SUPERBALLBOT - STRUCTURES FOR PLANETARY LANDING AND EXPLORATION

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OUTLINE

• Introduction to tensegrity structures and their advantages

• Presentation of the tensegrity robot and simulation tools

• Presentation of the developed controllers (reactive - CPG - hybrid)

• Simulator validation with real hardware

• Questions / discussion
TENSEGRITY STRUCTURES

Only pure tension or pure compression!
TENSEGRITY STRUCTURES

Only pure tension or pure compression!

tensile elements

compression elements
Executive Summary

Small, lightweight and low-cost missions will become increasingly important to NASA’s exploration goals. Ideally, teams of small, collapsible, lightweight robots will be conveniently packed during launch and would reliably separate and unpack at their destination. Such robots will allow rapid, reliable in-situ exploration of hazardous destinations such as Titan, where imprecise terrain knowledge and unstable precipitation cycles make single-robot exploration problematic. Unfortunately, landing lightweight conventional robots is difficult with current technology. Current robot designs are delicate, requiring a complex combination of devices such as parachutes, retrorockets and impact balloons to minimize impact forces and to place a robot in a proper orientation. Instead, we are developing a radically different robot based on a “tensegrity” structure and built purely with tensile and compression elements. Such robots can be both a landing and a mobility platform allowing for dramatically simpler mission profiles and reduced costs. These multi-purpose robots can be lightweight, compactly stored and deployed, absorb strong impacts, are redundant against single-point failures, can recover from different landing orientations and can provide surface mobility. These properties allow for unique mission profiles that can be carried out with low cost and high reliability. We believe tensegrity robot technology can play a critical role in future planetary exploration.

TENSEGRITY STRUCTURES

- Lightweight
- Compliant
- Robust to shocks
- Robust to failures
- Deployable
- Bio-inspired

Mission Scenario

- Tightly packed set of tensegrities, expand, spread out, fall to surface of moon, then safely bounce on impact. The same tensegrity structure which cushioned the landing is then used for mobility to explore moons such as Titan and small asteroids.

Our Phase I study explored:

1. Feasibility of applying tensegrities to a low-cost, high science return mission to Saturn's moon Titan
2. Ability to control these structures that exhibit oscillatory and nonlinear behavior through evolutionary and central pattern generator based algorithms

Figure 1:

Tensegrity structures are composed of pure compression and tension elements. They can be lightweight, reliable, deployable, and efficient to manipulate.
HOW TO MAKE TENSEGRITY ROBOTS MOVE?

- Not suitable for classical control designs
- High compliance
- Oscillating structure
- Few scientific studies
DRIVING PRINCIPLE

- Creation of a torque by
  - moving the center of mass
  - reducing the contact surface
REACTIVE - PRINCIPLE
REACTIVE - PRINCIPLE

\[ \vec{d} \]

\[ \vec{d}_1 \quad \vec{d}_2 \quad \vec{d}_3 \quad \vec{d}_4 \]
REACTIVE - PRINCIPLE

\[ \vec{d} \]

\[ \vec{\vartheta}_1 \quad \vec{\vartheta}_2 \]

\[ \vec{\vartheta}_3 \quad \vec{\vartheta}_4 \]
REACTIVE - PRINCIPLE
REACTIVE
The feedback signal (value of the scalar product) is very regular over time.

It can be stored in a dynamical system:

\[
\begin{align*}
    \dot{x} &= \gamma (\mu - (x^2 + y^2)) x - \omega y + \epsilon f(t) \\
    \dot{y} &= \gamma (\mu - (x^2 + y^2)) y + \omega x \\
    \dot{\omega} &= -\epsilon f(t) \frac{y}{x^2 + y^2}
\end{align*}
\]
Due to the ball-like structure of the tensegritys the signals we want to copy during the rolling phase can be assumed as sinusoids. Thus, instead of AWOs we can consider using Hopf oscillators defined by:

\[
\begin{align*}
\dot{x} &= \gamma + \mu - x^2 S y^2 q q x - \omega y S \\
\dot{y} &= \gamma + \mu - x^2 S y^2 q q y S \omega x + x S w q
\end{align*}
\]

where \(\gamma\) is a time constant, \(\mu\) is the target frequency, and \(\omega\) the target pulsation of the signal. This dynamical system can be adapted to synchronize to any periodic input signal. The resulting adaptive frequency Hopf oscillator is defined by the following set of equations:

\[
\begin{align*}
\dot{x} &= \gamma + \mu - x^2 S y^2 q q x - \omega y S f + t q + x S w q \\
\dot{y} &= \gamma + \mu - x^2 S y^2 q q y S \omega x + x S x q \\
\dot{\omega} &= -S f + t q y x^2 S y^2 q q y + x S y q
\end{align*}
\]

As with the AWOs, we can now record the periodic signal during a learning phase and store it as a stable limit cycle of the Hopf oscillator. This signal can later be used to drive the tensegrity.
CENTRAL PATTERN GENERATORS
INVERSE KINEMATICS

complicated closed form approximated by numerical methods

\[ \vec{p} = \vec{p}_0 + \vec{p}_1 \Delta \ell + \vec{p}_2 \Delta \ell^2 + \ldots \]

\[ \Delta \ell = f(\vec{p}) \]

Numerical method*

INVERSE KINEMATICS

Jérémie Despraz

INVERSE KINEMATICS

complicated closed form approximated by numerical methods

\[ \vec{p} = \vec{p}_0 + \vec{p}_1 \Delta \ell + \vec{p}_2 \Delta \ell^2 + \ldots \]

Numerical method*

\[ \Delta \ell = f(\vec{p}) \]

* - First order: Transpose Jacobian Method

* - Second order: Newton Method

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INVERSE KINEMATICS
HYBRID

- Controlling phase:

feedback \rightarrow \text{CPG} \rightarrow \text{motor command}

fading memory property:

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=0.5\textwidth,
    height=0.3\textwidth,
    xlabel={time [s]},
    ylabel={parameter value},
    xmin=0, xmax=10,
    ymin=0, ymax=1.4,
]
\addplot[blue] table [x={time}, y={\text{parameter value}}] {data.csv};
\end{axis}
\end{tikzpicture}
\end{center}

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=0.5\textwidth,
    height=0.3\textwidth,
    xlabel={x[m]},
    ylabel={z[m]},
    xmin=0, xmax=80,
    ymin=-10, ymax=60,
]
\addplot[black] table [x={x}, y={z}] {data.csv};
\addplot[orange] table [x={x}, y={z}] {data.csv};
\addplot[red] table [x={x}, y={z}] {data.csv};
\end{axis}
\end{tikzpicture}
\end{center}
RESULTS SUMMARY
Reservoir compliant tensegrity robot (ReCTeR)

Nasa tensegrity robotics toolkit (NTRT)
Figure 7: Kinematic comparison of the Euler-Lagrange and NASA Tensegrity Robot Toolkit simulators and ReCTeR motion capture data. The top left plot shows the experimental setup. Two actuated springs, dashed lines, track a range of string lengths. The full range of motion of the tracked node during the experiment is shown in light yellow, convex hull. The nodes indicated by small black squares are on the ground. The 3 other plots show the vertical displacement of the node indicated by the large black dot in the top left plot as a function of the two actuated string lengths. The node of which we trace displacement is not directly actuated and is floating. The nodal displacement as a function of the actuator position is non-linear, even for modest displacements. Note that the leftmost point \((0.05, 0.05, 0)\) is the reference point, as the displacements are relative to this initial state.
SIMULATOR VALIDATION

Static
SIMULATOR VALIDATION

Dynamics

$t = 0.00s$  $t = 0.50s$  $t = 1.00s$  $t = 1.50s$  $t = 2.00s$  $t = 2.50s$

robot

NTRT

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FUTURE WORK

Several promising options

Neural Networks

Evolutionary Algorithms

Soft Robotics

Fig. 4

Composition of functions as a graph

The connections are weighted such that the output of a function is multiplied by the weight of its outgoing connection. If multiple connections feed into the same function, it means that the downstream function takes the sum of their weighted outputs. Note that the topology is unconstrained and can represent any possible relationships. This representation is similar to the formalism of artificial neural networks with arbitrary activation functions and topologies. Because the absolute coordinate frame \((x, y)\) is input to the network, local interaction can be eliminated from the representation.
(video from University of Idaho Tensegrity Group)
RELATED PUBLICATION

“Design and control of compliant tensegrity robots through simulation and hardware validation”

Ken Caluwaerts, Jérémie Despraz, Atil Iscen, Andrew Sabelhaus, Jonathan Bruce and Vytas SunSpiral

Journal of the Royal Society Interface (2013)
Thank you!

Vytas SunSpiral
Auke Jan Ijspeert
Mostafa Ajallooeian
Jesse van den Kieboom
Ken Caluwaerts
Atil Iscen
SIMULATION FLOWCHART

- Bullet
  - move
  - feedback $\vec{o}, \vec{v}, \vec{h}, \ldots$

- Tensegrity Robot
- Motor Command
- CPG (Codyt)
- Impedance Controller

$\vec{l}, \vec{T}, \vec{l_t}$
CPG NETWORK
3 SEGMENTS MUSCLES

\[
\begin{align*}
F_i &= k_i (l_i - l) - \eta \frac{(l_i^{(t)} - l_i^{(t-1)})}{dt}, \\
0 &\quad , l_i > l_i
\end{align*}
\]

Figure 4y:
Super Ball Bot’s Structures for Planetary Landing and Exploration
Jérémie Despraz

This new class models tensile elements as massless and shapeless elements to spin on itself in a way that obviously breaks the laws of conservation of energy. In order to solve this problem, NTRT implements a new class of hookean springs to accurately simulate real tensegrity tensile components.