Tensegrity Robotics

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What you will learn in this class

- Short history of tensegrity structures
- Definition of a tensegrity structure
- How to regulate the compliance of a tensegrity structure
- 4 simple types of hand-designed tensegrity structures
- Topology and form finding problems
- Tensegrity in biology
- Potential advantages of tensegrity in robotics
- Some examples of tensegrity robots
- Evolutionary design of tensegrity structures and control

Russian Constructivism, early 20’s

“All new approaches to art arise from technology and engineering and move towards organisation and construction”

(Rodchenko, 1921)

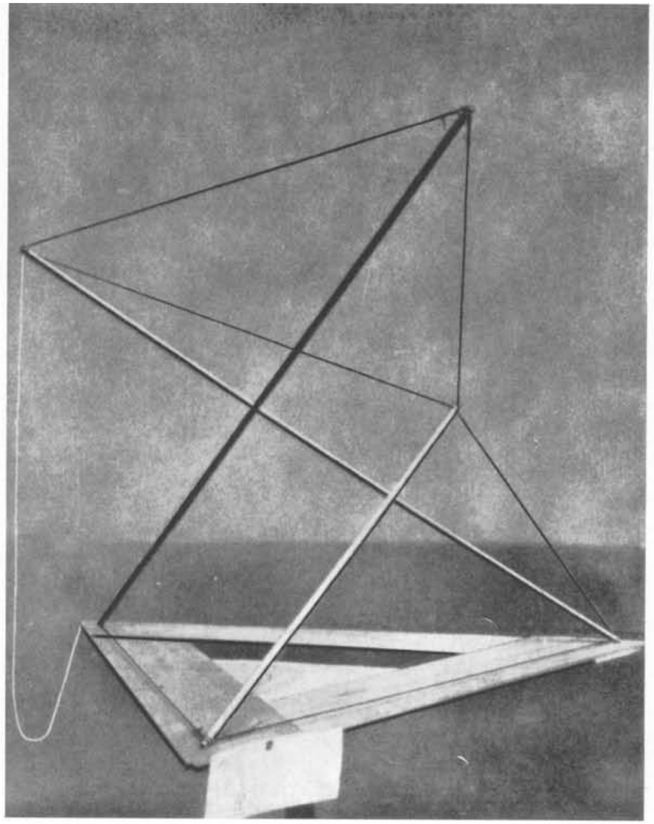


abb. 116 **johansen,** moskau 1921
gleichgewichtskonstruktion (zieht man an dem faden, gerät die plastik in eine andere, gleich wie die erste, ausbalancierte stellung).

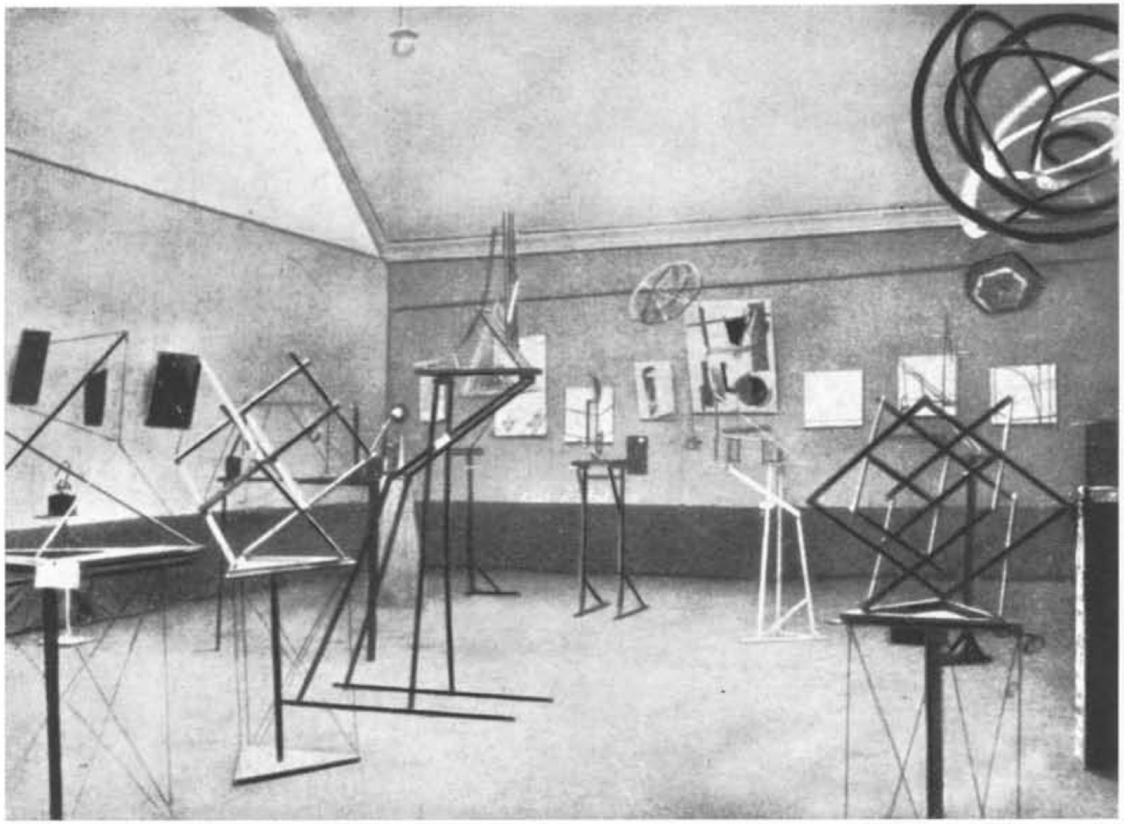


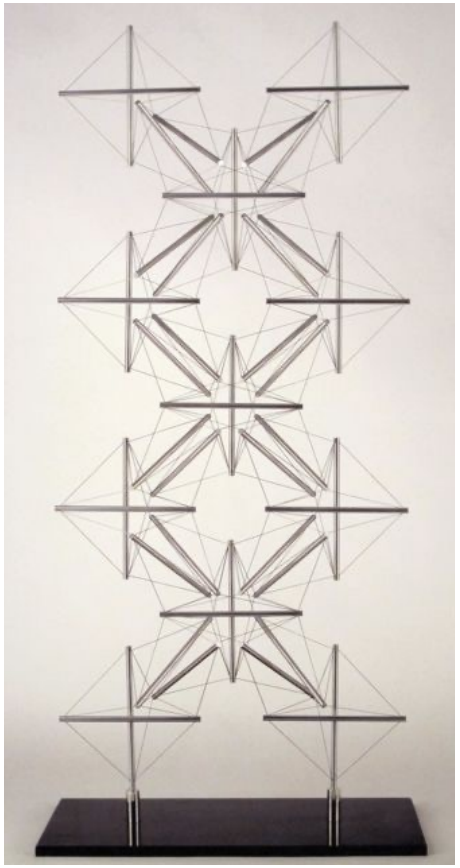
foto: buch neuer künstler

abb. 115 die ausstellung der russischen konstruktivisten in moskau 1921

Images: Laszlo Moholy Nagy, Von Materiel zu Arkitektur, Munich, 1929

Kenneth Snelson, 1927-2016

Early X-Piece, 1948

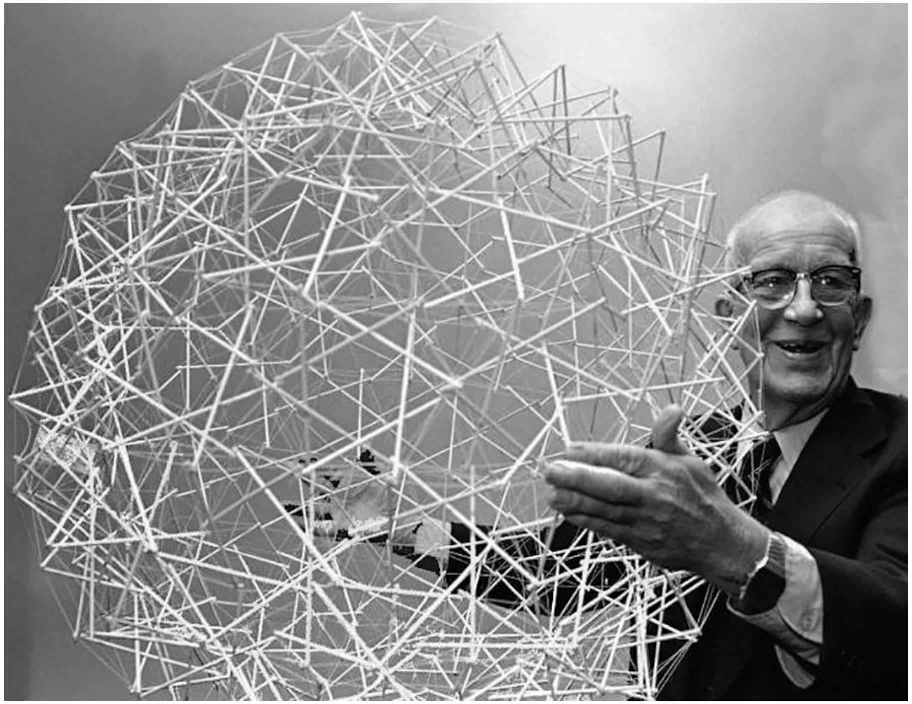


X-Planar tower, 1962-88

Easy landing (Baltimore, MA), 1977

R. Buckminster Fuller, 1895-1983

“Islands of compression in an ocean of tension; Tensional integrity -> Tensegrity”



Biosphère, Montreal, 1967
Expo 67, US Pavillon

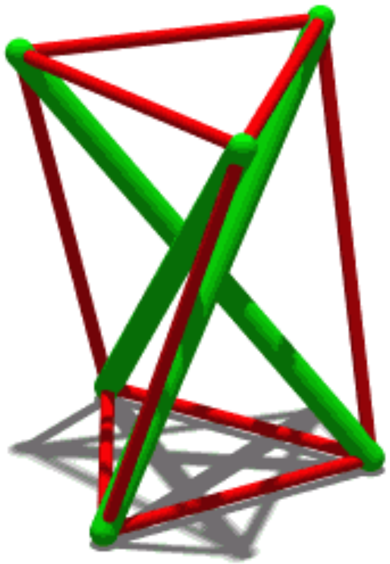
Passera-Pedretti, Yverdon, Expo 02

Furniture

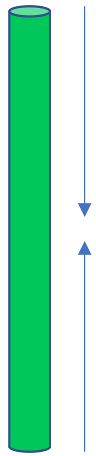
Image: www.kruegermany.com

Image: www.robbycuthbert.com

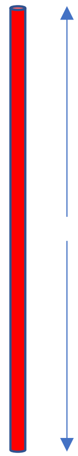
Elements of a tensegrity structure



T3 Prism (Image: Wikipedia)



Bar

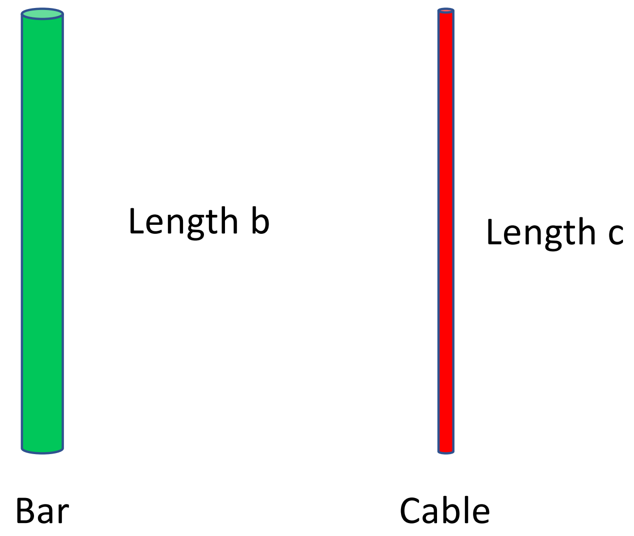


Cable

- Forces distribute axially through the structure
- Bars experience only compressive forces, cables experience only tensile forces
- Cables form a continuous set through which tensional forces distribute
- Bars form a discontinuous set and are under compression, independently of external forces
- *Bars are not directly connected to each other*
- *Each node receives only one compressed element*

Stable self-equilibrium & pre-stress

All forces are equilibrated and tensegrity assumes a well-defined shape only if cables are pre-stressed

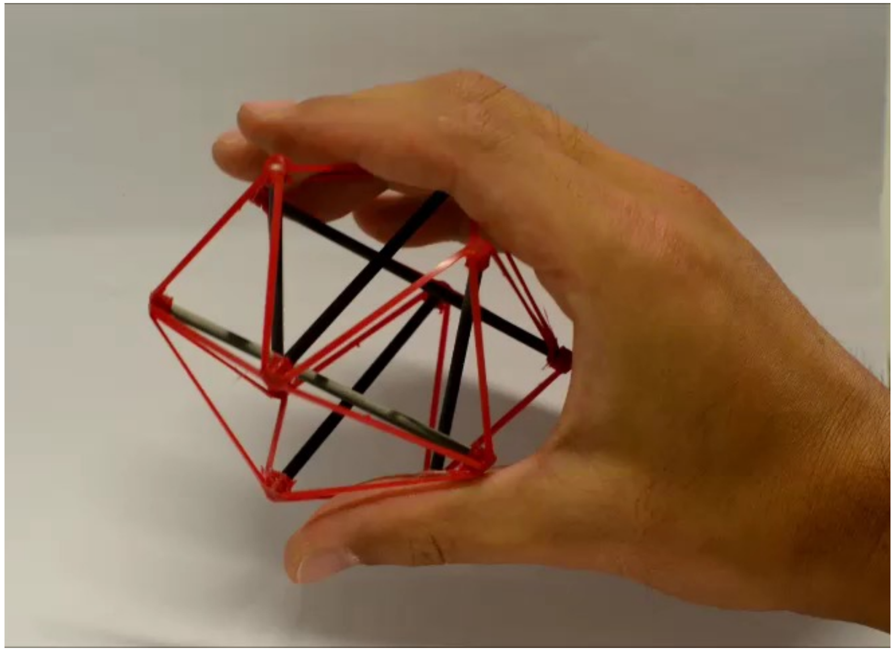


c>b shape is not defined
c<b shape is defined, tensegrity is self-stressed, structure is in stable self-equilibrium
c=b shape is defined (special case, called null self-stress, ideal case)

There is a minimum pre-stress requirement, but there is no upper limit

Cables form a continuous tensional network

Cables form a continuous network at the periphery of the tensegrity structure (*the ocean*)
Bars are discontinuous elements inside tensional network (*the islands*)



Tensional or compression forces externally applied at any point, redistribute through the cable network

How to define tensegrity stiffness

Once a minimal pre-stress level is identified for stability, a tensegrity structure

1) can be made **stiffer** by increasing pre-stress
2) can be made *softer* by using cables with lower Young modulus

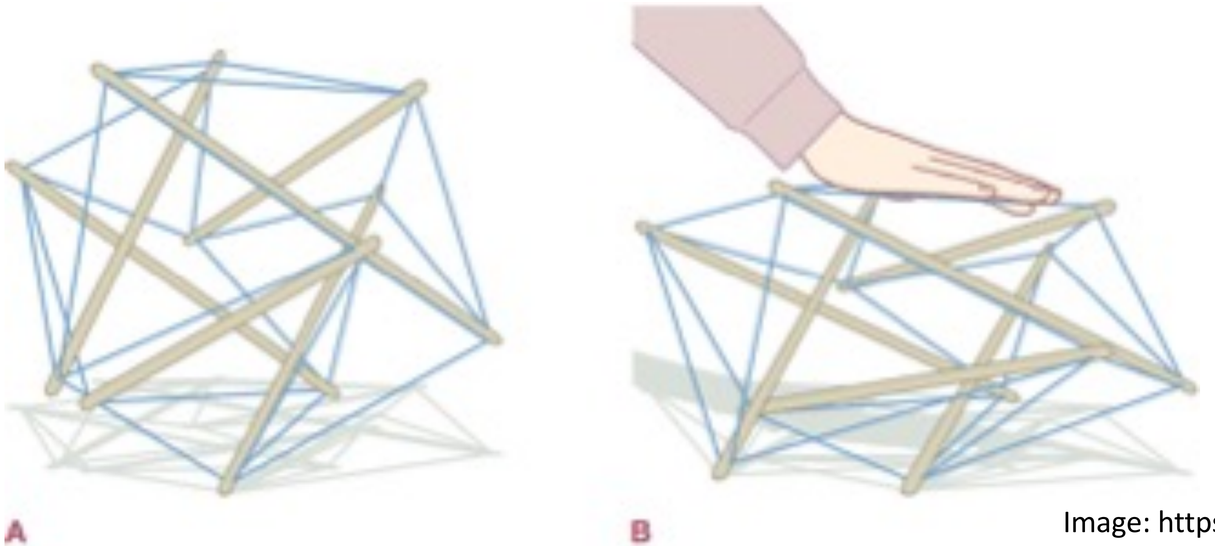
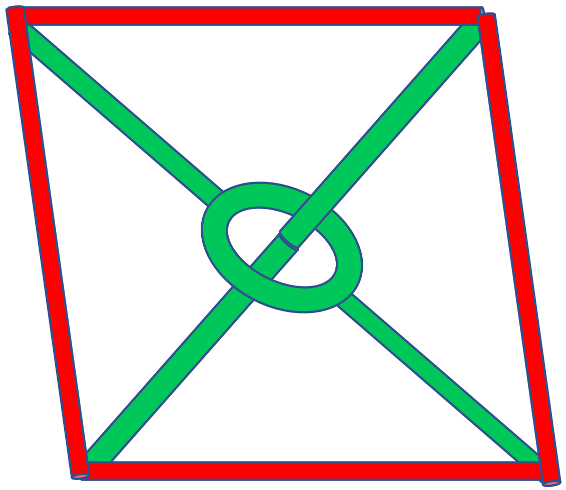


Image: https://www.anatomytrains.com/fascia/tensegrity/

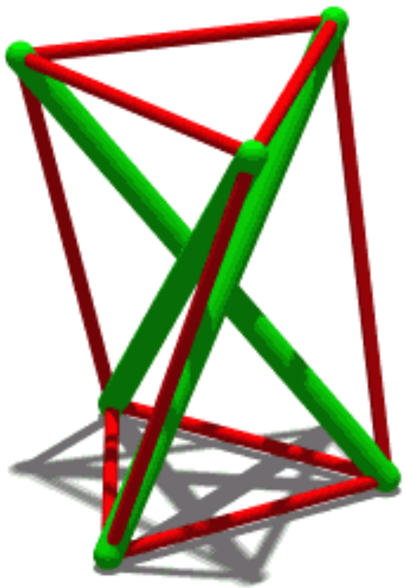
The tensegrity returns to its original shape after the external perturbation because it is in stable self-equilibrium

Simple tensegrity structures

1-Dimensional
1 bar, 1 cable

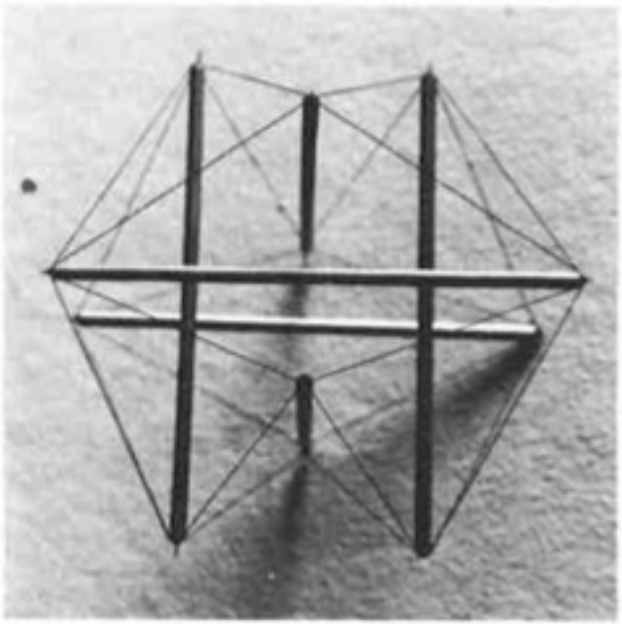


2-Dimensional
2 bars, 4 cables

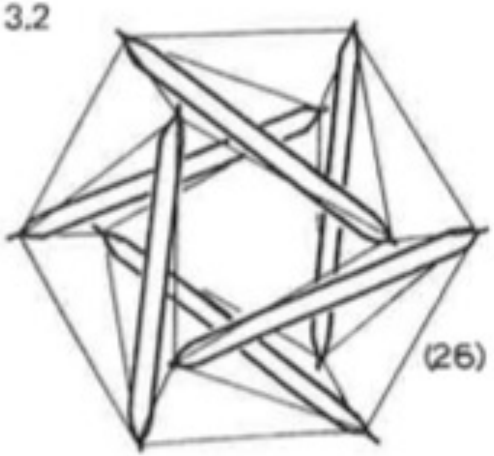


3-Dimensional
3 bars, 9 cables

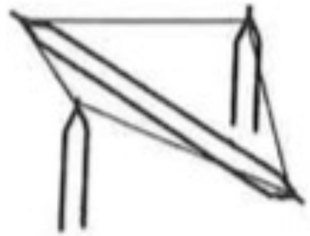
The icosahedron



3.2



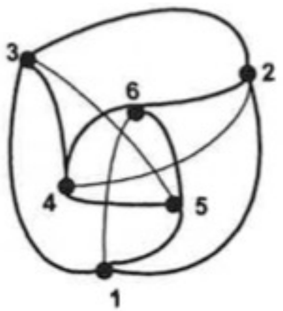
(26)



Images: A. Pugh, An introduction to tensegrity, University of California Berkeley Press, 1976

Identification of tensegrity structures is a challenge

Topology / connectivity

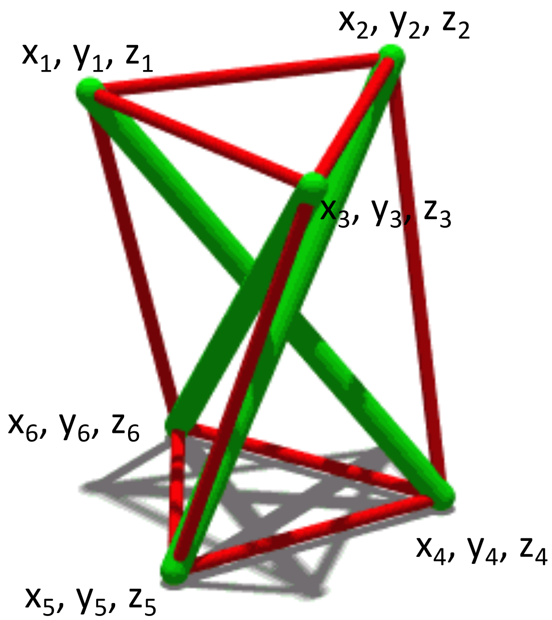


Element	Type	End 1	End 2
1	Compression	1	6
2	Compression	2	4
3	Compression	3	5
4	Tension	1	2
5	Tension	2	3
6	Tension	1	3
7	Tension	3	4
8	Tension	1	5
9	Tension	2	6
10	Tension	4	5
11	Tension	5	6
12	Tension	4	6

Not all topologies can be self-stressed

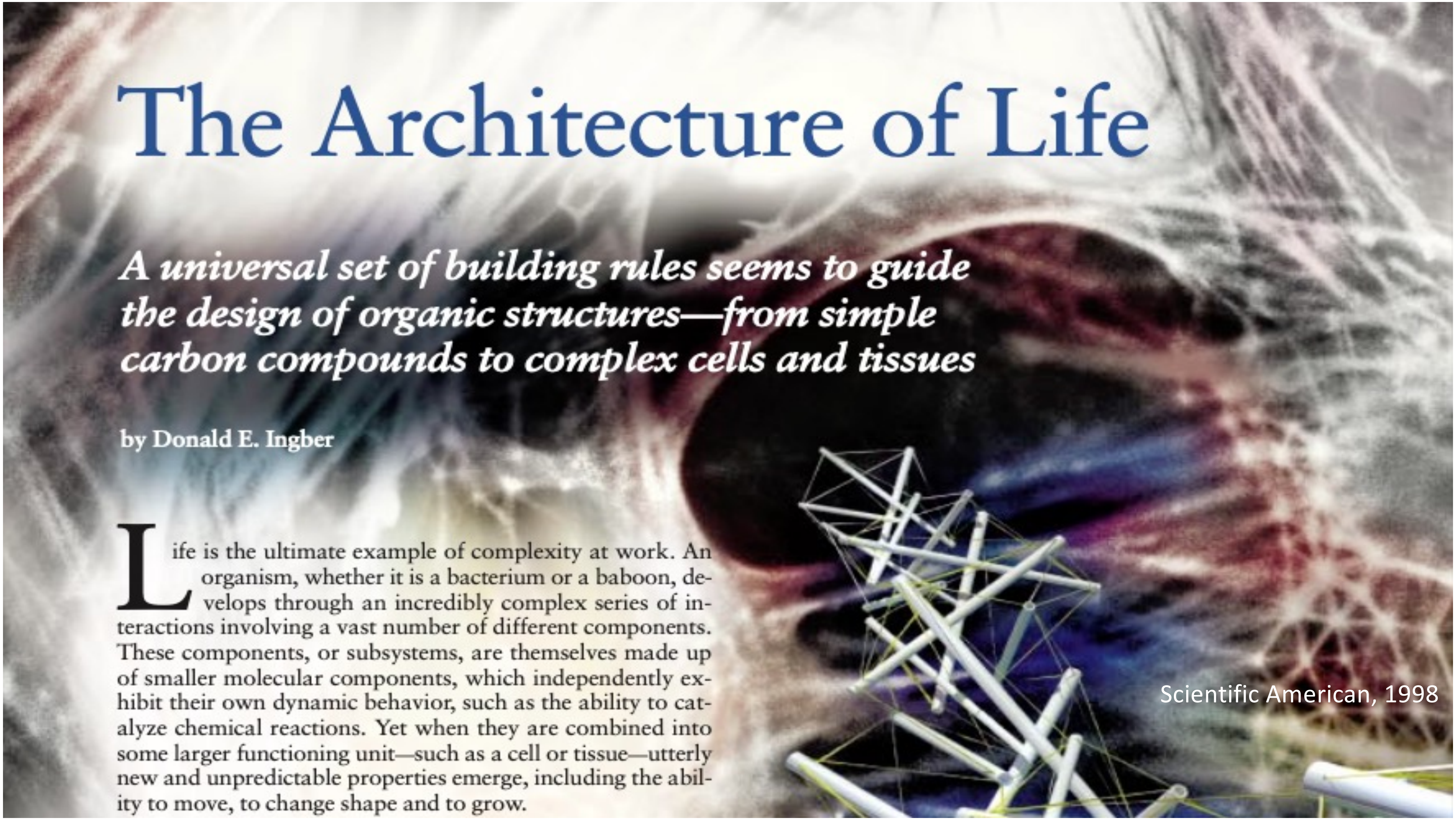
TOPOLOGY-FINDING PROBLEM

Form / geometry



Not all corresponding forms are in self-equilibrium

FORM-FINDING PROBLEM



The Architecture of Life

A universal set of building rules seems to guide the design of organic structures—from simple carbon compounds to complex cells and tissues

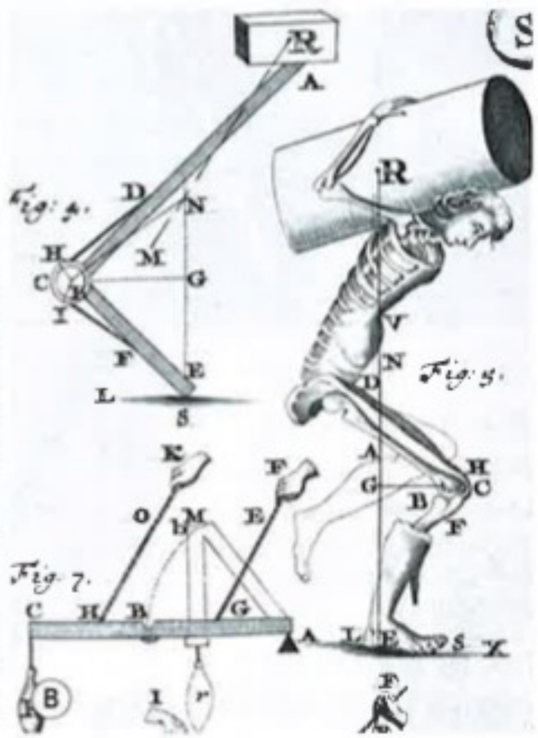
by Donald E. Ingber

Life is the ultimate example of complexity at work. An organism, whether it is a bacterium or a baboon, develops through an incredibly complex series of interactions involving a vast number of different components. These components, or subsystems, are themselves made up of smaller molecular components, which independently exhibit their own dynamic behavior, such as the ability to catalyze chemical reactions. Yet when they are combined into some larger functioning unit—such as a cell or tissue—utterly new and unpredictable properties emerge, including the ability to move, to change shape and to grow.

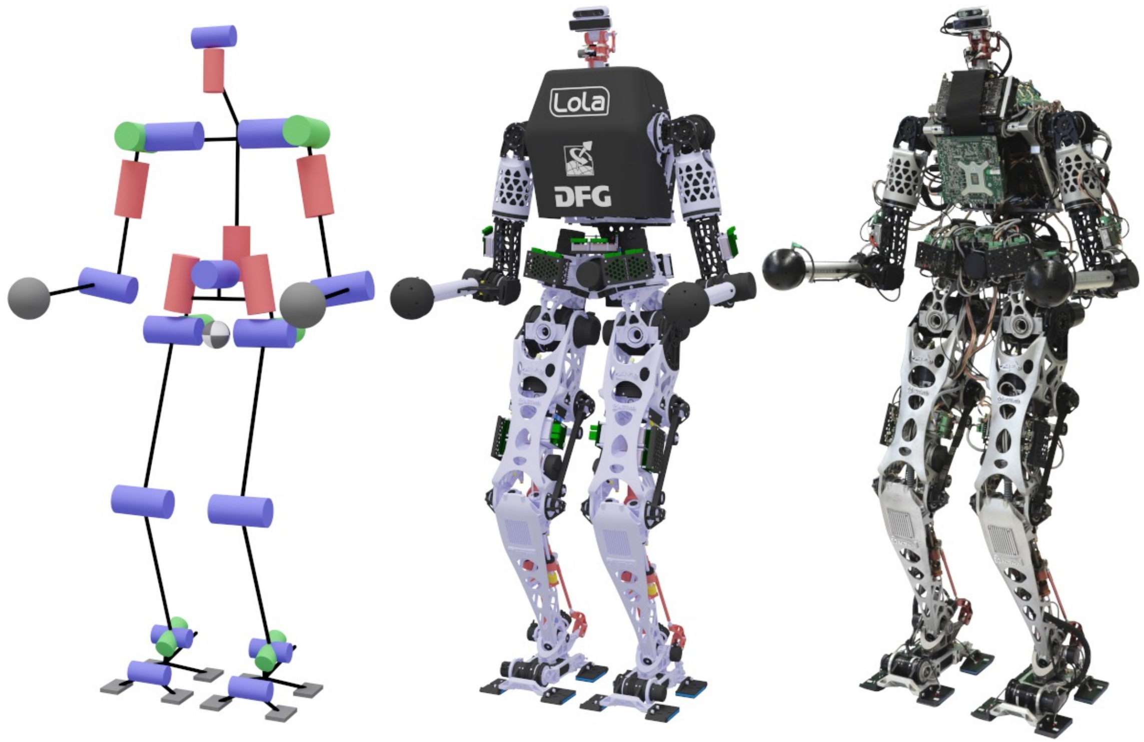
Scientific American, 1998

Old view of human bodies and modern robots

Vesalius, De Humani Corporis Fabrica, 1543



Borelli, De Motu Animalium, 1680

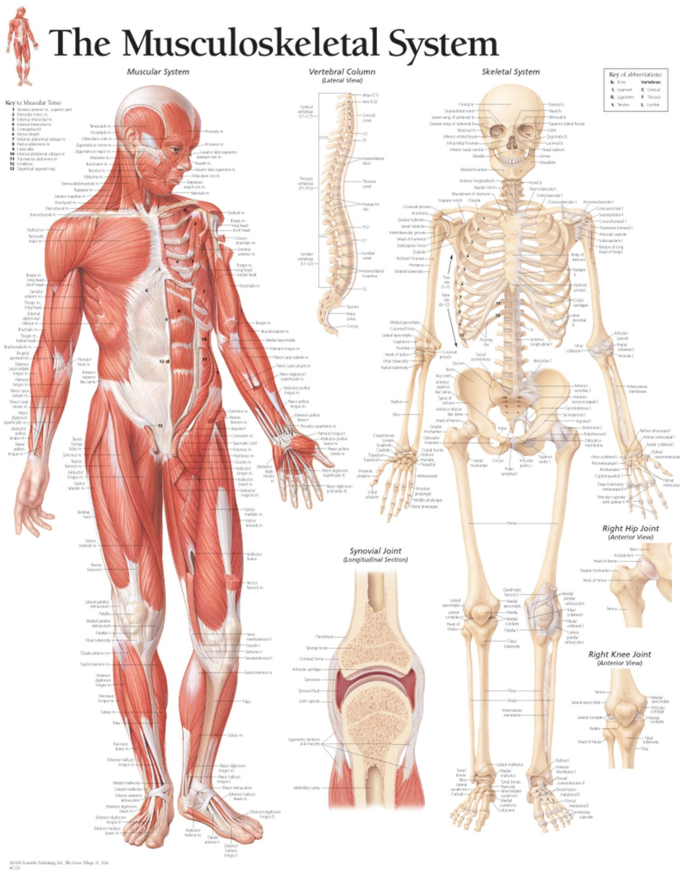


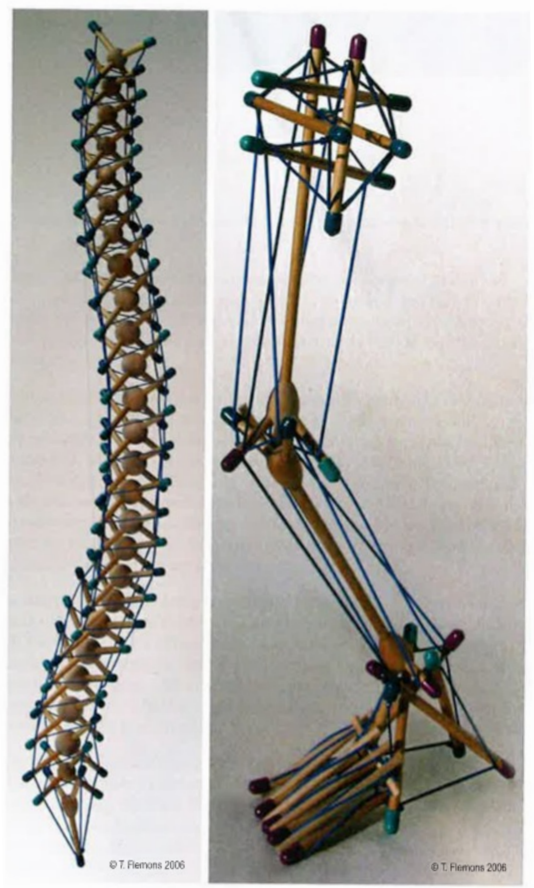
Lola, Technical University Munich (176 cm, 68 kg, 26 joints)

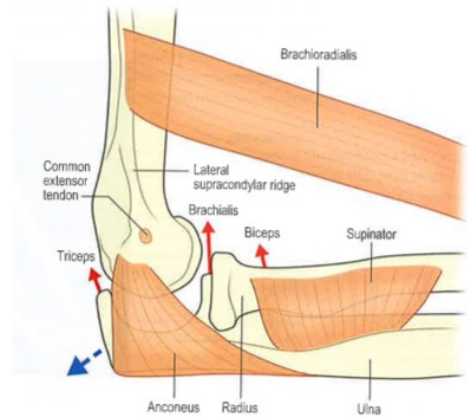
A cantilever system of connected rigid bodies

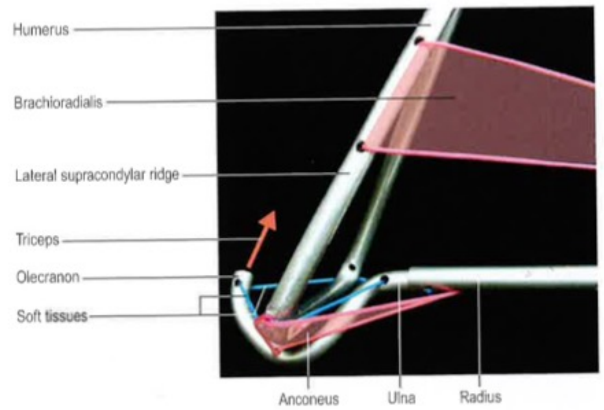
Musculoskeletal system as a tensegrity system

206 bones of the human body are supported by more than 300 skeletal muscles and 4000 tendons and ligaments.
Compressive forces on the bones are neutralized by tensile forces of muscles, ligaments, and tendons.









Images: Scarr, Biotensegrity, 2018

Tensegrity equilibrium

Skeleton of a Diplodocus, Museum für Naturkunde, Berlin.

Tensegrity structures maintain stable equilibrium by redistributing external and internal loads throughout the entire musculoskeletal system with minimal mass and energy. They can absorb impacts without breaking, comply or resist external loads by changing stiffness, and regain shape after deformations.

Why tensegrity-based robots?

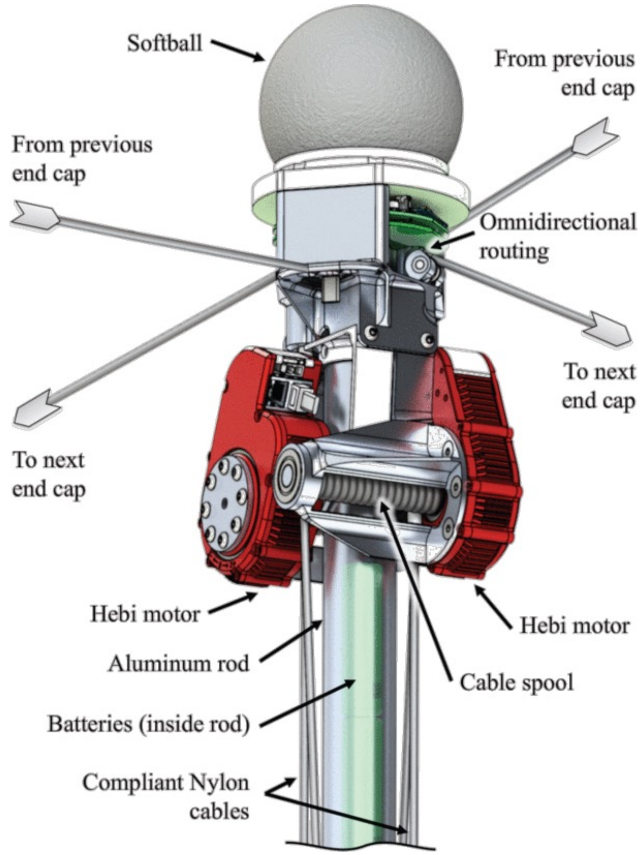
- **Lightweight**: minimal mass for load bearing unit
- **Compliant**: tensegrity structures can absorb shocks and regain original shape
- **Foldable**: structural flexibility enables packing into small volumes for transportation and on-site deployment
- **Shape changing**: changing cable and/or bar lengths can adapt to different requirements and generate motion
- **Empty volume**: enables positioning of protected payloads (sensors, CPUs, batteries, cargo)

Rolling by changing cable length with winch

Local deformation shifts center of mass forward towards front edge of the supporting polygon, and this makes the robot roll to another polygonal face.

6 bars, 24 actuated cables
Compliant nylon cables (15% stretch)

Initial design: MatLab Objects
Control in simulation: NTRT
Manufacturing



M. Vespignani, J. M. Friesen, V. SunSpiral and J. Bruce, "Design of SUPERball v2, a Compliant Tensegrity Robot for Absorbing Large Impacts," 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 2018, pp. 2865-2871, doi: 10.1109/IROS.2018.8594374.

Design of SUPERball v2, a Compliant Tensegrity Robot for Absorbing Large Impacts

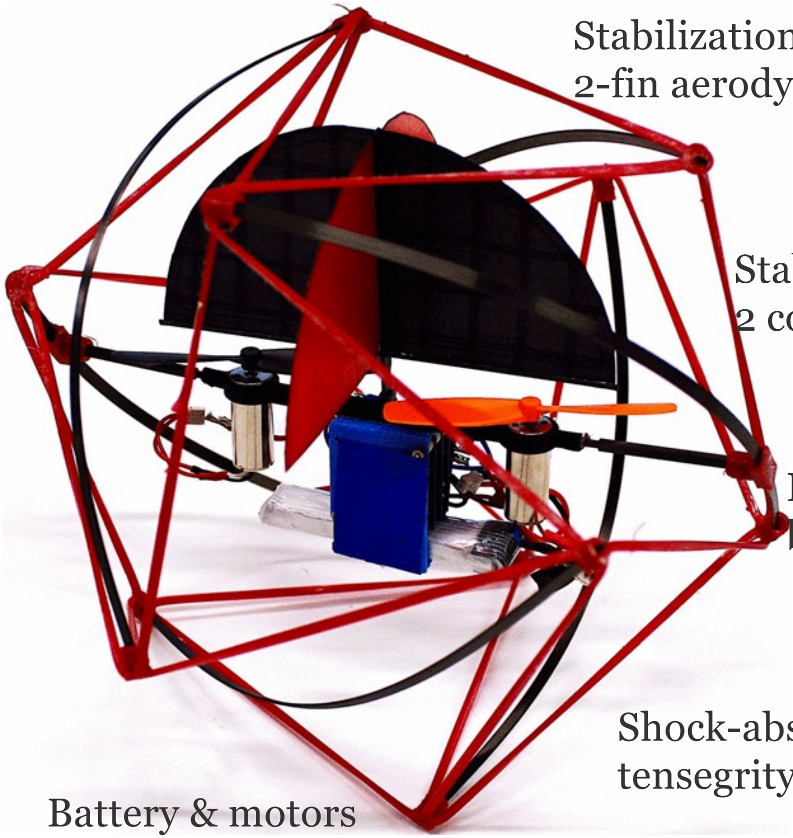
Massimo Vespignani[1], Jeffrey M. Friesen[2], Vytas SunSpiral[1], Jonathan E. Bruce[1]

[1] Dynamic Tensegrity Robotics Lab, Intelligent Robotics Group,
NASA Ames Research Center, Moffett Field CA 94035 USA

[2] UC San Diego Coordinated Robotics Lab, MC 0411, La Jolla CA, 92093 USA

Video attachment to IROS 2018

Hopping exploration



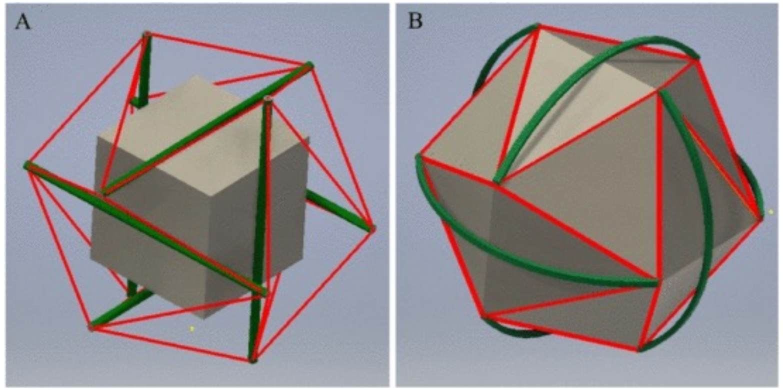
Stabilization in pitch and roll is given by 2-fin aerodynamic damper

Stabilization in yaw is given by 2 counter-rotating propellers

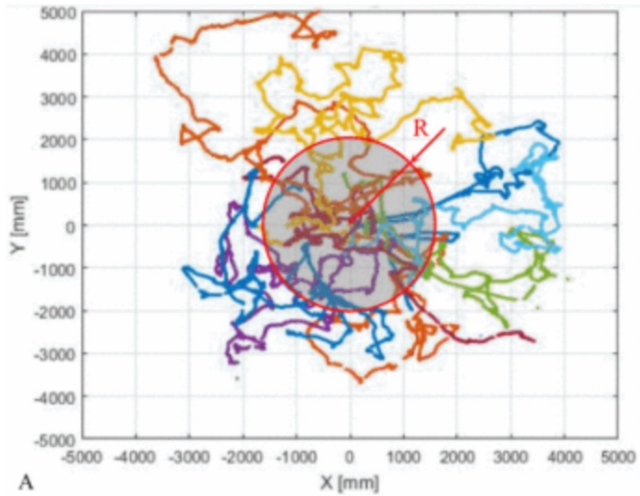
Freely rotating bushes

Shock-absorbing tensegrity shell

Battery & motors positioned for low CoM



Curved bars yield 4.7 times more volume



9 explorations starting from the center, 30 jumps each

S. Mintchev, D. Zappetti, J. Willemin and D. Floreano, "A Soft Robot for Random Exploration of Terrestrial Environments," 2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, QLD, Australia, 2018, pp. 7492-7497, doi: 10.1109/ICRA.2018.8460667.

A soft robot for random exploration of terrestrial environments

LIS

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

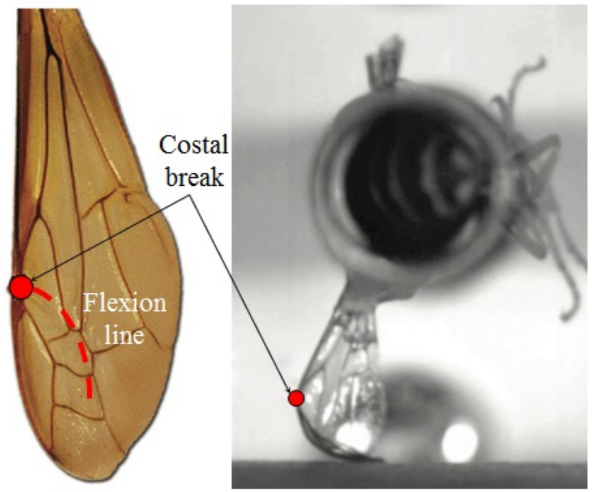
robotics

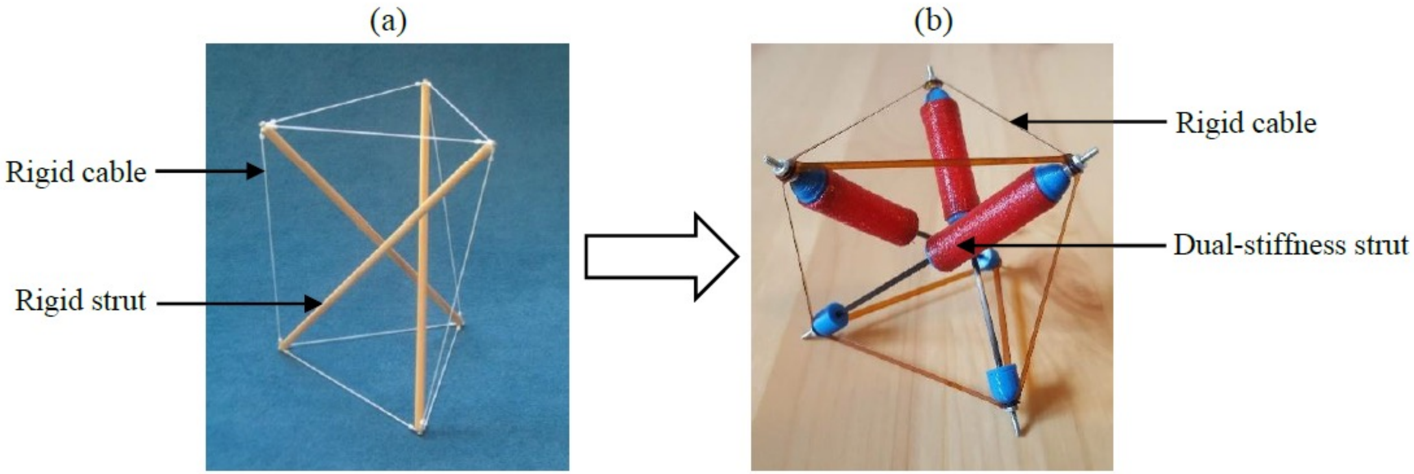
Swiss National Centre of Competence in Research

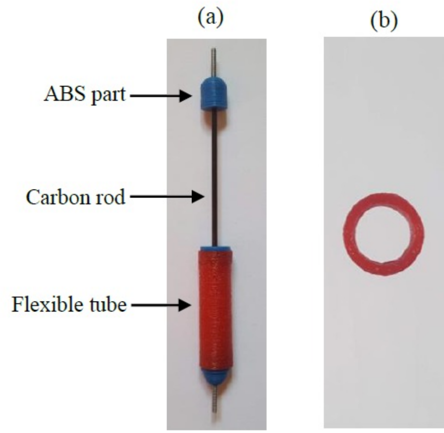
Dual-stiffness tensegrity

In some applications, it is necessary to withstand loads without deformations, but give way under higher loads to prevent breaking of the structures

Dual stiffness wing [2]

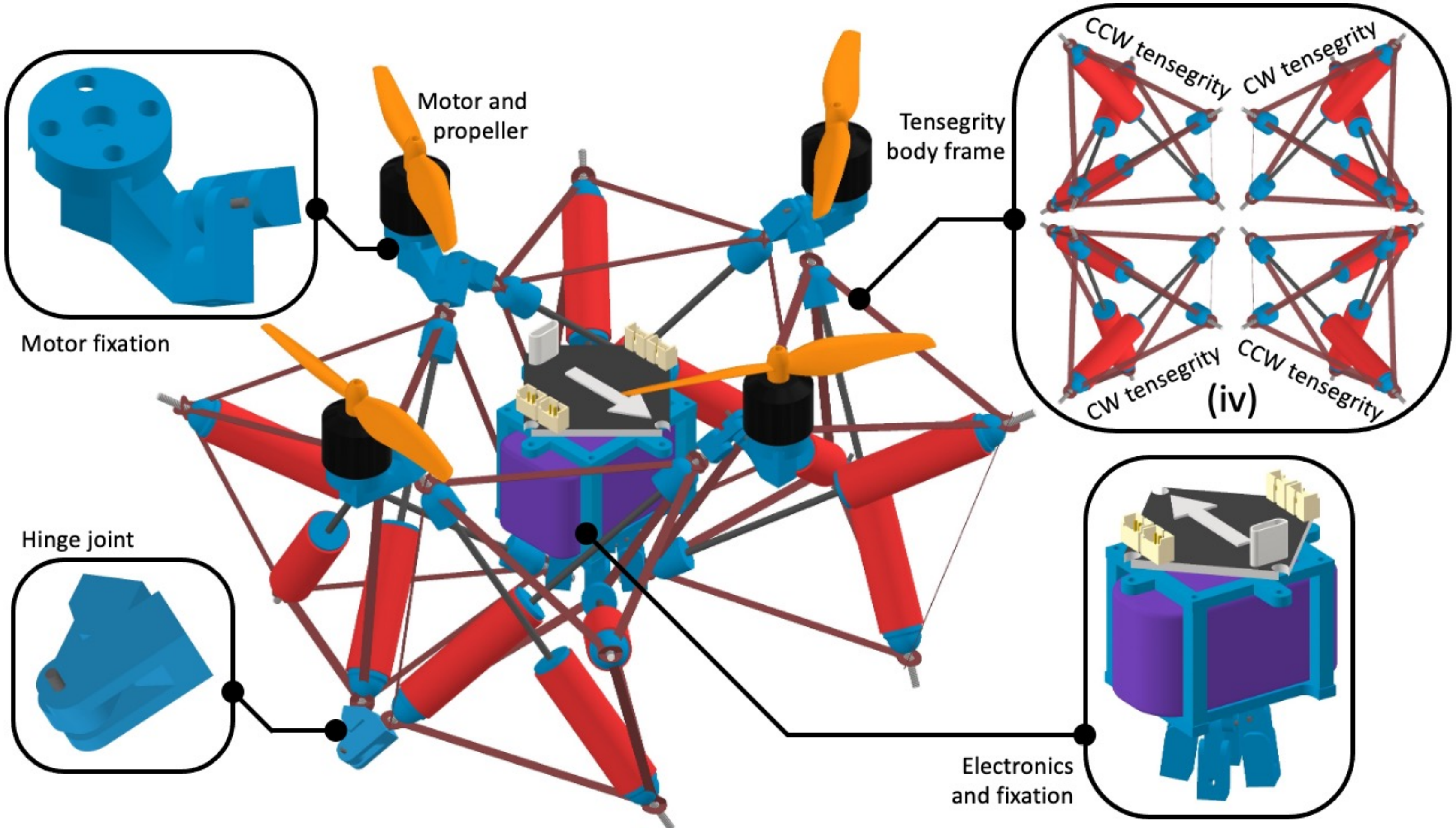


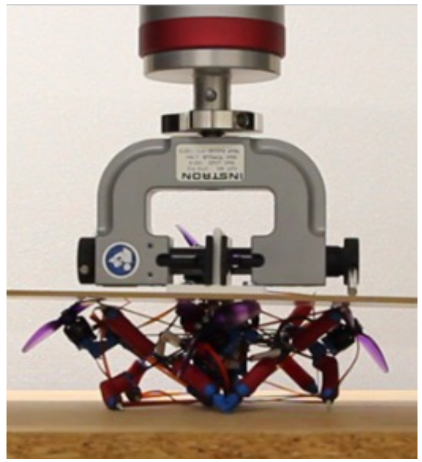




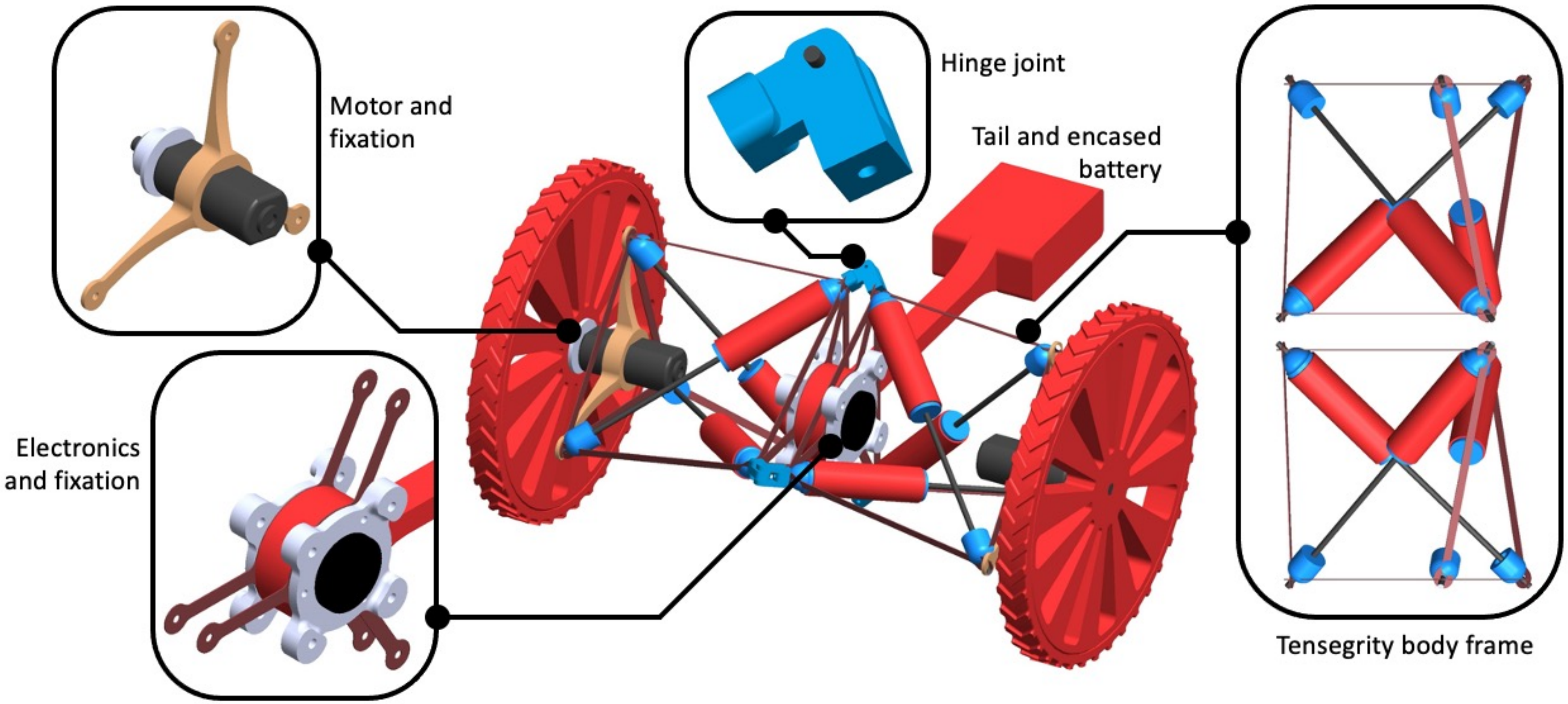
Zappetti, Sun, Mintchev, Floreano (in press)
Advanced Intelligent Systems

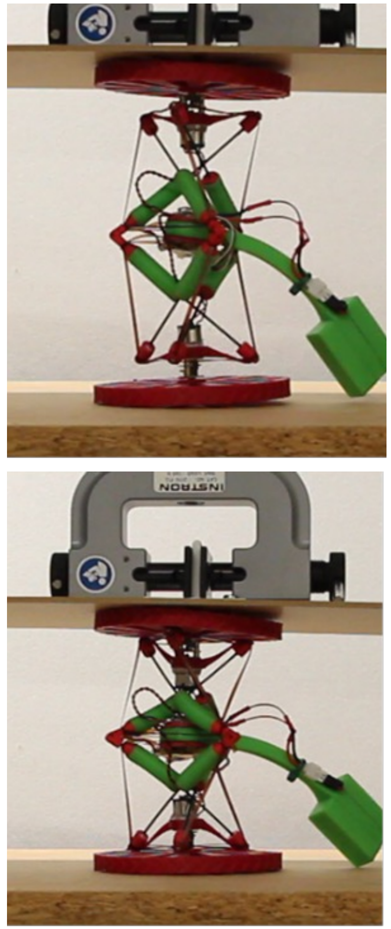
Dual-stiffness tensegrity drone

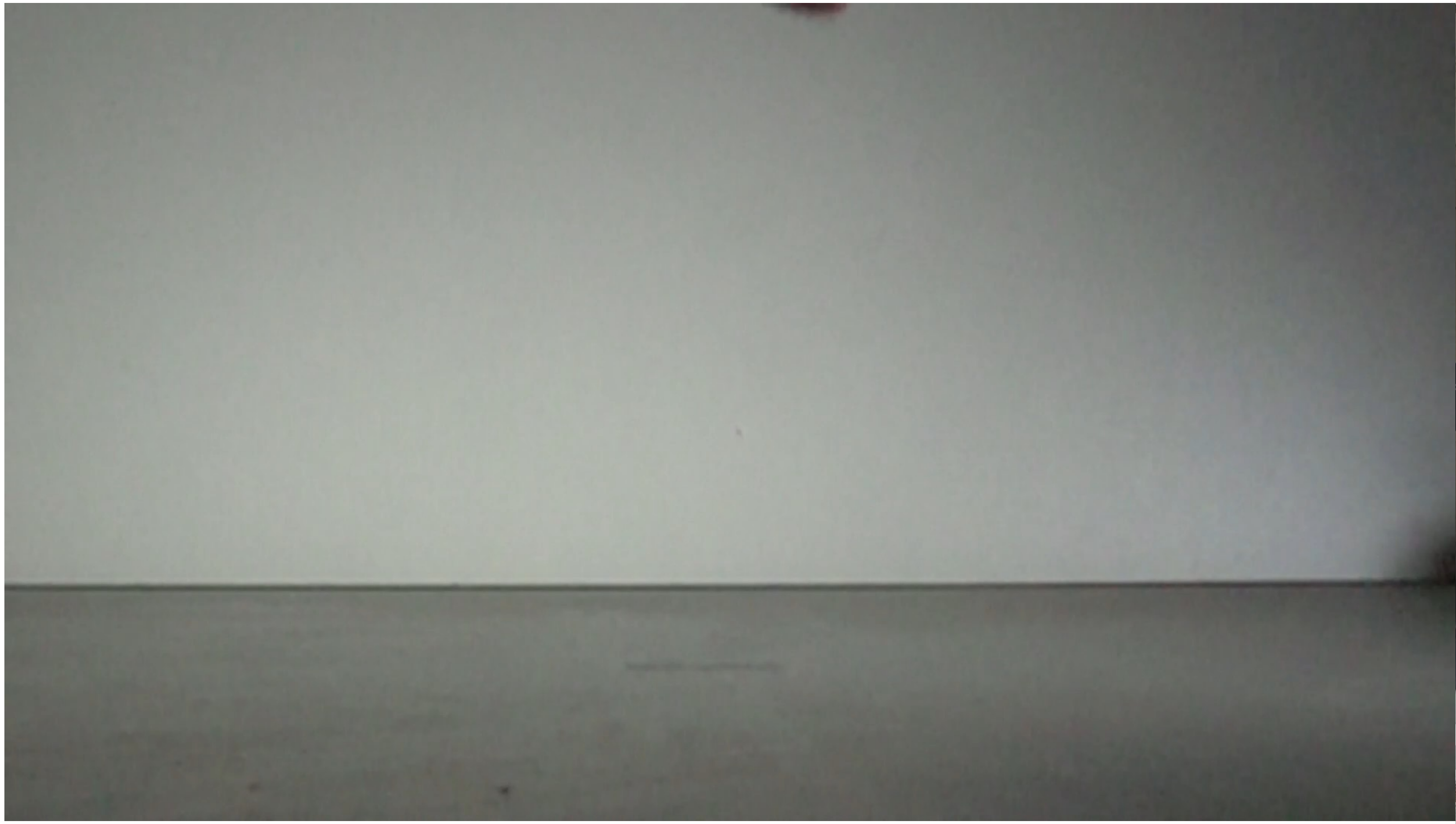




Dual-stiffness tensegrity cart





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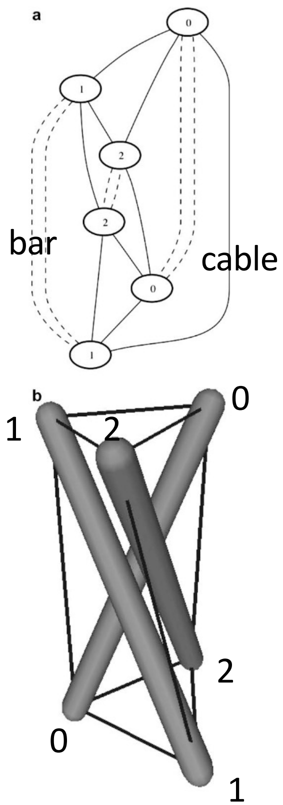
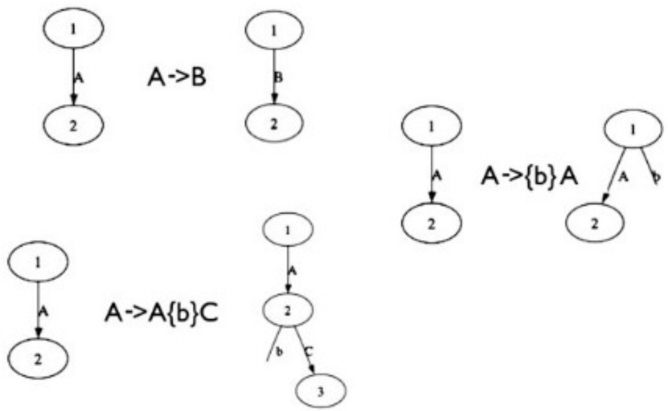
Growth of tensegrity architectures by L-Systems

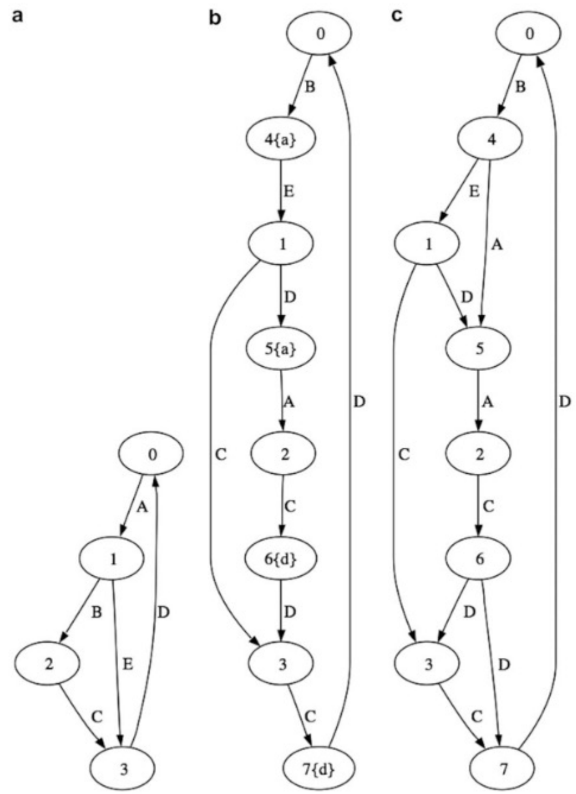
Graph representation



Production rules
are genetically encoded

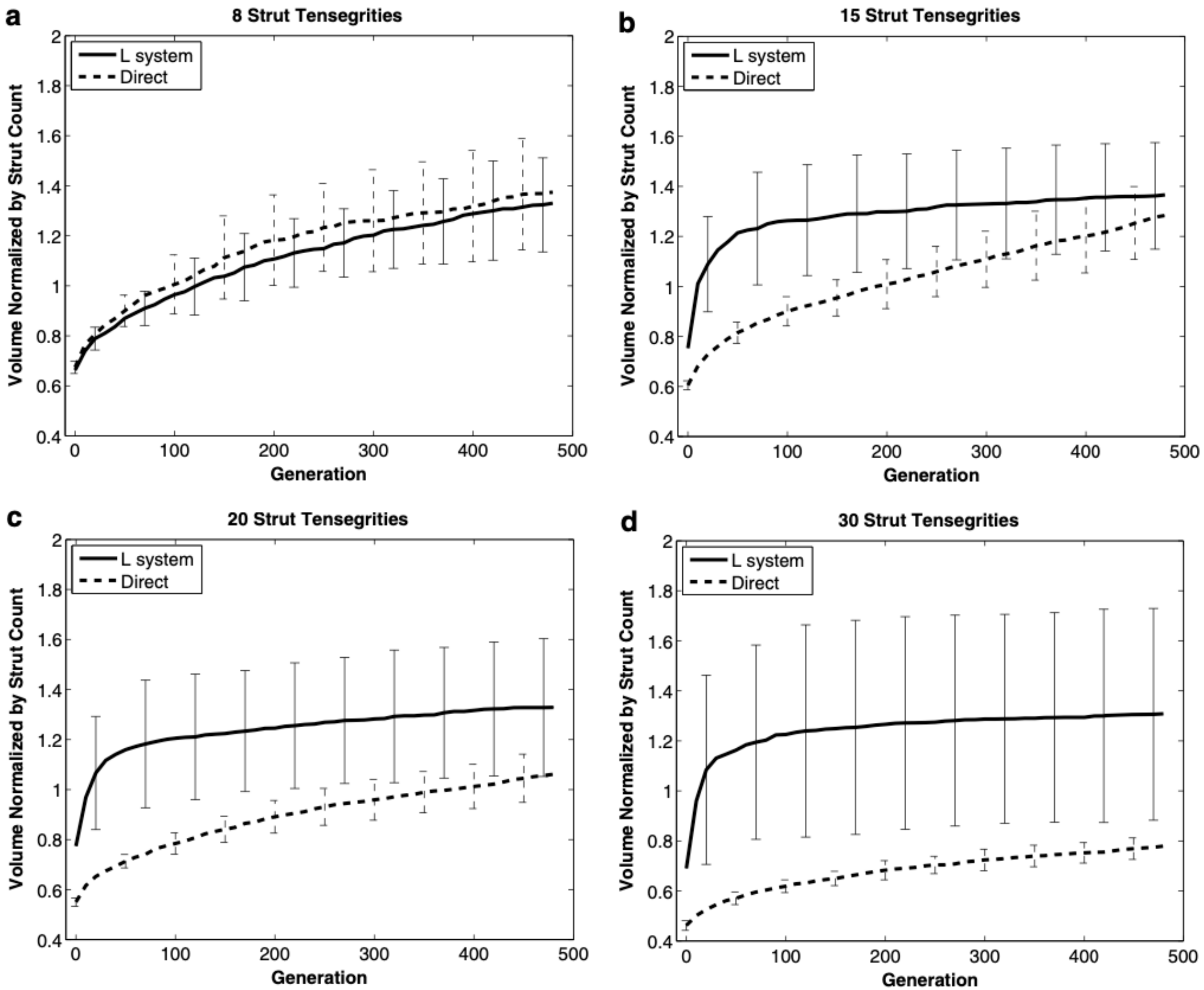


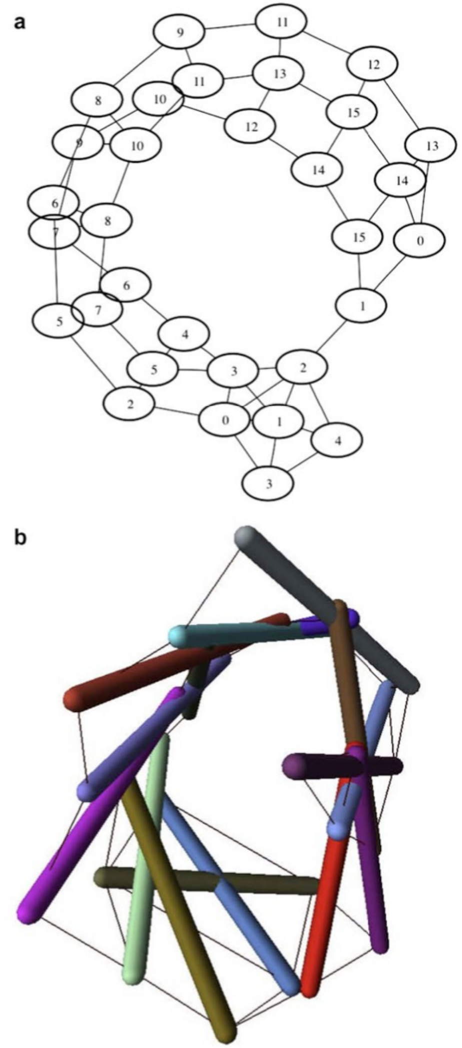
Growth



J. Rieffel, F. J. Valero-Cuevas and H. Lipson, "Automated discovery and optimization of large irregular tensegrity structures," *Computers and structures*, vol. 87, pp. 368-379, 2009

Volume maximization with strut minimization

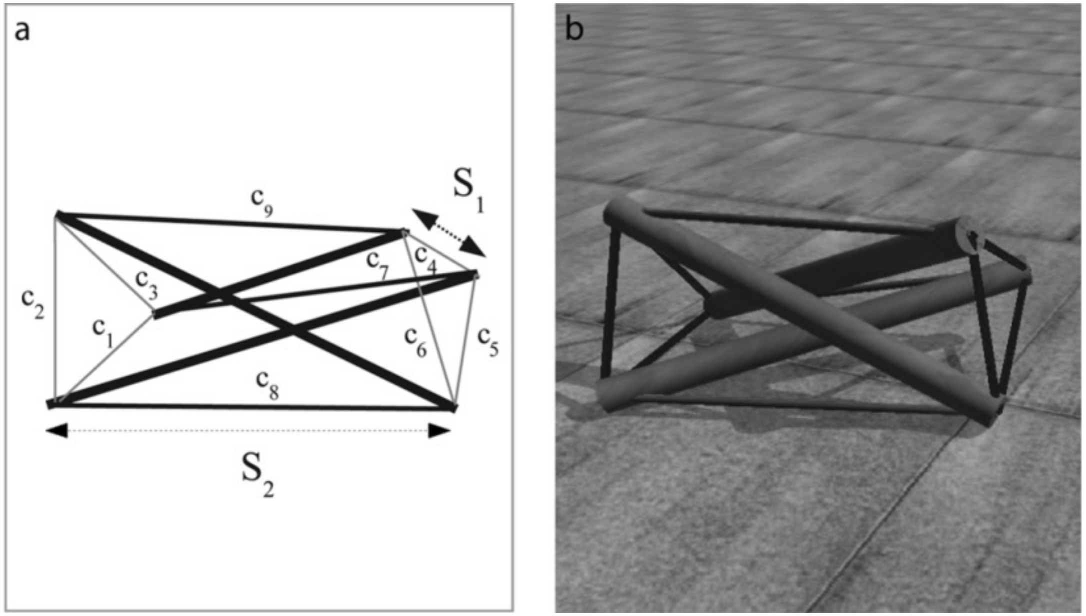




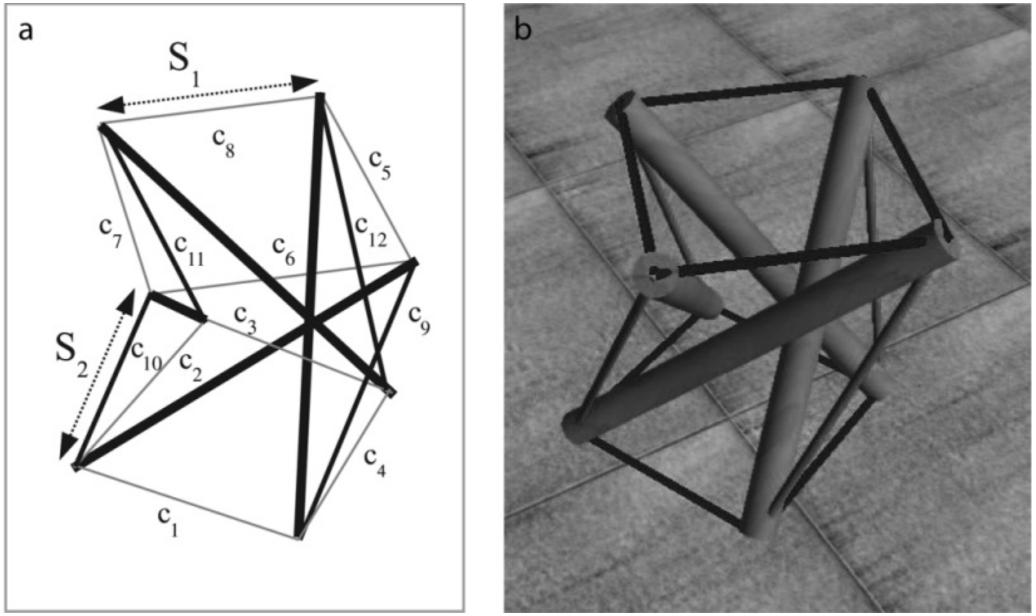
Evolution of gait control in tensegrity robots

Actuation occurs by reducing the length of longitudinal cables (length = S_2)
Genotype: gait period + [amplitude, phase, duration] of each longitudinal cable

3-strut prism tensegrity
3 actuated cables

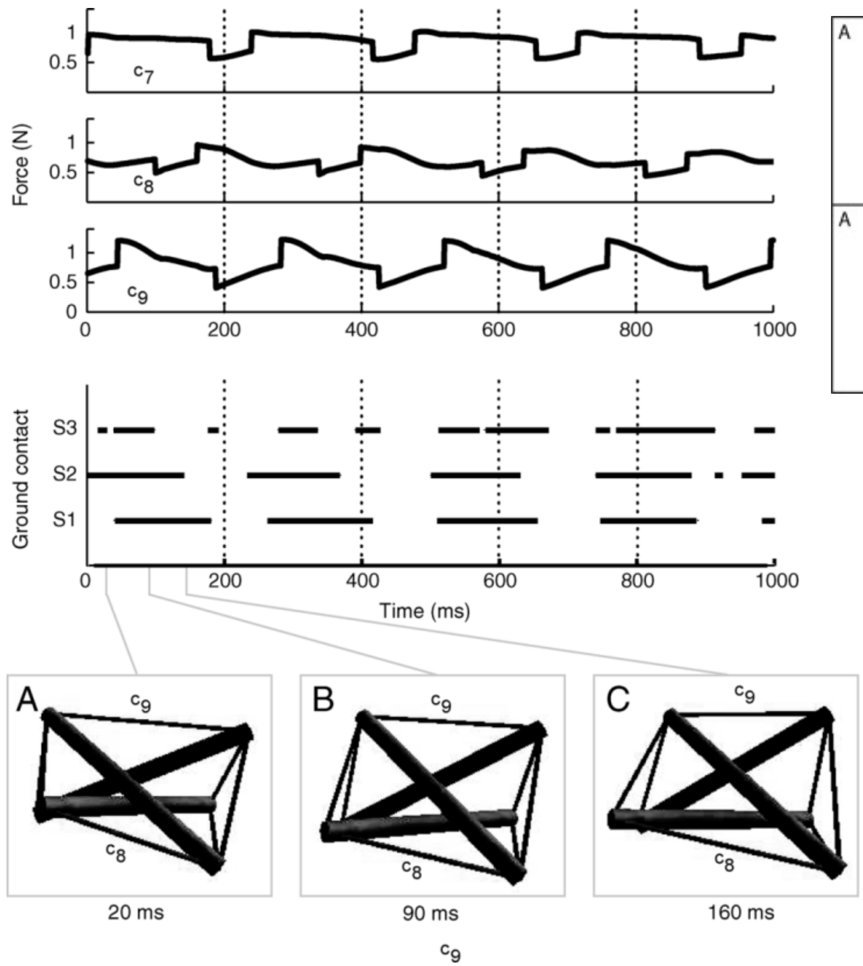


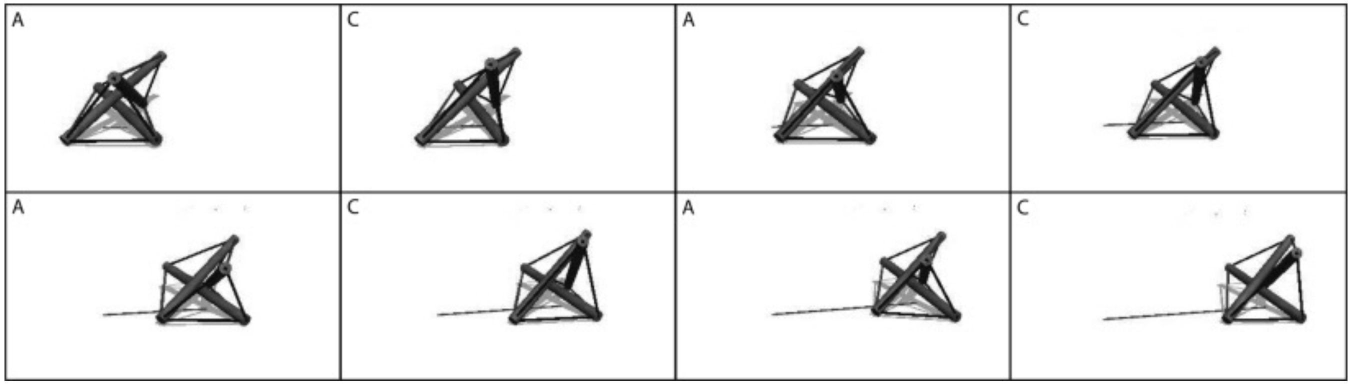
4-strut prism tensegrity
4 actuated cables

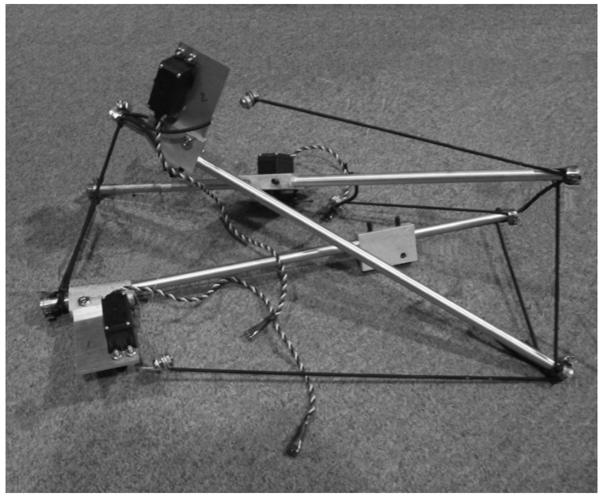


C. Paul, F. J. Valero-Cuevas and H. Lipson, "Design and control of tensegrity robots for locomotion," *IEEE Transactions on Robotics*, vol. 22, no. 5, pp. 944-957, Oct. 2006, doi: 10.1109/TRO.2006.878980.

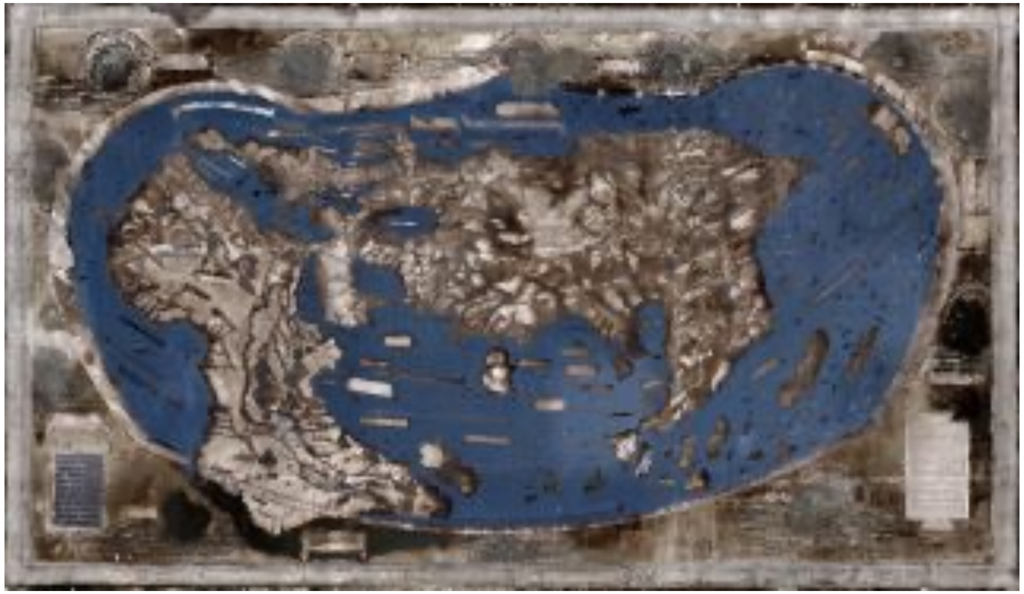
Evolved controller of 3-Prism Tensegrity







Tensegrity robotics is still unknown territory



Map of the world in 1491
Image by Lazarus Project / MegaVision / RIT / EMEL, courtesy of the Beinecke Rare Book and Manuscript Library

- Co-evolution of topology, form, and control of tensegrity robots
- Evolutionary exploration of more complex tensegrity architectures
- Exploration of the design and control space of modular tensegrities
- Applications to robotics, architecture, biomechanics, aerospace, …