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14. ABSTRACT

15. SUBJECT TERMS

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RPPR Final Report
as of 06-Jan-2022

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INVESTIGATOR(S):

Name: Ph.D. Brian P. Mann
Email: brian.mann@duke.edu
Phone Number: 9196605214
Principal: Y

Organization: **Duke University**

Address: C/O Office of Research Support, Durham, NC 277054677

Country: USA

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Final Report for Period Beginning 12-Jun-2017 and Ending 31-Aug-2021

Title: Non-smooth Dynamics of Constrained Task-oriented Dynamical Systems

Begin Performance Period: 12-Jun-2017

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Report Term: 0-Other

Submitted By: Ph.D. Brian Mann

Email: brian.mann@duke.edu

Phone: (919) 660-5214

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1

STEM Participants: 1

Major Goals: Power, physical stress, and force constraints are common in many human endeavors, but these constraints are also prevalent in robotics, autonomous vehicles, and other engineered systems. In addition to being constrained by power output, human and animal muscles are also constrained by a maximal force-elongation-velocity curve. The fact that all humans and animals are limited by such constraints requires them to think differently to achieve many complex tasks. It is the goal of this proposal to constrain the system actuation in our experimental systems, with one or more constraints; multiple methods will then be investigated to enable the complex dynamical systems to learn to achieve specific tasks.

Accomplishments: We have developed a model-free framework and forecasting strategy to enable dynamical systems to learn to efficiently exploit their natural dynamics. The work builds upon past literature in the area of reinforcement learning to advance the current understanding for nonlinear dynamical systems. We have also completed an initial investigation of constraining an actuator while building up momentum to achieve an attractor escape.

The aforementioned ideas have been applied to the problem of nonlinear systems switching attractors. The focus has been on constrained actuation and limiting the energy expenditure when applying control.

RPPR Final Report

as of 06-Jan-2022

Training Opportunities: A total of 5 PhD students took part in this grant. Many of them went on to be funded by other grants or fellowships, but all received some training towards their PhD as a part of this grant. Here is a list of students involved:

1. James Turner (PhD) - partial support was been provided until Jim won a NDSEG fellowship. Although Jim continues to work on this topic, he is now actually supported by that national fellowship. Jim graduated with a PhD in Fall 2021.
2. Levi Manning (PhD) - support was provided for Levi to work on this project. Levi did an internship at Los Alamos National Labs and then was sponsored by Los Alamos until degree completion.
3. Jared Little (PhD) - support was provided for Jared to work on this project to help build an experimental demonstration of the conceptual ideas. He graduated with a PhD in Fall 2019.
4. Xueshe Wang (PhD) - was supported by an external fellowship, but contributed to our research group's efforts and wrote several papers. He graduated with a PhD in Summer 2020.
5. Samuel Moore (PhD) - Sam started in Fall 2021 and has contributed to this grant since he started.

Results Dissemination: Research dissemination was primarily done through publications listed below. However, one student, Jim Turner, went to work for the Navy Research Lab which may result in additional transfer.

1. Moore, S.A., Culver, D., Mann, B.P., "Supervised learning for abrupt change detection in a driven eccentric wheel," Proceedings of the 37th International Modal Analysis Conference, Orlando, FL, 2022.
2. Moore, S., Culver, D., Mann, B.P., 2021, "The Eccentric Disk and Its Eccentric Behavior," European Journal of Physics, V. 42, No. 6, 065012, DOI: 10.1088/1361-6404/ac2799.
3. Little, J.A., Turner, J.D., and Mann, B.P., 2020, "Improving empirical characteristic multiplier estimation through a change of basis," Journal of Sound and Vibration, V. 488, No. 115613, DOI 10.1016/j.jsv.2020.115613.
4. Little, J.A., and Mann, B.P., 2019, "Optimizing logarithmic decrement damping estimation through uncertainty propagation," Journal of Sound and Vibration, V. 457, pp. 368–376, DOI 10.1016/j.jsv.2019.05.040.
5. Wang, X., Turner, J.D., and Mann, B.P., 2020, "Constrained attractor selection using deep reinforcement learning," Journal Vibration and Control, V. ?, pp. ? DOI 10.1177/1077546320930144.
6. Culver, D., Mann, B.P., Stanton, S.C., 2018, "Passive subharmonic elimination," Applied Physics Letters, V. 113, Issue. 14, No. 144101, DOI 10.1063/1.5046858.
7. Stanton, S.C., Culver, D., Mann, B.P., 2020, "Tuning inertial nonlinearity for passive nonlinear vibration control," Nonlinear Dynamics, V. 99, pp. 495–504, DOI 10.1007/s11071-019- 05349-z.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)

Participant: Samuel Moore

Person Months Worked: 12.00

Project Contribution:

National Academy Member: N

Funding Support:

RPPR Final Report
as of 06-Jan-2022

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 2-Awaiting Publication
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Publication Identifier Type: DOI **Publication Identifier:** 10.1177/1077546320930144
Volume: **Issue:** **First Page #:** 107754632
Date Submitted: **Date Published:** 5/1/20 4:00AM
Publication Location:

Article Title: Constrained attractor selection using deep reinforcement learning

Authors: Xue-She Wang, James D Turner, Brian P Mann

Keywords: Machine Learning Reinforcement Learning Control

Abstract: This paper describes an approach for attractor selection (or multi-stability control) in nonlinear dynamical systems with constrained actuation. Attractor selection is obtained using two different deep reinforcement learning methods: 1) the cross-entropy method (CEM) and 2) the deep deterministic policy gradient (DDPG) method. The framework and algorithms for applying these control methods are presented. Experiments were performed on a Duffing oscillator, as it is a classic nonlinear dynamical system with multiple attractors. Both methods achieve attractor selection under various control constraints. While these methods have nearly identical success rates, the DDPG method has the advantages of a high learning rate, low performance variance, and a smooth control approach. This study demonstrates the ability of two reinforcement learning approaches to achieve constrained attractor selection.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
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Partners

I certify that the information in the report is complete and accurate:

Signature: Brian Mann

Signature Date: 1/6/22 10:40AM

Non-smooth Dynamics of Constrained Task-oriented Dynamical Systems W911NF-12-R-0012-04

Summary

Power, physical stress, and force constraints are common in many human endeavors, but these constraints are also prevalent in robotics, autonomous vehicles, and other engineered systems. In addition to being constrained by power output, human and animal muscles are also constrained by a maximal force-elongation-velocity curve. The fact that all humans and animals are limited by such constraints requires them to think differently to achieve many complex tasks. It is the goal of this proposal to constrain the system actuation in our experimental systems, with one or more constraints; multiple methods will then be investigated to enable the complex dynamical systems to learn to achieve specific tasks.

1 Specific Scientific Tasks and Objectives

This research seeks to build a research foundation for highly nonlinear dynamical systems that learn to achieve tasks when limited by internal or environmental constraints. The primary goals are to: (1) develop a model-free framework and forecasting strategy to enable dynamical systems to learn to efficiently exploit their natural dynamics for otherwise unattainable tasks; (2) to investigate task achievement, such as the building up of momentum to escape from one attractor to another, through a series of theoretical and experimental demonstrations that require a sequence of properly timed and constrained actuation. It is believed the proposed research is fundamentally important to many future generation military applications and specifically important to future robotics applications.

2 Progress

We have developed a model-free framework and forecasting strategy to enable dynamical systems to learn to efficiently exploit their natural dynamics. The work builds upon past literature in the area of reinforcement learning to advance the current understanding for nonlinear dynamical systems. We have also completed an initial investigation of constraining an actuator while building up momentum to achieve an attractor escape.

The aforementioned ideas have been applied to the problem of nonlinear systems switching attractors. The focus has been on constrained actuation and limiting the energy expenditure when applying control.

3 Students

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2. Levi Manring (PhD) - support was provided for Levi to work on this project. Levi did an internship at Los Alamos National Labs and then was sponsored by Los Alamos until degree completion.
3. Jared Little (PhD) - support was provided for Jared to work on this project to help build an experimental demonstration of the conceptual ideas. He graduated with a PhD in Fall 2019.
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4 Products

1. Moore, S.A., Culver, D., Mann, B.P., "Supervised learning for abrupt change detection in a driven eccentric wheel," Proceedings of the 37th International Modal Analysis Conference, Orlando, FL, 2022.
2. Moore, S., Culver, D., Mann, B.P., 2021, "The Eccentric Disk and Its Eccentric Behavior," *European Journal of Physics*, V. 42, No. 6, 065012, DOI: 10.1088/1361-6404/ac2799.
3. Little, J.A., Turner, J.D., and Mann, B.P., 2020, "Improving empirical characteristic multiplier estimation through a change of basis," *Journal of Sound and Vibration*, V. 488, No. 115613, DOI 10.1016/j.jsv.2020.115613.
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5. Wang, X., Turner, J.D., and Mann, B.P., 2020, "Constrained attractor selection using deep reinforcement learning," *Journal Vibration and Control*, V. ?, pp. ? DOI 10.1177/1077546320930144.
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7. Stanton, S.C., Culver, D., Mann, B.P., 2020, "Tuning inertial nonlinearity for passive nonlinear vibration control," *Nonlinear Dynamics*, V. 99, pp. 495–504, DOI 10.1007/s11071-019-05349-z.

8. Wang, X. and Mann, B.P., 2019, “Nonlinear dynamics of a non-contact translational-to-rotary magnetic transmission ,” *Journal of Sound and Vibration*, V. 459, No. 114861, DOI 10.1016/j.jsv.2019.114861.