Applying Principles from the Locomotion of Small Animals to the Design and Operation of Robots

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Origins of bio-inspired design

Renaissance discovery:

- Understanding the body as a marvelous machine
- Understanding machine elements as examples of limbs, skeletons, muscles and tendons

Da Vinci notebooks
Da Vinci’s programmable spring-powered cart
Why the recent proliferation of biomimetic designs?
Biology: better tools for understanding biological systems in detail

Setal shaft

100μm

Lamella

1mm

Spatular shaft

2μm

Spatula

200nm

Arrays of Setae

75 μm

Seta

20 μm

Spatulae

1 μm
Engineering: better analysis tools, fabrication methods and materials

- Embedded Component
- Part
- Support

Deposit (part)

Shape

Deposit (support)

Embed

SDM multi-material fabrication

Synthetic dry adhesive: polymer molds from dual, angled-exposure lithography + micromachining

380μm
Behaviors now: discrete, isolated
Biomimetics

Natural Selection is not Engineering

Evolution - “just good enough”
Lessons from biology for bio-inspired design:

1. Reduce Complexity - Collapse Dimensions

2. Manage Energy

3. Use Multifunctional Materials - Tuned, Integrated & Robust

4. Exploit Interaction with Environment
“Curse of Dimensionality”

Designs appear hopelessly complex
No detailed history of design plans

72 DOF
230 Muscles
? Neurons

Full and Ahn, 1995

R.J. Full
Reducing dimensionality: the sagittal leg spring

SIX- Legged

Cockroach

Full and Tu, 1990

TWO- Legged

Human

vertical force

fore-aft force

time

Cavagna et al., 1977

EIGHT- Legged

Crab

Blickhan and Full, 1987

FOUR- Legged

Dog

R.J. Full
Lessons from Biology

1. Reduce Complexity - Collapse Dimensions

2. Manage Energy

3. Use Multifunctional Materials - Tuned, Integrated & Robust

4. Effective Interaction with Environment
Shape Deposition Manufacturing (SU/CMU)

- Embedded Component
- Part
- Support

Deposit (part)

Deposit (support)

Embed
Robot leg with embedded actuator, valves, sensor and circuitry

Embedded components

Sequence of geometries for fabrication

1. Support material
2. Part material
3. Embedded sensor
4. Part material
5. Embedded parts
6. Part material
7. Top support*

Detail of part just after inserting embedded components

Finished parts

[Cham et al. 1999]
SDM: part number reduction, increased robustness, controlled compliance, damping

Left: Kinematic prototype of linkage with 31 parts
Center: SDM linkage with thick flexures, 1 part
Right: SDM linkage with fabric-reinforced flexures
Biological Inspiration

- Control heirarchy
  - Passive component
  - Active component

- Biological Inspiration

  - Control heirarchy
    - Passive component
    - Active component

**Mechanical System**

- Feedforward
  - Motor program acting through moment arms
- Reflex
  - Neural feedback loops
  - Slow acting

**Neural System**

- Preflex
  - Intrinsic musculo-skeletal properties
- Predictive
  - Rapid acting
- Passive Dynamic Self-stabilization
- Active Stabilization

Full and Koditschek, 1999
Solution Approach: Analyze and “Optimize”
Dynamic Model in ADAMS

3D model with geometric similarity to robot
- Rigid body with six legs
- Linear pneumatic actuators (with valve delays)
- Spring-damper rotational joints in sagittal plane
- Friction and ground contact models
Study biological materials, components, and their roles in locomotion.

Study Shape Deposition Manufacturing (SDM) materials and components.

Example: mapping from passive mechanical properties of insects to biomimetic robot structures

Models of material behavior and design rules for creating SDM structures with desired properties
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2. Bioinspiration for **smooth climbing**

- **Bioinspiration**
  - how do they do it?

- **Biology**
  - examine literature, work with biologists

- **Hypotheses**
  - regarding the principles at work

- **Analysis**
  - test and analyze results

- **Robotics**
  - implementations of principles

- **SDM technology**
Principles for climbing with dry adhesion

1. Hierarchical compliance

2. Directional adhesives

3. Distributed force control
Compliant peeling toe

- Tendon (steel cable)
- Hard polyurethane
- Soft polyurethane
- Teflon tube
- Directional Polymeric Stalks
- Living hinge
- Fiber mesh embedded
Anisotropic gecko adhesion

Gecko setae dragging with curvature

Dragging against curvature

25 mN of Adhesion

Colored: Normal force
Gray: Shear force

No Adhesion
Gecko Force-Space Results

Autumn et al. JEB 2006

loaded against stalk angle: **Coulomb friction**

Load, then pull off at various angles, and measure force ➔ **limit curve**

loaded with stalk angle: **adhesion ~ tangential stress**
Force Control
optimal strategy for inverted surface

Johnson-Kendall-Roberts

Frictional Adhesion

Rear Foot Flipped

Generalization: Formulate as linear programming problem to control foot orientation & internal forces for arbitrary loading conditions [Santos, JAST09].
Control foot orientation + internal forces
Directional adhesion facilitates control of forces for smooth, efficient locomotion.
Current work: compliant *hierarchical* structures

The gecko’s hierarchical adhesive system spans length scales from 1 cm to 100 nm.

20 \( \mu m \) wedges atop 380 \( \mu m \) directional stalks (SEM photo)

Synthetic adhesives require *hierarchical, directional compliance* to conform to rough surfaces and distribute loads over large areas.
Stanford hierarchical, directional adhesive

Directional Polymer Stalks (DPS)

Hierarchical System

MicroWedges
Bio-Inspired?
How to get nearly uniform loading over the entire toe, with tolerance to a range of loading angles?

(Russell J. Morphology 1982)
Loading angles: alignment compensation

4 leg version of RiSE platform
4 kg gross
Scaling to larger areas and loads: tiled arrays

- compliant support
- adhesive
- rigid tile
- pulley
- pressure plate
- pressurized sac
- tile tendon
- main tendon

Approx. 80cm²

40 kg
Scaling to larger areas and loads: results

![Graph showing the relationship between Normal Stress (kPa) and Shear Stress (kPa). The graph includes data points for single tiles and pentadactyl hands at angles of 20° and 15°.]
Acknowledgements