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RA2 Control for Modular Materials

Michael Šebek

Department of Control Engineering

Faculty of Electrical Engineering, ČVUT

14. 3. 2024

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Robotics and Advanced Industrial Production
CZ.02.01.01/00/22_008/0004590

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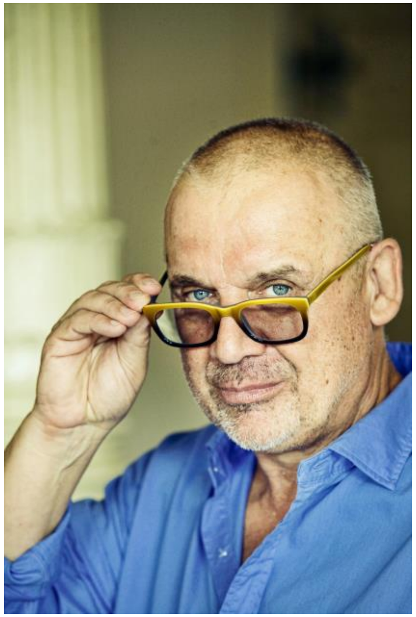

Michael Šebek
RG Leader

Zdeněk Hurák
Excellent TT

Kristian
Hengster-Movric
Excellent TT

Jiří Zemánek
Postdoc

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People

Docs & Students involved

To be hired:

2 postdocs and 2 docs

RA2: Cooperation with other RAs

RA1/G1, T. Vyhlídal
Control of distributed-parameter systems and complex robotic structures
RA3/G3, D. Henrion
Convex relaxations for non-convex problems in materials and industrial design
RA4/G4, J. Zeman
Computer-aided design, simulation, and manufacturing of modular materials
RA5/G5, T. Polcar
Automation for nanoscale surface engineering

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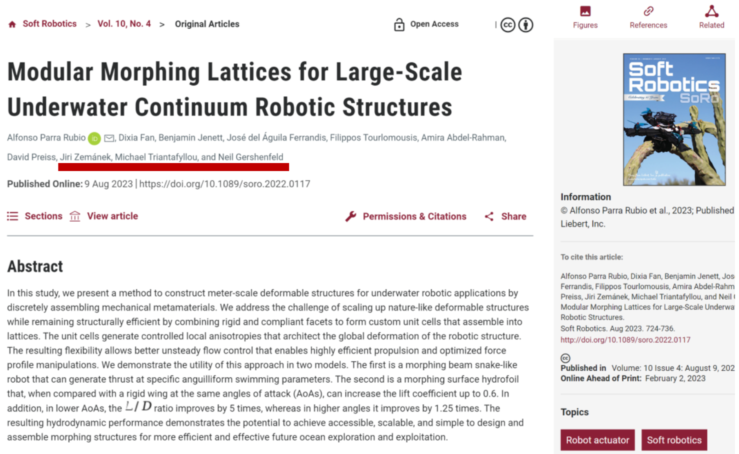
RA2 International collaborations

Prof. Neil Gershenfeld - Center for Bits and Atoms, MIT



Soft Robotics > Vol. 10, No. 4 > Original Articles

Open Access

Modular Morphing Lattices for Large-Scale Underwater Continuum Robotic Structures

Alfonso Parra Rubio, Dixia Fan, Benjamin Jenett, José del Águila Ferrandis, Filippos Tourlomousis, Amira Abdel-Rahman, David Preiss, Jiri Zemánek, Michael Triantafyllou, and Neil Gershenfeld

Published Online: 9 Aug 2023 | https://doi.org/10.1089/soro.2022.0117

Abstract

In this study, we present a method to construct meter-scale deformable structures for underwater robotic applications by discretely assembling mechanical metamaterials. We address the challenge of scaling up nature-like deformable structures while remaining structurally efficient by combining rigid and compliant facets to form custom unit cells that assemble into lattices. The unit cells generate controlled local anisotropies that architect the global deformation of the robotic structure. The resulting flexibility allows better unsteady flow control that enables highly efficient propulsion and optimized force profile manipulations. We demonstrate the utility of this approach in two models. The first is a morphing beam snake-like robot that can generate thrust at specific anguilliform swimming parameters. The second is a morphing surface hydrofoil that, when compared with a rigid wing at the same angles of attack (AoAs), can increase the lift coefficient up to 0.6. In addition, in lower AoAs, the L/D ratio improves by 5 times, whereas in higher angles it improves by 1.25 times. The resulting hydrodynamic performance demonstrates the potential to achieve accessible, scalable, and simple to design and assemble morphing structures for more efficient and effective future ocean exploration and exploitation.

Information
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Online Ahead of Print: February 2, 2023

Topics

Robot actuator Soft robotics

Prof. Farnaz A. Yaghmaie
Automatic Control Group,
Linköping University

INTERNATIONAL JOURNAL OF
Robust and Nonlinear Control

RESEARCH ARTICLE

Differential graphical games for H_∞ control of linear heterogeneous multiagent systems

Farnaz Adib Yaghmaie, Kristian Hengster Movric, Frank L. Lewis, Rong Su

First published: 02 April 2019 | https://doi.org/10.1002/rnc.4538 | Citations: 11

Volume 29, Issue 10
10 July 2019
Pages 2995-3013

Summary

Differential graphical games have been introduced in the literature to solve state synchronization problem for linear homogeneous agents. When the agents are heterogeneous, the previous notion of graphical games cannot be used anymore and a new definition is required. In this paper, we define a novel concept of differential graphical games for linear heterogeneous agents subject to external unmodeled disturbances, which contain the previously introduced graphical game for homogeneous agents as a special case. Using our new formulation, we can solve both the output regulation and H_∞ output regulation problems. Our graphical game framework yields coupled Hamilton-Jacobi-Bellman equations, which are, in general, impossible to solve analytically. Therefore, we propose a new actor-critic algorithm to solve these coupled

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Optimal Control Applications and

Modular / Digital Materials

RO 2.1: Methodology for collaborative assembly of modular structures

K. Hengster-Movric, J. Zemánek

- Generate the construction plan and low-level local strategies from their high-level goal.
- Develop distributed self-assembly methods, possibly via biologically inspired control paradigms.
- Coordinate multiple assemblers/robots by collaborative control, cooperative consensus of multi-agent systems, or simultaneous manipulation by force fields.

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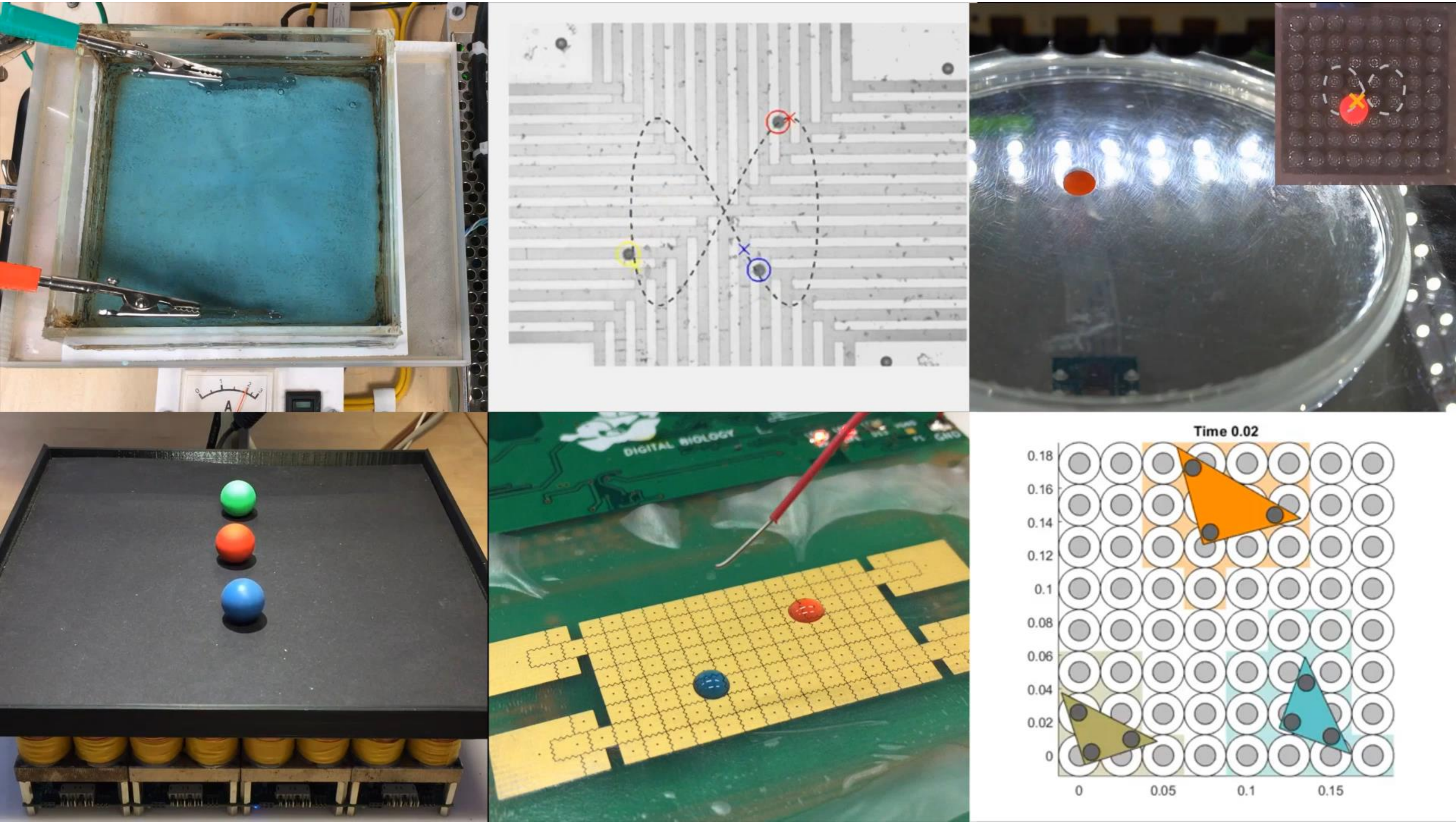

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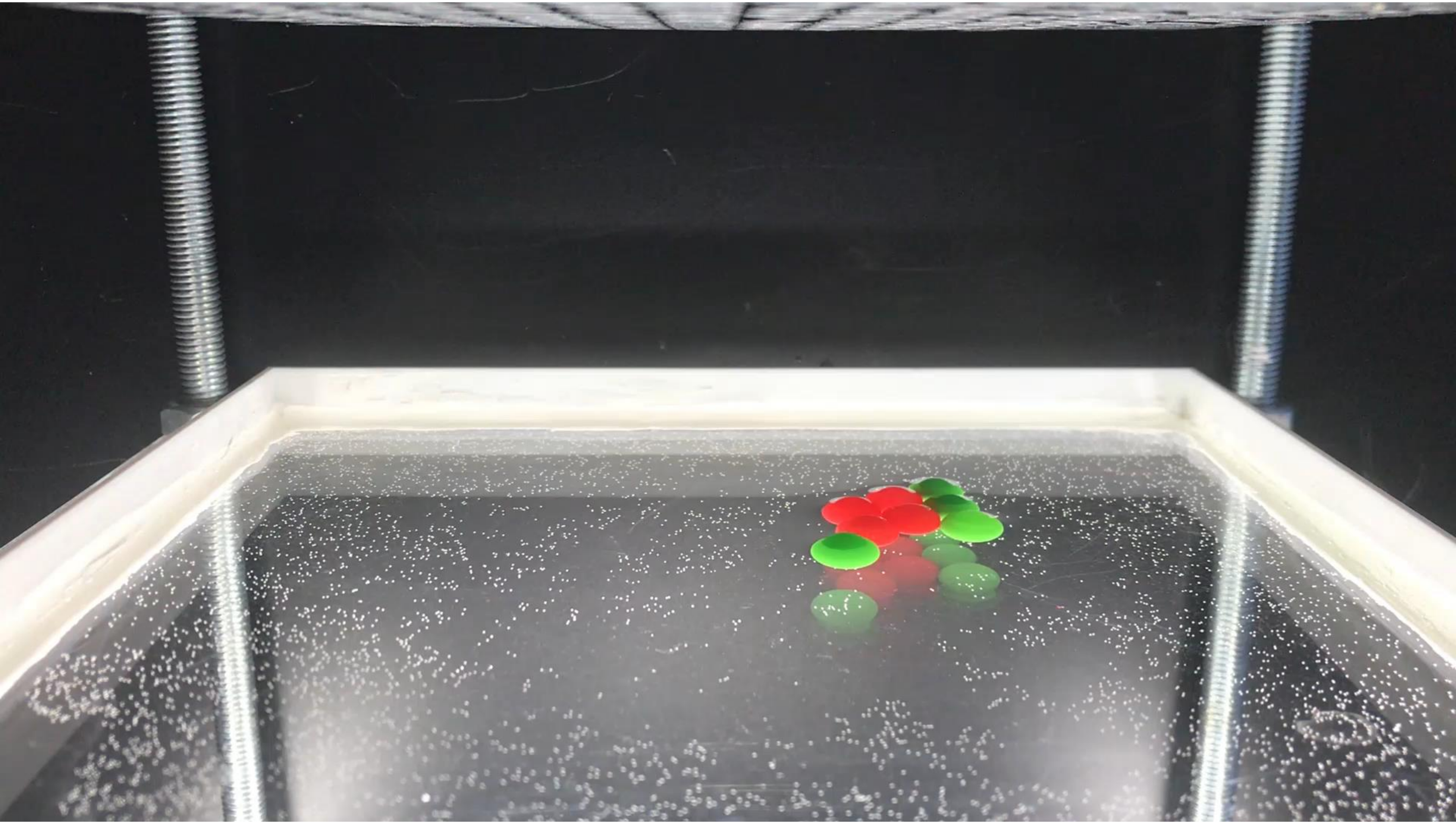
RO 2.1: Methodology for collaborative assembly of modular structures



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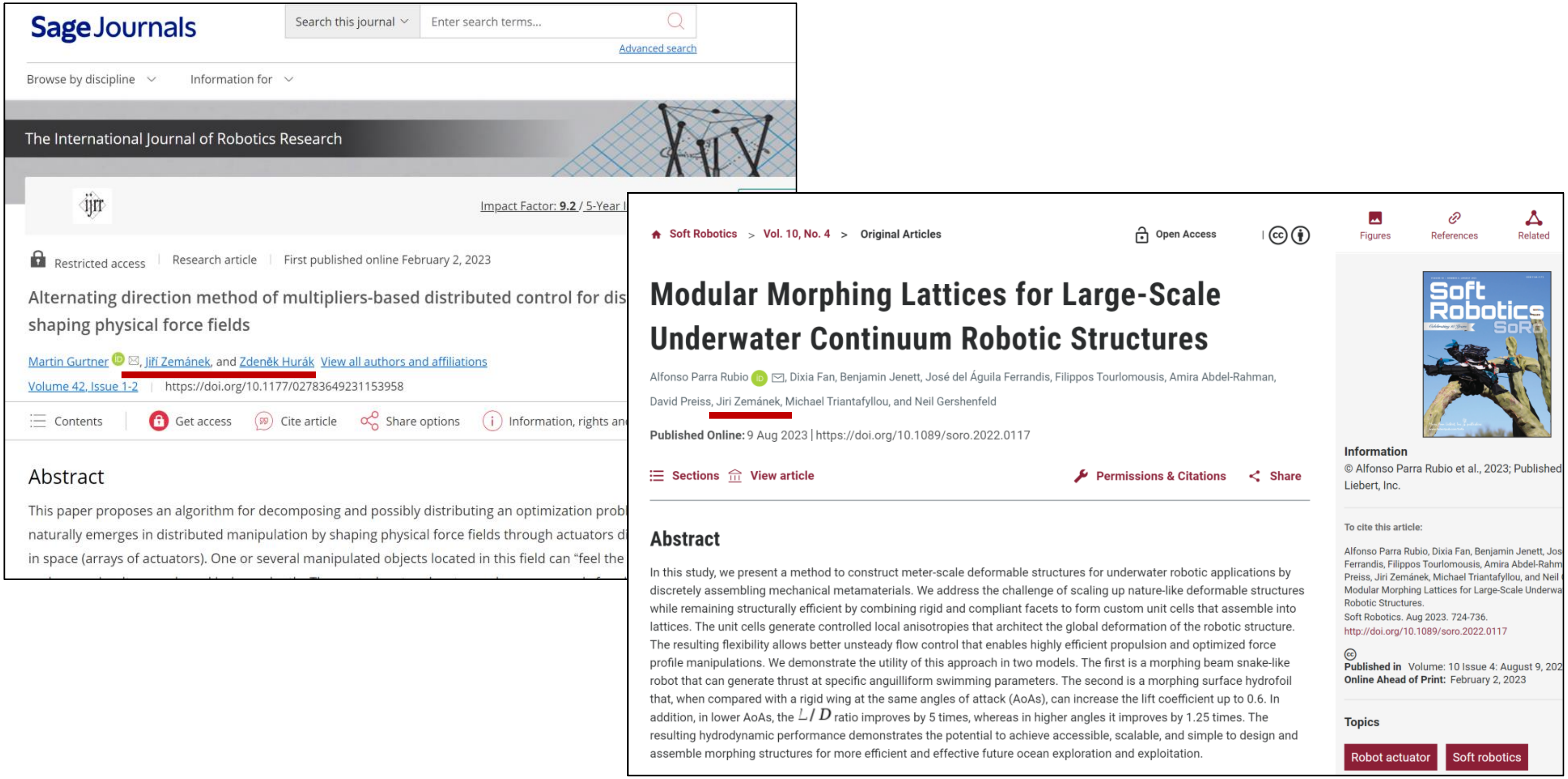

The International Journal of Robotics Research

Impact Factor: **9.2** / 5-Year I

Restricted access | Research article | First published online February 2, 2023

Alternating direction method of multipliers-based distributed control for dis
shaping physical force fields

Martin Gurtner, Jiří Zemánek, and Zdeněk Hurák View all authors and affiliations

Volume 42, Issue 1-2 | https://doi.org/10.1177/02783649231153958

Abstract

This paper proposes an algorithm for decomposing and possibly distributing an optimization prob
naturally emerges in distributed manipulation by shaping physical force fields through actuators di
in space (arrays of actuators). One or several manipulated objects located in this field can "feel the

Modular Morphing Lattices for Large-Scale Underwater Continuum Robotic Structures

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Topics

Robot actuator
Soft robotics

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RO 2.2: Methodology for control of assembled modular structures

Z. Hurák, M. Šebek, J. Zemánek

- Develop accurate (with quantified uncertainties) yet simple mathematical models for model-based control.
- Explore data-driven approaches.
- Treat and exploit nonlinear and weakly damped dynamics.
- Exploit the module interconnection structure that heavily influences these systems‘ dynamic behavior.

RO 2.2: Methodology for control of assembled modular structures

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Abstract

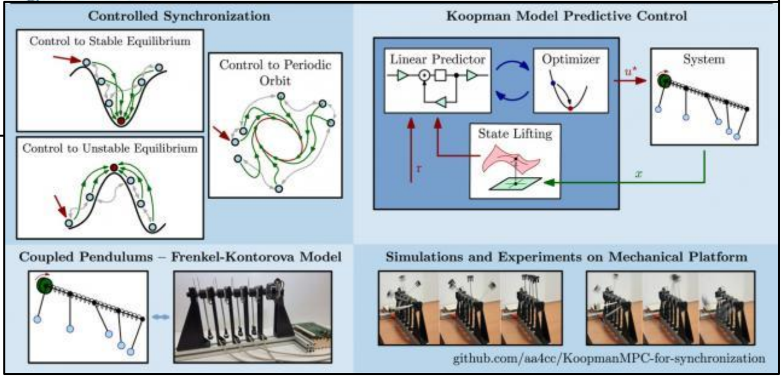
Control Engineering Practice

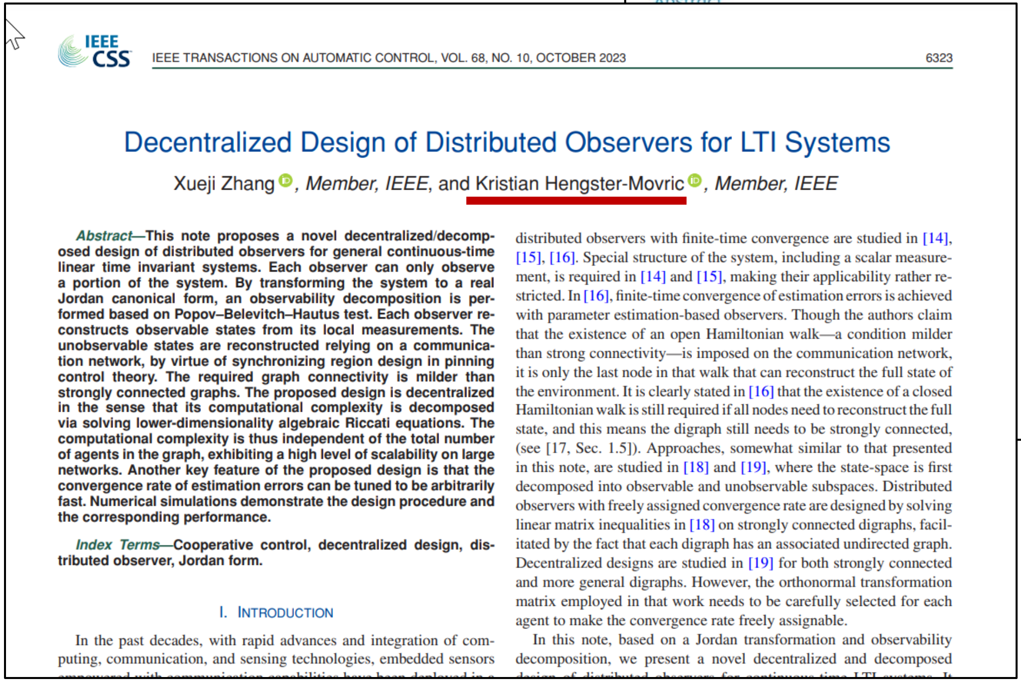
Volume 139, October 2023, 105629

ELSEVIER

Controlled synchronization of coupled pendulums by Koopman Model Predictive Control

Loi Do [a], Milan Korda [b], Zdeněk Hurák [a]





IEEE CSS IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 68, NO. 10, OCTOBER 2023 6323

Decentralized Design of Distributed Observers for LTI Systems

Xueji Zhang, *Member, IEEE*, and Kristian Hengster-Movric, *Member, IEEE*

***Abstract*—This note proposes a novel decentralized/decomposed design of distributed observers for general continuous-time linear time invariant systems. Each observer can only observe a portion of the system. By transforming the system to a real Jordan canonical form, an observability decomposition is performed based on Popov–Belevitch–Hautus test. Each observer reconstructs observable states from its local measurements. The unobservable states are reconstructed relying on a communication network, by virtue of synchronizing region design in pinning control theory. The required graph connectivity is milder than strongly connected graphs. The proposed design is decentralized in the sense that its computational complexity is decomposed via solving lower-dimensionality algebraic Riccati equations. The computational complexity is thus independent of the total number of agents in the graph, exhibiting a high level of scalability on large networks. Another key feature of the proposed design is that the convergence rate of estimation errors can be tuned to be arbitrarily fast. Numerical simulations demonstrate the design procedure and the corresponding performance.**

***Index Terms*—Cooperative control, decentralized design, distributed observer, Jordan form.**

I. INTRODUCTION

In the past decades, with rapid advances and integration of computing, communication, and sensing technologies, embedded sensors

distributed observers with finite-time convergence are studied in [14], [15], [16]. Special structure of the system, including a scalar measurement, is required in [14] and [15], making their applicability rather restricted. In [16], finite-time convergence of estimation errors is achieved with parameter estimation-based observers. Though the authors claim that the existence of an open Hamiltonian walk—a condition milder than strong connectivity—is imposed on the communication network, it is only the last node in that walk that can reconstruct the full state of the environment. It is clearly stated in [16] that the existence of a closed Hamiltonian walk is still required if all nodes need to reconstruct the full state, and this means the digraph still needs to be strongly connected, (see [17, Sec. 1.5]). Approaches, somewhat similar to that presented in this note, are studied in [18] and [19], where the state-space is first decomposed into observable and unobservable subspaces. Distributed observers with freely assigned convergence rate are designed by solving linear matrix inequalities in [18] on strongly connected digraphs, facilitated by the fact that each digraph has an associated undirected graph. Decentralized designs are studied in [19] for both strongly connected and more general digraphs. However, the orthonormal transformation matrix employed in that work needs to be carefully selected for each agent to make the convergence rate freely assignable.

In this note, based on a Jordan transformation and observability decomposition, we present a novel decentralized and decomposed

RA2: Project Papers

Fig. 1: (a) The rigid face, (b) the compliant face, an assembled voxel (c), and larger structure (d)

Fig. 3: Demonstation of the real actuated voxel (a) at rest; (b) tilted to the left; (c) tilted to the right

Fig. 4: Comparison of actuators type

Data-driven Feedback Control of Lattice Structures with Localized Actuation and Sensing

Dominik Fischer, Loi Do, and Jiří Zemánek

Abstract—**Lattices are periodic structures consisting of discrete building blocks, enabling the composition of large, heterogeneous, and easily reconfigurable objects. Because of the underlying structure, such materials are being referred to as digital materials. In recent years, researchers reported constructions of various structures and even robotic systems from digital materials. However, the existing literature has predominantly presented open-loop control. In this paper, we present a novel approach to feedback control of digital lattice structures, leveraging real-time measurements of system's dynamics. We introduce an actuated voxel which constitutes a novel means for actuation of lattice structures. Our control method is based on the Extended Dynamical Mode Decomposition algorithm in conjunction with the Linear Quadratic Regulator and the Koopman Model Predictive Control. A key advantage of our approach lies in its purely data-driven nature, not relying on any a priory information of system's structure. We illustrate the developed method on a custom-built flexible lattice beam, showing its ability to accomplish various tasks even with minimal sensing and actuation resources. In particular, we address two problems: stabilization together with disturbance attenuation, and reference tracking.**

Index Terms—**lattice structures, digital materials, extended dynamic mode decomposition, Koopman model predictive control**

I. INTRODUCTION

Lattice structures are commonly found in nature and their high stiffness-to-weight ratio is one of the reasons why researchers across multiple domains, such as robotics, civil engineering, and architecture, have been studying these materials. Such structures are also referred to as *digital* structures, as they are composed of discrete elements instead of continuous matter. The periodicity of lattices allows for their decomposition into repeated discrete blocks. Arranging building elements in repeating patterns is also typical for metamaterials – artificial materials with unique, and unconventional properties.

Having discrete blocks simplifies the process of making changes and repairs to the system since malfunctioning blocks can be easily replaced. Along with that, reconfigurability, modularity, and replicability are among the main reasons why digital structures are suitable for many applications. Unlike the conventional approaches to fabrication, this approach enables the assembly of large, heterogeneous structures by combining individual blocks with (possibly) different properties. Additionally, discrete structure allows for automated (dis)assembly of these materials.

Digital structures have been predominantly studied in connection to their structural design [1], [2], [3], [4] and static behavior [5]. Comprehensive description of feed-forward and integral force feedback control of lattice-structured satellites was given in [6]. In recent years the focus has been shifting also towards studying and controlling the dynamic properties of metamaterials. In [7], the authors presented two structures composed by assembling building elements into a lattice: a morphing aircraft wing and an underwater snake-like robot. Active control was introduced into these structures allowing the wing to change shape and the robot to achieve swimming, nature-inspired motion. Among other fields where digital materials find relevance are soft robotics, production of wearable devices, prosthetics [8], as well as optimized electronic devices [9]. Possible applications of digital metamaterials extend even to the construction of space structures [10], showcasing their diverse potential.

Our primary focus is on structures akin to those presented in [7]. These structures have so far been subjected to precomputed input sequences, leaving space for more advanced control algorithms to be explored and applied. In this paper, we present a novel mechanism of actuation of digital lattice structures and develop a systematic method for feedback control synthesis. Controlling digital structures presents a challenge. This is mainly because of the involved process of obtaining a dynamical model of a structure with many distinct building blocks. Furthermore, flexible structures naturally exhibit nonlinear dynamics. In light of that we opted for a data-driven modeling approach based on the Extended dynamic mode decomposition (EDMD) algorithm [11]. Using the EDMD, we were able to obtain a linear predictor, allowing us to use standard linear control synthesis methods. We use Linear Quadratic Regulator (LQR) and Koopman Model Predictive Control (KMPC) to address the tasks of stabilization disturbance attenuation, and reference tracking. The steps taken and results presented in this paper will facilitate the solution of more complex tasks and expand the potential applications of digital lattice-based structures.

II. SYSTEM DESCRIPTION AND PROBLEM DEFINITION

A. Cuboctahedron as Building Block

We focus on lattice structures where the single building block is a cuboctahedron, i.e., polyhedron with eight triangular and six square faces. In particular, we adopt a construction design developed by the *Center for Bits and Atoms* at MIT published in [12]. We assemble a single cuboctahedron by

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Dominik Fischer, Loi Do, and Jiří Zemánek are with Faculty of Electrical Engineering, Czech Technical University in Prague {`fischdom, doloi, jiri.zemanek`}`[at]fel.cvut.cz`

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separate distinct module, an actuated *joint*. In contrast, the actuation mechanism presented in this paper is self-contained in a single voxel. Additionally, the housing voxel is identical to other building blocks, which simplifies the construction of the overall structure. See Fig. 4 for an illustration of differences between the mechanisms.

C. Sensing Voxel

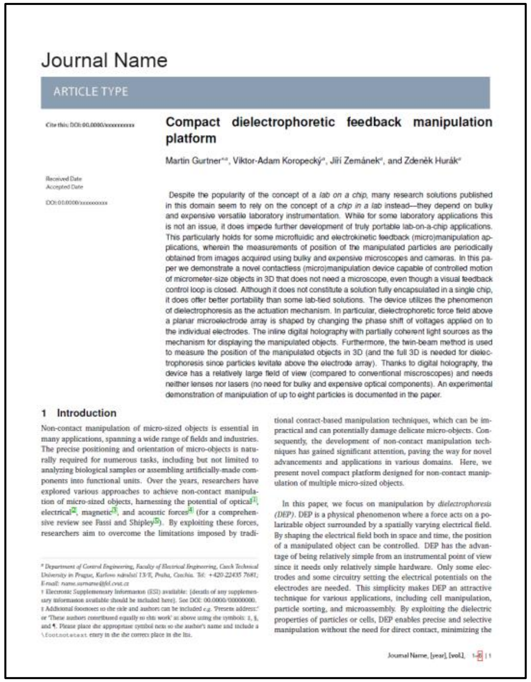
For measuring the system's motion, we use an inertial measurement unit (IMU) inserted into a voxel, see Fig. 5. Comparably to the actuated voxel, the sensing is also self-contained within a single voxel. We created the housing voxel using only rigid faces, but different options could also be possible with minor changes to the construction. We used *MPU9250* IMU, which allows measurement of acceleration, angular speed, and (estimated) orientation along all three axes.

D. Problem Definition

Consider a general (arbitrary) voxel-lattice structure with fixed arrangement of empty, actuated and sensing voxels. We assume, that the structure's arrangement allows controlling the output y with the input u.

Fig. 5: Sensing Voxel

→ IEEE CDC



Journal Name

ARTICLE TYPE

Cite this: DOI: 00.0000/xxxxxxxxxx

Compact dielectrophoretic feedback manipulation platform

Martin Gurtner*[a], Viktor-Adam Koropecký[a], Jiří Zemánek[a], and Zdeněk Hurák[a]

Received Date
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Despite the popularity of the concept of a *lab on a chip*, many research solutions published in this domain seem to rely on the concept of a *chip in a lab* instead—they depend on bulky and expensive versatile laboratory instrumentation. While for some laboratory applications this is not an issue, it does impede further development of truly portable lab-on-a-chip applications. This particularly holds for some microfluidic and electrokinetic feedback (micro)manipulation applications, wherein the measurements of position of the manipulated particles are periodically obtained from images acquired using bulky and expensive microscopes and cameras. In this paper we demonstrate a novel contactless (micro)manipulation device capable of controlled motion of micrometer-size objects in 3D that does not need a microscope, even though a visual feedback control loop is closed. Although it does not constitute a solution fully encapsulated in a single chip, it does offer better portability than some lab-tied solutions. The device utilizes the phenomenon of dielectrophoresis as the actuation mechanism. In particular, dielectrophoretic force field above a planar microelectrode array is shaped by changing the phase shift of voltages applied on to the individual electrodes. The inline digital holography with partially coherent light sources as the mechanism for displaying the manipulated objects. Furthermore, the twin-beam method is used to measure the position of the manipulated objects in 3D (and the full 3D is needed for dielectrophoresis since particles levitate above the electrode array). Thanks to digital holography, the device has a relatively large field of view (compared to conventional miscroscopes) and needs neither lenses nor lasers (no need for bulky and expensive optical components). An experimental demonstration of manipulation of up to eight particles is documented in the paper.

1 Introduction

Non-contact manipulation of micro-sized objects is essential in many applications, spanning a wide range of fields and industries. The precise positioning and orientation of micro-objects is naturally required for numerous tasks, including but not limited to analyzing biological samples or assembling artificially-made components into functional units. Over the years, researchers have explored various approaches to achieve non-contact manipulation of micro-sized objects, harnessing the potential of optical[1], electrical[2], magnetic[3], and acoustic forces[4] (for a comprehensive review see Fassi and Shipley[5]). By exploiting these forces, researchers aim to overcome the limitations imposed by traditional contact-based manipulation techniques, which can be impractical and can potentially damage delicate micro-objects. Consequently, the development of non-contact manipulation techniques has gained significant attention, paving the way for novel advancements and applications in various domains. Here, we present novel compact platform designed for non-contact manipulation of multiple micro-sized objects.

In this paper, we focus on manipulation by *dielectrophoresis (DEP)*. DEP is a physical phenomenon where a force acts on a polarizable object surrounded by a spatially varying electrical field. By shaping the electrical field both in space and time, the position of a manipulated object can be controlled. DEP has the advantage of being relatively simple from an instrumental point of view since it needs only relatively simple hardware. Only some electrodes and some circuitry setting the electrical potentials on the electrodes are needed. This simplicity makes DEP an attractive technique for various applications, including cell manipulation, particle sorting, and microassembly. By exploiting the dielectric properties of particles or cells, DEP enables precise and selective manipulation without the need for direct contact, minimizing the

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[a] *Department of Control Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague, Karlovo náměstí 13/E, Praha, Czechia. Tel: +420 22435 7681; E-mail: name.surname@fel.cvut.cz*

† Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 00.0000/00000000.

‡ Additional footnotes to the title and authors can be included e.g. 'Present address:' or 'These authors contributed equally to this work' as above using the symbols: ‡, §, and ¶. Please place the appropriate symbol next to the author's name and include a `\footnotetext` entry in the the correct place in the list.

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