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14. ABSTRACT
In this report, we briefly summarize the important results we have obtained over the grant period, in two separate categories: measurement based control design and Multi-agent networked control system (NCS). In measurement based approach, we design new methodologies for fault-tolerant controllers such that every controller in the set preserves closed-loop stability of a given multi-variable plant. In the area of multi-agent networked control system we design resilient control algorithms against malicious denial of service attacks on a convoy of robots and false data injection attacks against the electric power grid. Further, we propose a two level sampling rate adaptation

15. SUBJECT TERMS
resilient control, multi-agent systems, denial of service attacks, fragility of controllers, robustness of controllers

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FINAL REPORT (2017)
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PERSONAL: L.H. Keel, S. Sathananthan, L. Hong.

BRIEF OUTLINE OF RESEARCH FINDINGS:

1. Title: Exact Multivariable Controller Design Using SISO Methods: Recent Results
Proceedings of the IEEE Multi-Conference on Systems and Control, pp. 215-223, Buenos Aires, Argentina, September 19-22, 2016.

Authors: L.H. Keel, and S.P. Bhattacharyya.

Abstract: In this paper we describe some very recent methods developed by the authors to design multivariable controllers exploiting single input single output (SISO) design methods. These methods allow the designer to accommodate several useful design criteria such as low order, steady state tracking and disturbance rejection, overshoot and settling time control and gain and phase margin. The main tool is the Smith- McMillan form of the transfer function which can be used to reduce an nn multivariable design problem into an equivalent set of n single input single output problems. An additional advantage of the method is that a state space realization is not needed and many criteria that are beyond the reach of quadratic optimization can be achieved.

2. Title: Robustness and Fragility of High Order Controllers: A Tutorial.
Proceedings of the IEEE Multi-Conference on Systems and Control, pp. 191-202, Buenos Aires, Argentina, September 19-22, 2016.

Authors: L.H. Keel, and S.P. Bhattacharyya

Abstract: In this tutorial paper we begin by providing a brief history of the field of classical robust control, namely, Blacks feedback amplifier, the Nyquist criterion and Bodes frequency domain methods. In this classical period there was an underlying emphasis on design for robustness measured via gain and phase margins in the complex plane or in terms of frequency response plots. In the modern period (post 1960) the design emphasis shifted to quadratic optimization, state space models and state feedback and observers. Stability was obtained automatically and Kalman showed that as far as state feedback was concerned excellent universal gain and phase margins were obtained as a by product of optimization. It took almost twenty years for the community to realize that these margins could disappear under output feedback implementations. The response of researchers, to this realization, was to develop design methods that accounted for plant uncertainty from the outset. This led to the development of H^∞ control theory. In 1997 the present authors showed that controllers designed by these methods could and frequently would, produce high order controllers which were fragile in the sense that minuscule perturbations of the controller would destabilize the closed loop system. This second failure of quadratic optimization to deliver robustness, provoked a resurgence of interest in low order output feedback and Proportional Integral Derivative (PID) controllers. In the last twenty years the beginnings of a modern approach to PID control has developed incorporating the efficient computation of stabilizing sets, achievable performance in terms of gain and phase margins, multi-objective design and finally exact design of low order multivariable controllers using single-input single output (SISO) methods. These are briefly introduced in the present paper and elaborated on in the succeeding papers of this session.

3. Title: Advanced Tuning for Ziegler-Nichols Plants.
Proceedings of the IFAC world Congress, pp. 1841-1846, Toulouse, France, July 9-15, 2017.

Authors: Ivan D. Diaz Rodriguez, Sangjin Han, L.H. Keel, and S.P. Bhattacharyya

Abstract: In this paper, we describe an advanced tuning approach for the design of PI (Proportional-Integral) and PID (Proportional-Integral-Derivative) controllers for the Ziegler- Nichols plants, that is First

Oder Plus Time-Delay (FOPTD) continuous-time LTI (Linear Time Invariant) systems. The objective is to provide to the designer an efficient tool to design PI or PID controllers where it is possible to select simultaneous performance specifications of gain margin, phase margin, and gain crossover frequency from a set of achievable performance design curves for Ziegler-Nichols plants. To succeed in this, we first construct the stabilizing set of PI or PID controllers corresponding to the Ziegler-Nichols plant. Next, we generate an achievable performance set displayed as design curves in the gain and phase margin plane, indexed by gain crossover frequencies. Each point in this achievable performance plot represents a prescribed gain margin, phase margin, and crossover frequency, obtained by a PI or PID controller contained in the stabilizing set. Then, by selecting a point from the achievable performance set, a unique PI or PID controller achieving these simultaneous specifications is found from the intersection of an ellipse and straight line parametrized from constant magnitude and constant phase loci in the space of controller gains. We present illustrative examples to validate the proposed approach.

4. **Title:** A Measurement-based Approach to Designing Fault-tolerant Controllers for Multi-variable Systems. *International Journal of Adaptive Control and Signal Processing*, Vol.30, Issue 8-10, pp.1355-1374, 2016.

   Authors: P. Kallakuri, L.H. Keel, and S.P. Bhattacharyya

   Abstract: This paper presents new methodologies to design a set of controllers such that every controller in the set preserves closed-loop stability of a given multivariable plant under prescribed loop failures. The proposed approaches differ from existing techniques in two ways: First, our methods are strictly based on frequency response data of the plant that can be easily measured by experiments. No mathematical models or system identification processes are used. Second, while most control design methods find one controller, we design a set of controllers satisfying the control objective. Two approaches are presented with examples illustrating the respective advantages.

5. **Title:** Model-Based Resilient Control for a Multi-agent System Against Denial of Service Attacks. *Proceedings of the 2016 World automation Congress*, Puerto Rico, July 31-August 4, 2016.

   Authors: E. Amullen, S. Shetty, and L.H. Keel.

   Abstract: The computerization of critical infrastructure such as control systems means that these systems interact with information technology (IT) to an extent that makes them susceptible to malicious attacks. While IT security places emphasis on data accuracy easily attainable through simple error correction schemes such as packet re-transmission , control systems emphasize timely and accurate transmission of control signals in which delays or re-transmissions can have detrimental effects on the system. This motivates the need for resilient control algorithms that guarantee normal operation of critical infrastructure subject to malicious attacks and disturbances both at the physical layer and communication layer. In this paper, a team of networked autonomous agents whose collective objective is formation control is used to represent a cyber-physical system. A distributed formation control algorithm in which each agent depends only on its local information and that received from one neighbor to cooperatively carry out the group mission is employed. We develop a model-based resilient control algorithm that enables the team of autonomous agents accomplish their formation task even in the presence of a malicious denial of service (DOS) attack disrupting inter-agent communication. The technique is demonstrated through a laboratory experiment with 6 pioneer 3DX robots.

PRESENTATIONS:

1. L. H. Keel and S.P. Bhattacharya, Robust and Fragility of High Order Controllers: A Tutorial, IEEE Multi-Conference on Systems and Control, Buenos Aires, Argentina, September 19-22, 2016 (Presented by L.H. Keel).

2. L. H. Keel and S.P. Bhattacharya, Exact Multivariable ControlDesign Using SISO Methods:Recent Results, IEEE Multi-Conference on Systems and Control, Buenos Aires, Argentina, September 19-22, 2016 (Presented by L.H. Keel).

3. EvanL.D. Diaz Rodriguez, Sangjin Han, and L. H. Keel, Advanced Tuning for Ziegler-Nichols Plants, IFAC World Congress, Toulouse, France, July 9-15, 2017 (Presented by L.H. Keel).

4. E. Amullen, S. Shetty, and L.H. Keel, A Model based Resilient Control for a Multi-agent System Against Denial of Service Attacks, World Automation Congress, Puerto Rico, July 31-August 4, 2016 (presented by E. Amullen). (Presented by E. Amullen).

5. E. Amullen and L.H. Keel, Multi-Agent Systems for Detecting False Data Injection Attacks Against the Electric Power Grid, 39th Annual University Wide Research Symposium, Tennessee State University, Nashville, TN 37209, April 17-21, 2017. (Presented by E. Amullen).

6. A. Rahman, L. Hong and L.H. Keel, Experimental Implementation of Network Resource management for Cloud Based Networked Control System, 39th Annual University Wide Research Symposium, Tennessee State University, Nashville, TN 37209, April 17-21, 2017. (Presented by A. Rahman).

7. Chris Clegg, L. Hong and L.H. Keel, A Proof of Concept of Counter-Measures to GPS Spoofing, 39th Annual University Wide Research Symposium, Tennessee State University, Nashville, TN 37209, April 17-21, 2017. (Presented by Chris Clegg).

8. Elliot Steen, L. Hong and L.H. Keel, GPS Spoofing Detection Via Independent Localization, 39th Annual University Wide Research Symposium, Tennessee State University, Nashville, TN 37209, April 17-21, 2017. (Presented by Elliot Steen).