A Systematic Approach for Design, Modeling, and Control of Soft Robotic Systems

Brandon Jonathan Caasenbrood

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Proefschrift

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door

Brandon Jonathan Caasenbrood

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Abstract

A Systematic Approach for Design, Modeling, and Control of Soft Robotic Systems

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Contents

Nomenclature

Vector and matrix notation

x	Scalar notation
$\boldsymbol{x}$	Vector notation
$\boldsymbol{X}$	Matrix notation
$\boldsymbol{\mathcal{X}}$	Tensor notation
$\boldsymbol{\mathcal{Q}}$	Manifold

Compact sets

$\emptyset$	Empty set
$\mathbb{R}$	Set of real numbers
$\mathbb{R}^n$	n-dimensional Euclidean space
$\mathbb{R}_{>0}$	Strictly positive reals
$\mathbb{R}_{\geq 0}$	Positive reals
$\mathbb{N}$	Set of natural numbers
$\mathbb{T}$	Finite time horizon
$\mathbb{X}$	1-dimensional spatial set or domain (*i.e.*, line)
$\mathbb{V}$	3-dimensional spatial set or domain (*i.e.*, volume)

Groups

id	Identity
$\mathrm{SO}(n)$	Lie group of rotations on $\mathbb{R}^n$ (*i.e.*, special orthonormal matrices)
$\mathrm{SE}(n)$	Lie group of homogeneous transformations on $\mathbb{R}^n$
$\mathrm{so}(n)$	Lie algebra of $\mathrm{SO}(n)$
$\mathrm{se}(n)$	Lie algebra of $\mathrm{SE}(n)$

Vector- and matrix operations

$\dot{(\cdot)}$	First time derivative
$\ddot{(\cdot)}$	Second time derivative
$\hat{(\cdot)}, (\cdot)^\wedge$	Isomorphism from $\mathbb{R}^6 \to \mathrm{se}(3)$
$\check{(\cdot)}, (\cdot)^\vee$	Isomorphism from $\mathrm{se}(3) \to \mathbb{R}^6$
$(\cdot)_0$	Reference configuration
$(\cdot)^\top$	Transpose
$(\cdot)^{-1}$	Square matrix inverse
$(\cdot)^\dagger$	Moore-Penrose pseudo inverse
$(\cdot)^+$	Generalized matrix inverse
$(\cdot)^d$	Generalized matrix inverse

Operators and letter-like symbols

δ	Variation of a field
∂	Boundary of a set
int	Interior of a set
$\sup_t$	Supremum over continuous time t
dim	Dimension of vector
trace	Trace of matrix
$\\|\cdot\\|_{\mathrm{ma}}$	Mean absolute norm
$\\|\cdot\\|_{\mathrm{rms}}$	Root-mean-square norm

Acronyms

CoM	Center of mass
CoR	Coefficient of restitution

1

Introduction

1.1 A Brief History of Soft Robotics

Definition

The term '*soft robotics*' is the abbreviated form of '*soft material robotics*'. Although the words '*soft*' and '*robotics*' have a clear definitions independently, the collocation of the two has sparked vivid discussions in the robotics community for many years – even touching the territories of the philosophical. Consequently, the exponential scientific interest in soft robotics around 2008 – may be seen as a historical cornerstone that has revolutionized our perspective on the divergent field of robotics and rekindled its original ambitions. Although the debate on the exact terminology is still ongoing, which may never be closed; we propose a definition for '*soft robotics*' applicable for this work based on an ensemble of prior literature :

> **Terminology: Soft robotics** *is the study of robotic systems with purposefully designed compliant elements embedded into their mechanical structure whose goal is to endow the robotic system with biological motion.*

The definition above is mostly adopted from Della Santina et al. [], yet modified to purposefully highlight the importance of soft materials to mimic biological motion – also referred to as '*bio-mimicry*'. The ambition of closely mimicking biological creatures is perhaps not often associated with the field of robotics in general. yet the inception of robotics actually originates in bio-mimicry.

However, as opposed to many biological systems, the physical structure of conventional rigid robots have been generally stiff. The inception for such design choices stems from industrial-oriented tasks for fast, precise and repeatable motion. Naturally this leads to mechanical systems composed for rigid materials supported by fast mechanical actuators, i.e., electromechanical systems.

Perhaps a subtle point in the terminology above, is its mention to biology. Although the area of soft robotics has grown exponentially since the early 2010's, the field of soft robotics dates back to the early 60's.

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I

Design Optimization

II

Modeling of Soft Robots

III

Control and Sensing Strategies

IV

Appendices

A
Appendix name

A.1 Section header

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Acknowledgements

List of publications

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Curriculum Vitae