISE Applications: Some applications of RISE will be discussed including the following:

Image-Based State Estimation: The continuous RISE estimator strategy is utilized to asymptotically identify the six degree-of-freedom velocity of a moving object using a single fixed camera. The design of the estimator is facilitated by the fusion of homography-based techniques with Lyapunov design methods. Similar to the stereo vision paradigm, the proposed estimator utilizes different views of the object from a single camera to calculate 3D information from 2D images. In contrast to some of the previous work in this area, no explicit model is used to describe the movement of the object.

Muscle Stimulation: The RISE method is used in the neuromuscular electrical stimulation (NMES) to enable a human shank to track any continuous desired trajectory (or constant set point) by controlling the human quadriceps femoris muscle undergoing non-isometric contractions. The performance of the controller is demonstrated through a series of closed-loop experiments on human subjects. The experiments illustrate the ability of the controller to enable the leg shank to track single and multiple period trajectories with different periods and ranges of motion, and also track desired step changes with changing loads.

WORKSHOP SCHEDULE

Time	**Topic**	**Presenter**
8:00-8:30	Welcome and Introduction	W. Dixon
8:30-9:00	**Robust Integral of the Sign of the Error (RISE)** Historical Perspective Basic Architecture Extensions to Higher Order Systems **Implicit Learning and Friction Identification** RISE as implicit learning tool Friction identification Experimental Results	W. Dixon
9:00-10:00	**Adaptive and Neural Network-Based Control** Motivation for Adaptive Control Modification to include adaptive elements Experimental results Extension to Non-LP systems using neural networks Universal approximation theorem and on-line learning Architecture for single and multilayer networks New stability analysis and update law design Experimental results	P. Patre
10:00-10:30	Coffee Break	

10:30-11:30	**Modular Adaptive Control** Motivation Historical perspective New class of modular adaptive design Modular adaptation for neural networks Experimental results	P. Patre
11:30-1:00	Lunch	
1:00-2:00	**Composite Adaptation** Motivation Historical perspective Challenges due to non-LP disturbances New swapping design Experimental results	P. Patre
2:00-2:30	**Optimal Control** HJB optimization scheme Use of RISE implicit learning Stability analysis Simulation results	W. Dixon
2:30-3:00	Coffee Break	
3:00-4:00	**Input Uncertainty** Model reference adaptive control Input uncertainty with non-square gain matrix Adaptive dynamic inversion Simulation results	W. Dixon

4:30-5:00	RISE Applications
	   Image-Based State Estimation
	   Muscle Stimulation
	Future Research Problems
	Open Discussion and Closing Remarks
		P. Patre
		W. Dixon

ORGANIZER and PRESENTERS' BIOGRAPHIES

The presenters are spearheading the development of the proposed workshop topic. Professor Dixon has led a workshop on RISE control. Parag is a NASA post doctoral fellow at the Langley Research Center and has been pursuing research on RISE-based control, and is the lead author of book "RISE-Based Robust and Adaptive Control of Nonlinear Systems", which is under contract with Birkhäuser Boston.

Warren Dixon (Organizer and Presenter) received his Ph.D. degree in 2000 from the Department of Electrical and Computer Engineering from Clemson University. After completing his doctoral studies he was selected as a Eugene P. Wigner Fellow at Oak Ridge National Laboratory (ORNL) where he worked in the Robotics and Energetic Systems Group. In 2004, Dr. Dixon joined the faculty of the University of Florida in the Mechanical and Aerospace Engineering Department. Dr. Dixon's main research interest has been the development and application of Lyapunov-based control techniques for uncertain nonlinear systems. He has published 2 books, an edited collection, 4 chapters, and over 180 refereed journal and conference papers. Dr. Dixon was awarded the 2001 ORNL Early Career Award for Engineering Achievement for his contributions to Lyapunov-based control methods. He was awarded the 2004 DOE Outstanding Mentor Award for his student advising at ORNL. He was awarded a NSF CAREER award in 2006 for new development and application of Lyapunov-based control methods. He was also awarded the 2006 IEEE Robotics and Automation Society (RAS) Early Academic Career Award. Dr. Dixon is a senior member of IEEE. He serves on the IEEE CSS Technical Committee on Intelligent Control, is a primary member of the ASME DSC Division Mechatronics Technical Committee, is a member of numerous conference program committees, and serves on the conference editorial board for the IEEE CSS and RAS and the ASME DSC. He served as an appointed member to the IEEE CSS Board of Governors for 2008. He is currently an associate editor for *IEEE Transactions on Systems Man and Cybernetics: Part B Cybernetics*, *Automatica*, *International Journal of Robust and Nonlinear Control*, and *Journal of Robotics*.

Parag Patre (Organizer and Presenter) received his B. Tech. degree in mechanical engineering from the Indian Institute of Technology Madras, India, in 2004. Following this he was with Larsen & Toubro Limited, India until 2005, when he joined the graduate school at the University of Florida. He received the M.S. and Ph.D. degrees in mechanical engineering in 2007 and 2009, respectively, and is currently a NASA postdoctoral fellow at the NASA Langley Research Center, Hampton, VA. His areas of research interest are Lyapunov-based design and analysis of control methods for uncertain nonlinear systems, robust and adaptive control, control of robots, and neural networks. He has published 18 refereed journal and conference papers and the monograph RISE-Based Robust and Adaptive Control of Nonlinear Systems.