Morphogenesis as a Reference Architecture for Engineered Systems

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3rd Morphogenetic Engineering Workshop @ ECAL '11

Work sponsored by DARPA; the views and conclusions contained in this document are those of the authors and not DARPA or the U.S. Government.

iRobot Raytheon BBN Technologies

How to grow a robot from an egg…

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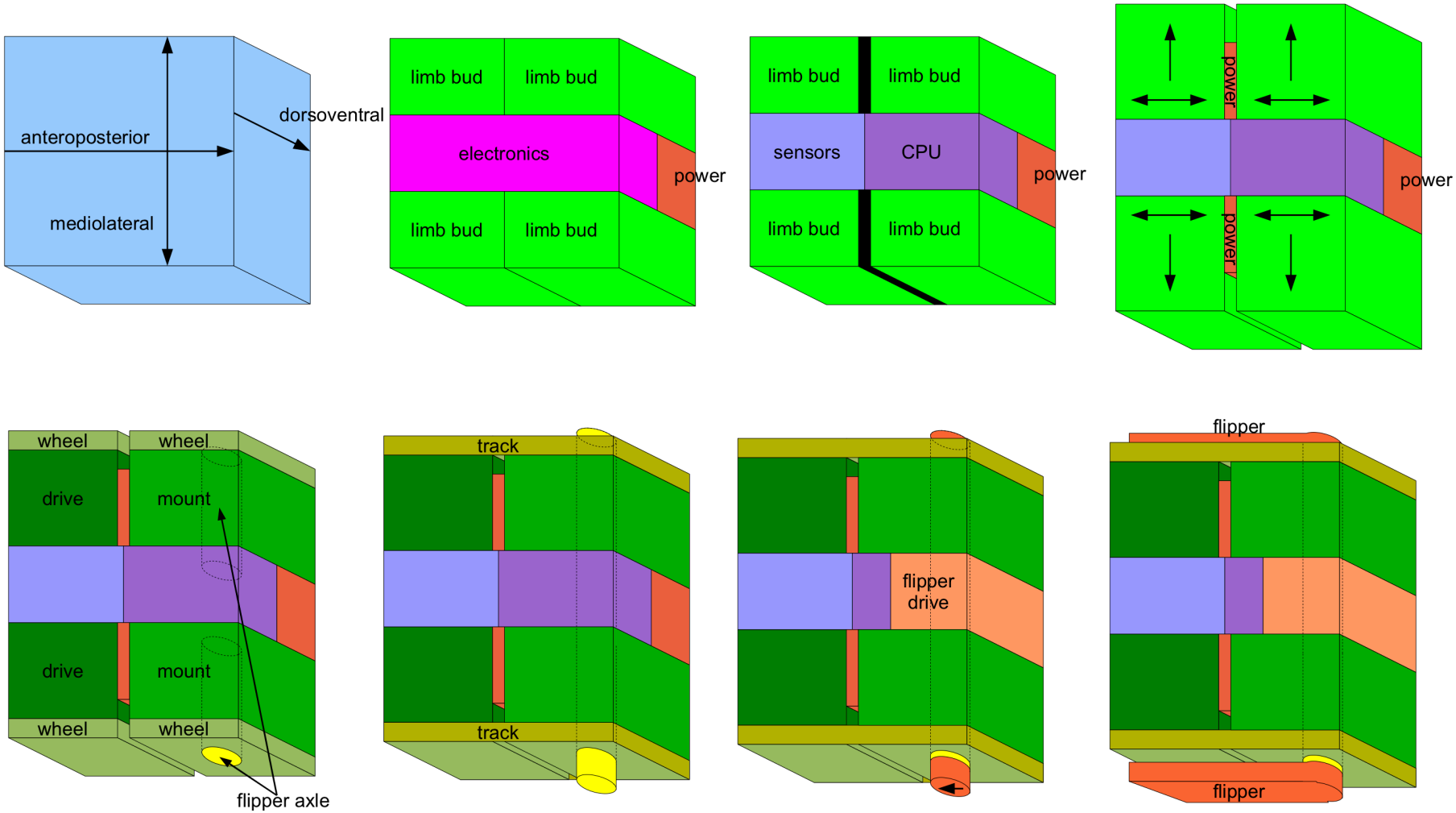

… and why it matters with current manufacturing

Morphogenetically Assisted Design Variation

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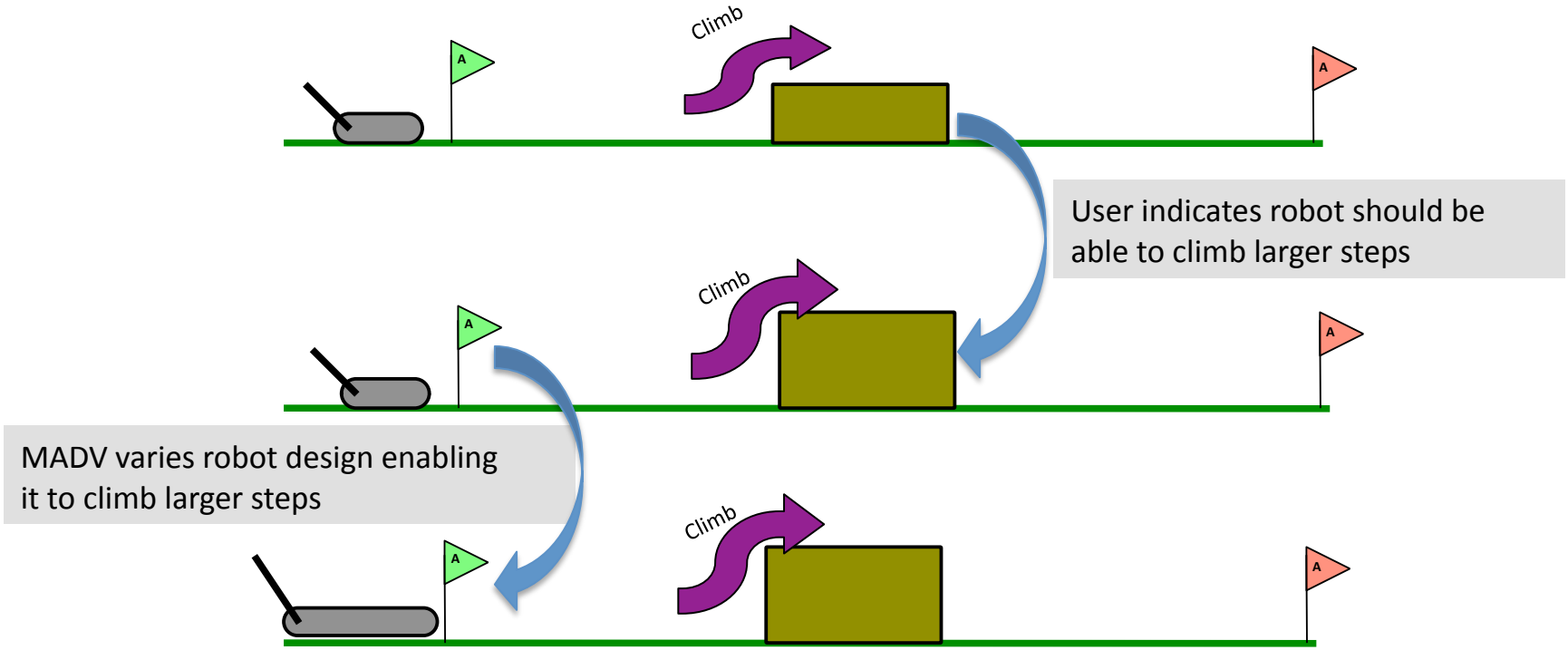
- An interactive design tool providing non-experts the ability to vary robot design
  - User modifies evaluation parameters e.g., conditions of an obstacle course, and robot design is automatically varied to cope with new situation



Design Challenges

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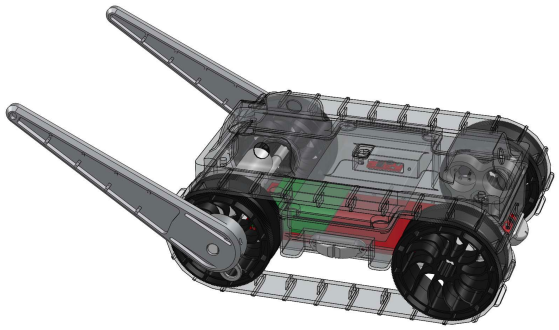
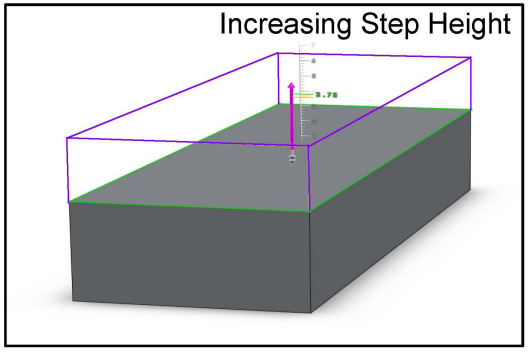
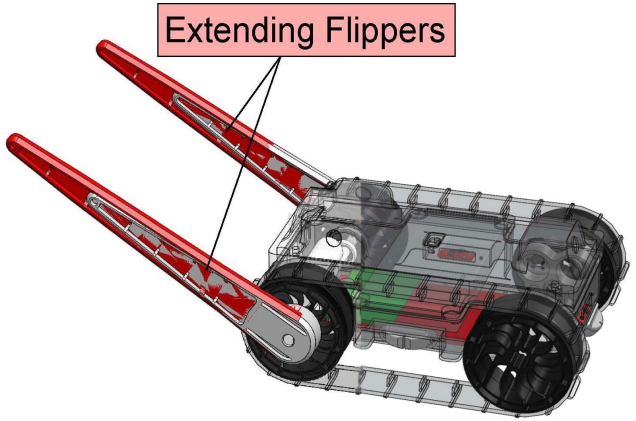
- What needs to change for new conditions?
- How does a change impact other systems?







Problem: Propagating Changes

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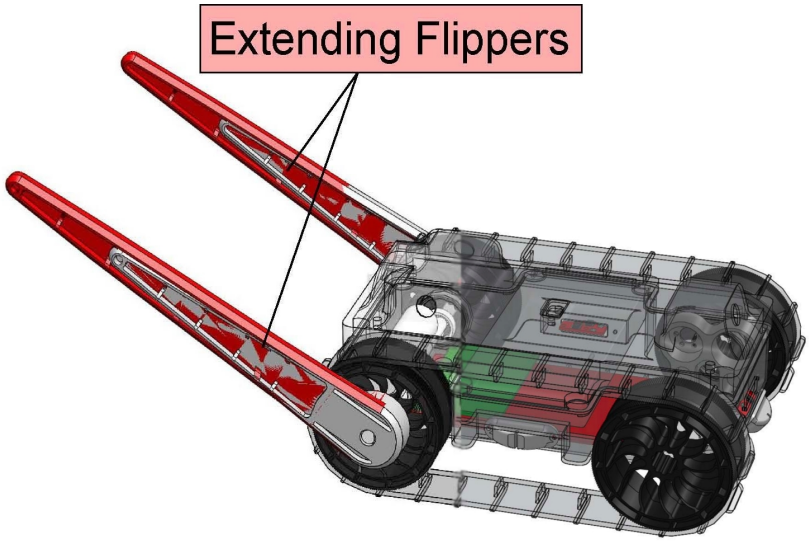
A small change ...



Problem: Propagating Changes

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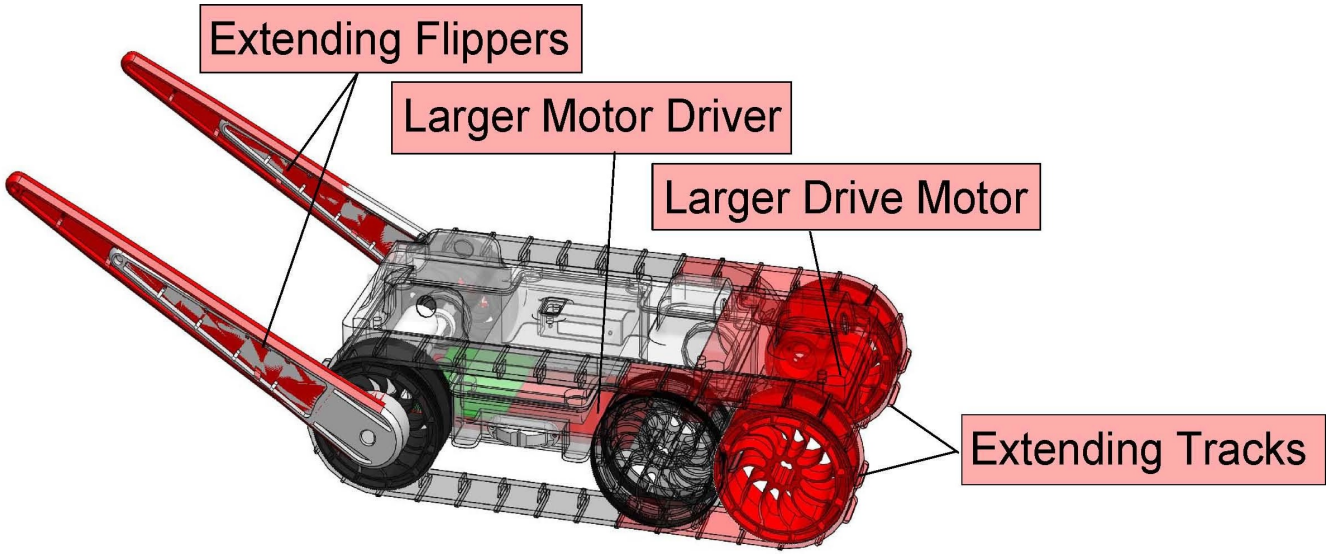
A small change ... has many consequences



Morphogenesis enables natural variation

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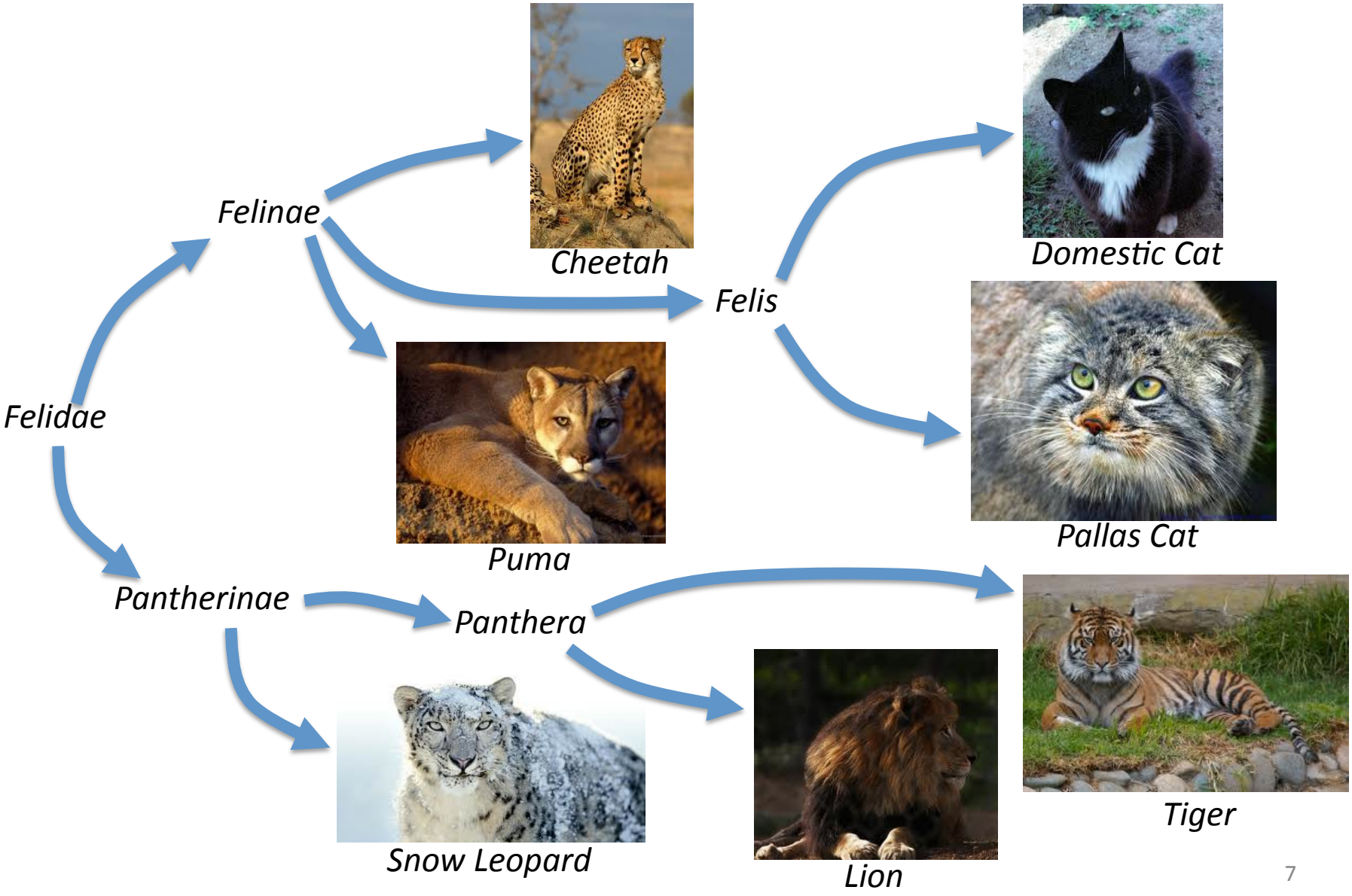

A phylogeny of engineered systems?

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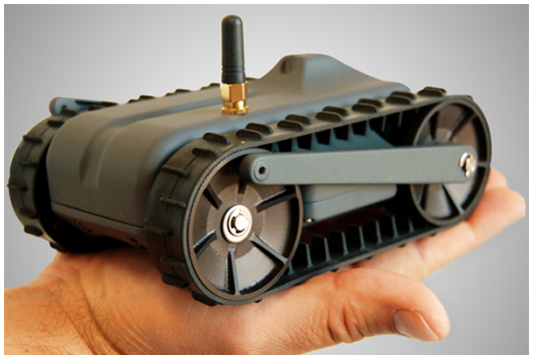
SUGV

Warrior

PackBot



LANdroid

miniDroid

Our Approach: Functional Blueprints

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- Functional blueprints specify design as functional goals and a means to adjust the structure when the goals are not met
- Functional blueprints capture dependencies that are hard to represent with traditional blueprints
- Stress is used as the coordinating signal driving structural changes

Functional Blueprint Definition

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1. Functional behavior that degrades gracefully
2. Metric for degree and direction of stress
3. Incremental adjustment program for stress relief
4. Initial viable system

Functional Blueprints: Stress Functions

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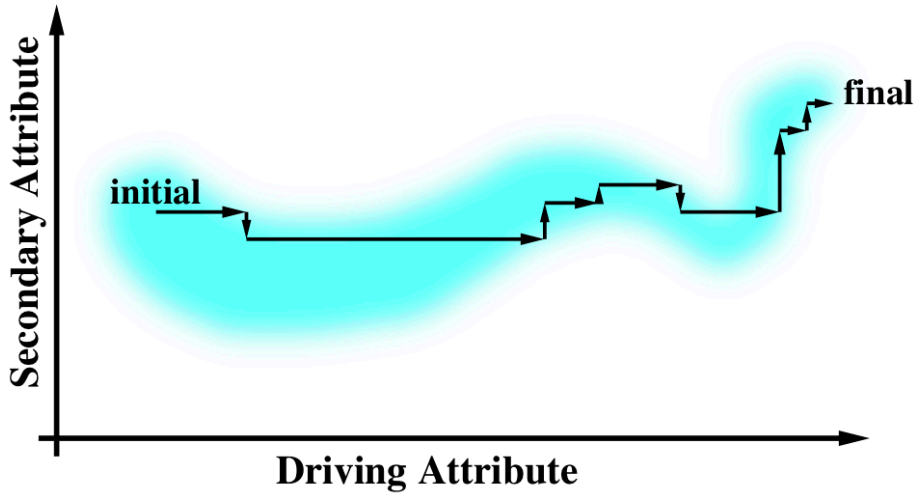
- Idea: keep the design always working, navigate through viable space



Functional Blueprints: Stress Functions

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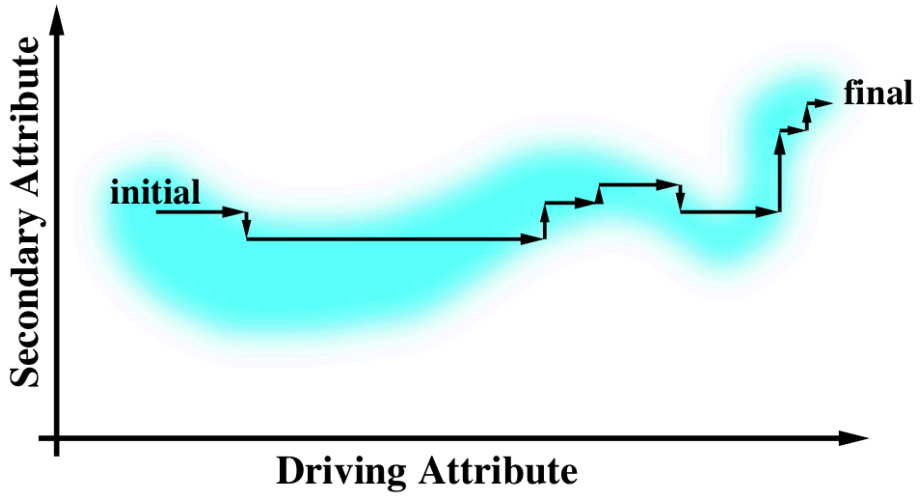

- Stress functions define viable and non-viable space

Functional Blueprints: Previous Results

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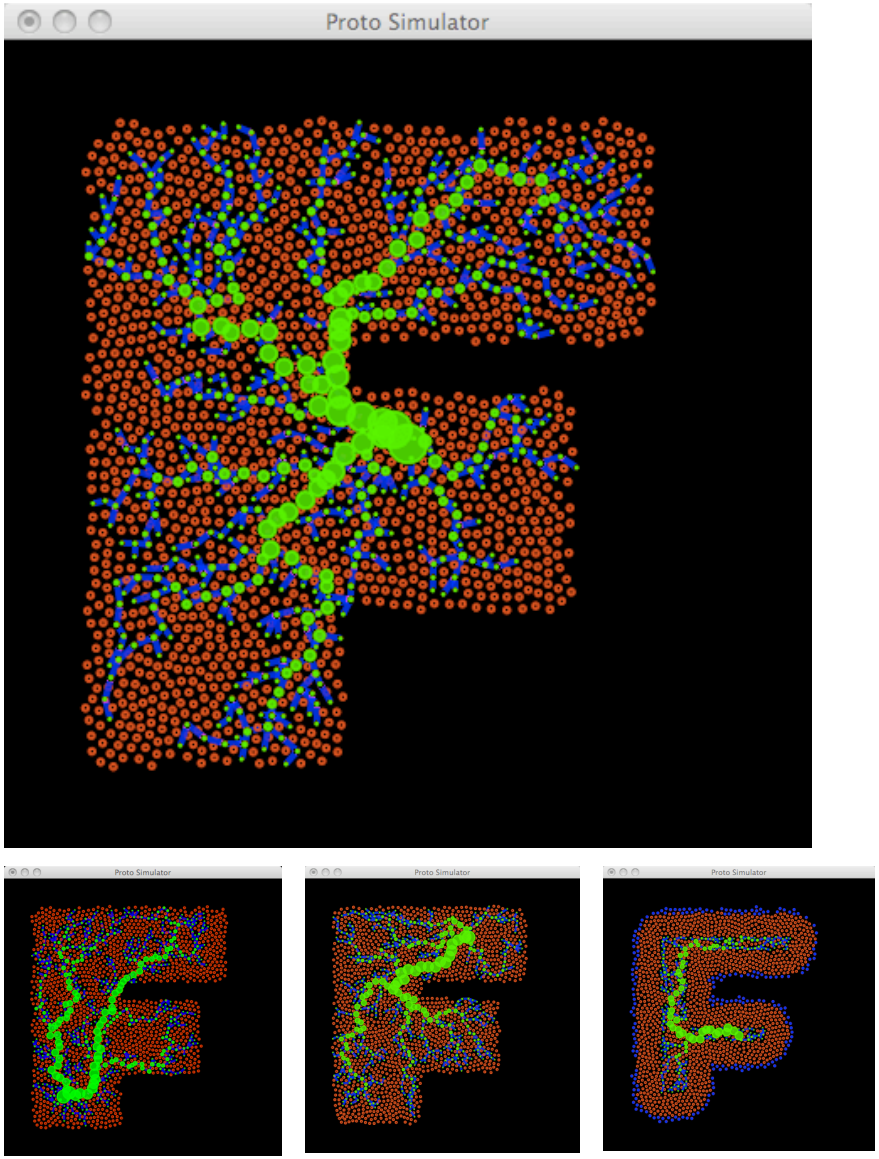
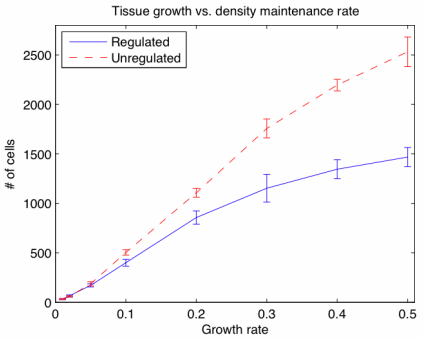
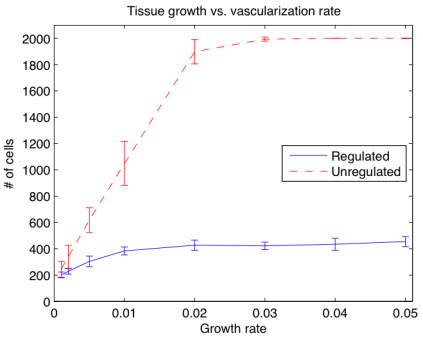


- Functional blueprint model of vascularization
  - Stress: oxygen, elastic stress
  - Adjustment: leaking, vessel grow/shrink
- Red cells are healthy, blue cells are oxygen-deficient
- Can model vasculatization and density co-regulation





Moving to robots…

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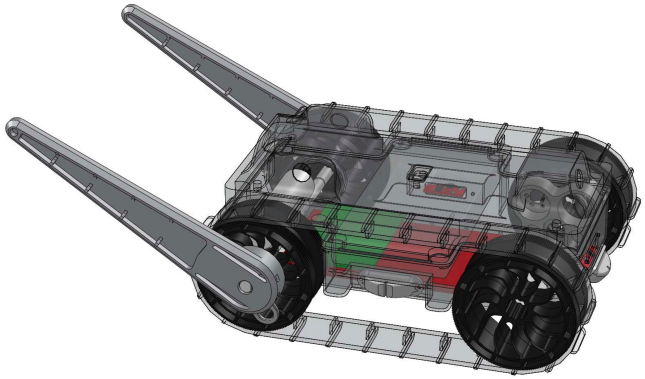
- How do we apply preliminary work to electromechanical systems?
  - How to **evaluate** function?
  - How can the functional blueprints be **composed**?
  - How to **safely integrate** user input?
  - What types of **stress and update** functions make sense?
  - How to **transform** the design into a variant?



MADV Architecture

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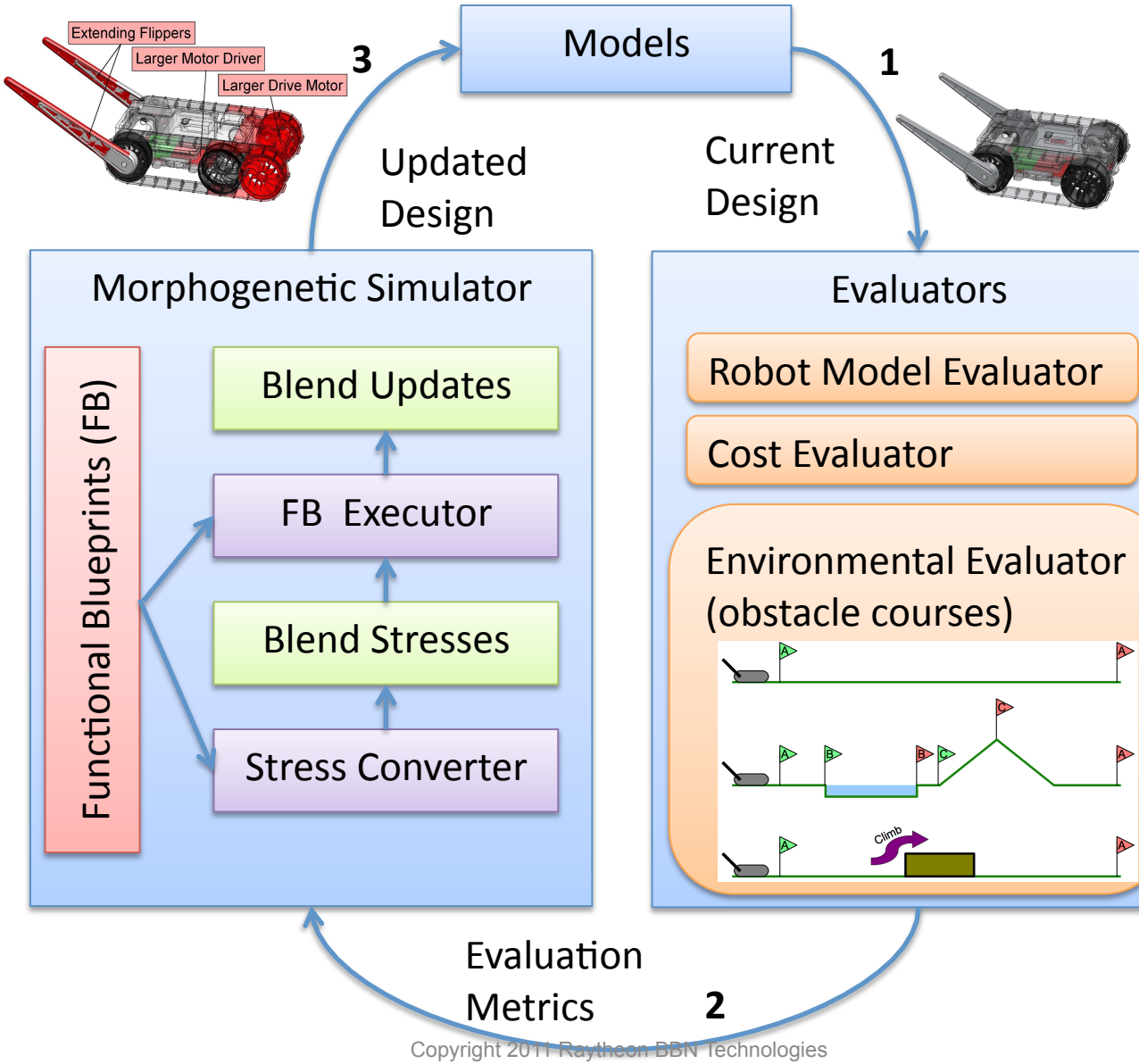

Initial Target: Step Climbing

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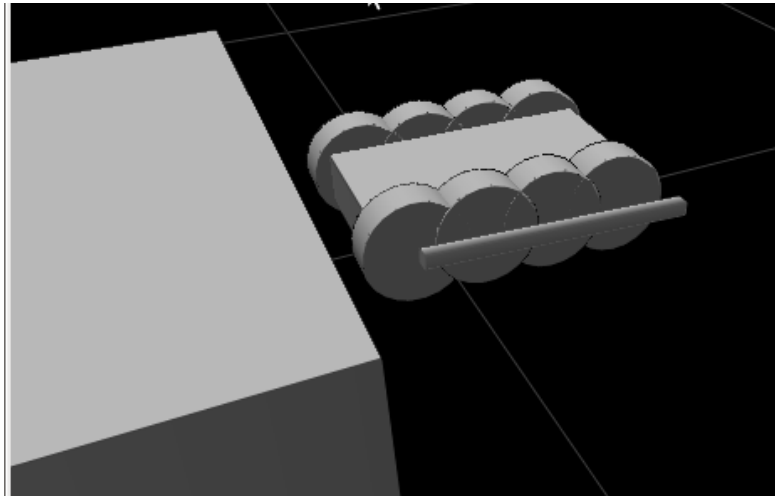
- Required extending initial functional blueprint model
  - Added indirect stress generation: evaluation of design includes system properties and **derived properties**, e.g., time to accomplish a task
  - Define stress as a function of evaluator outputs
- Robot design evaluated using Open Dynamics Engine (ODE) simulation
- Robot Model is based on miniDroid design
- Initial indirect stress functional blueprint: step climbing



Stair Climbing Metrics

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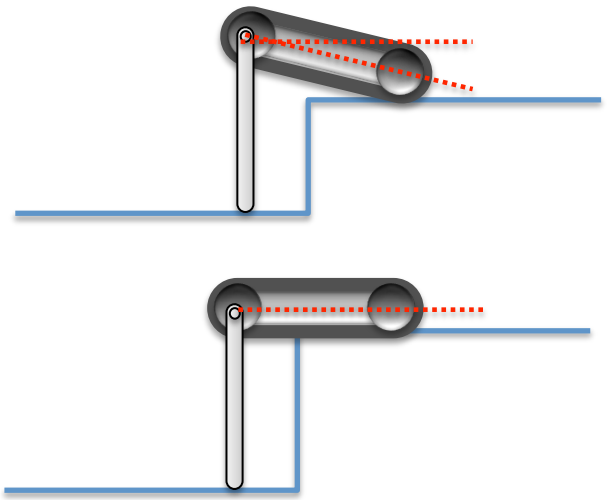
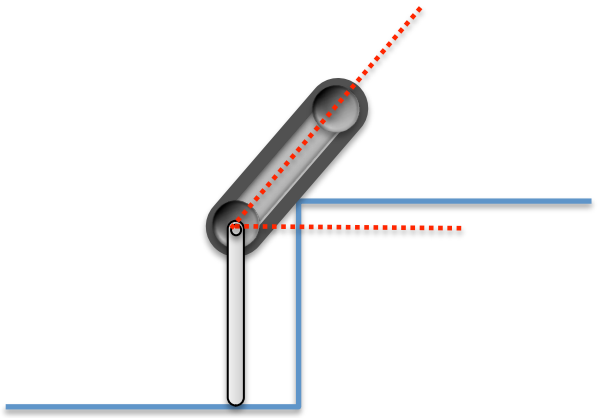
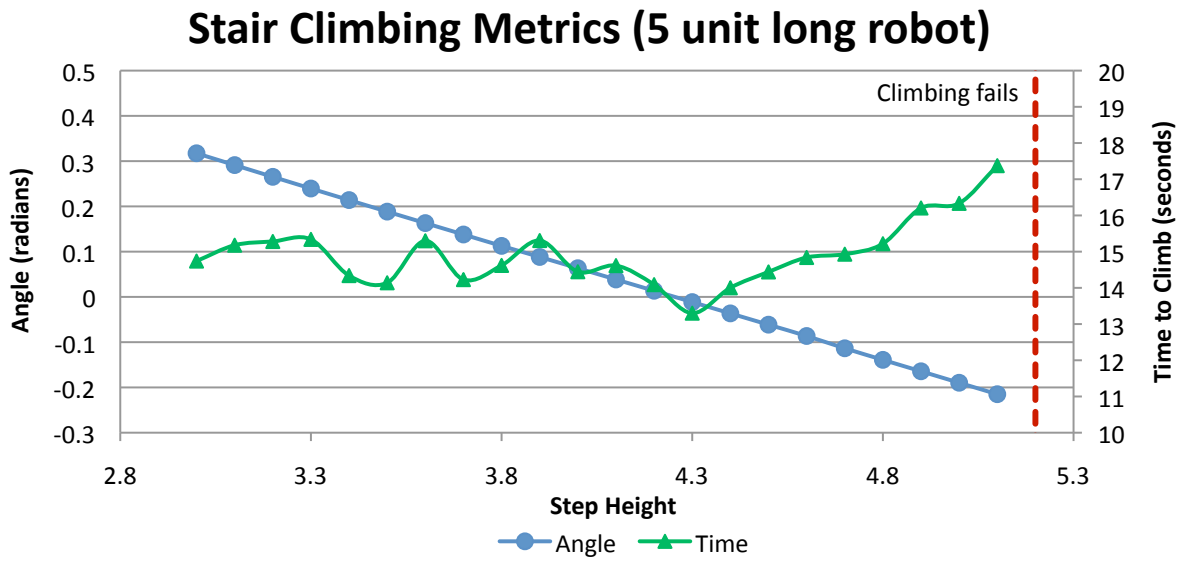
- Currently using body angle at "critical point" – flipper perpendicular to ground
- Good metric choice is critical
  - e.g., climbing time not good because failure and stress not well separated.



Not stressed



Stressed



Where are Functional Blueprints used?

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- To represent robot **capabilities**
  - e.g., FBs for climbing a step and flipping over
- To safely integrate **user requested changes**
  - Jumping to the user desired value may put the design in non-viable space
  - Generic, parametric perturbation FBs created on the fly to incrementally incorporate user requested changes
- To represent constraints enforced by **component libraries**
  - e.g., the size and torque of a servo required by the design must match a servo in the component library

Functional Blueprints for MiniDroid

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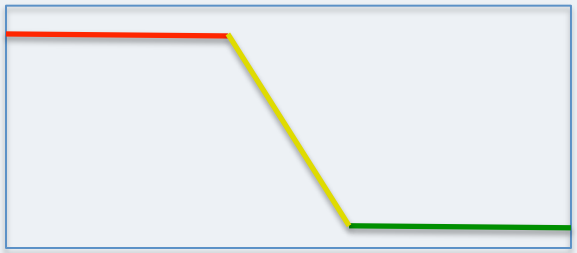
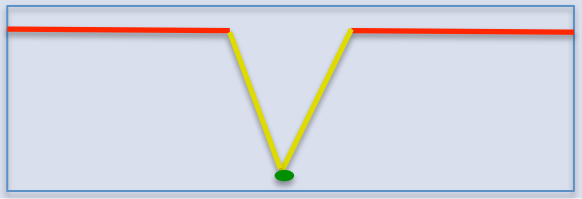
FB	Stress Function	Update Functions
Max Torque		Decrease torque
Flipping		Increase torque
Body Proportion		Decrement flipper length
Climb		Increase flipper and body length
Servo Viability		Decrease torque and increase motor mass
Servo Mass		Increase/decrease motor mass
Perturbation on X		Increase/decrease perturbed attribute X

MADV Prototype with Seven FBs

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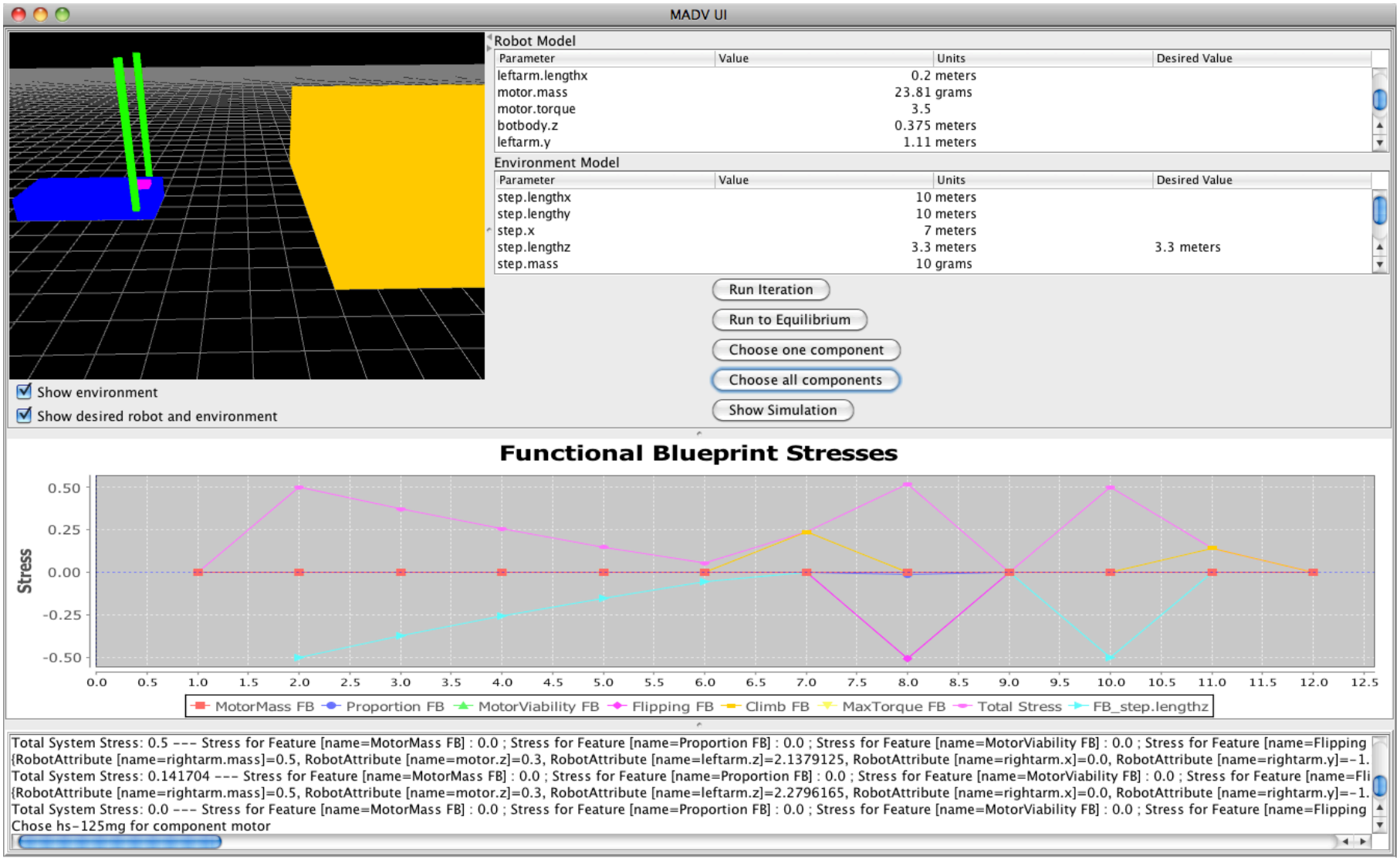

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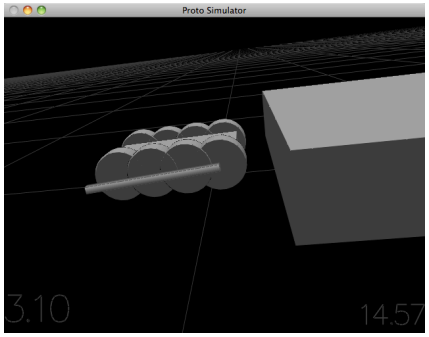
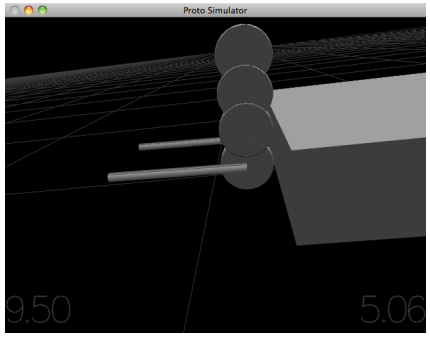
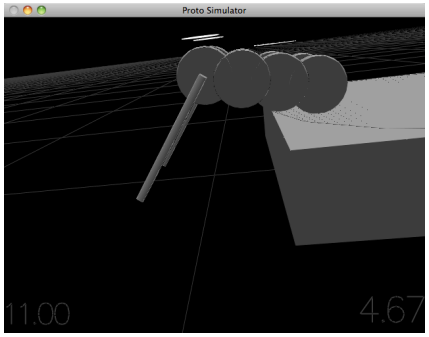
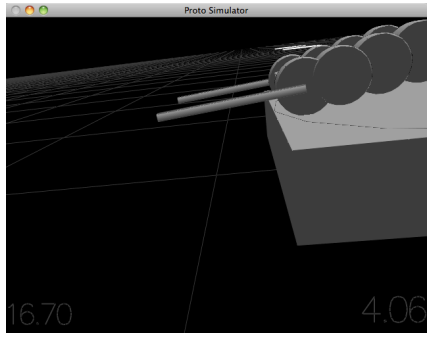
Initial simulation:

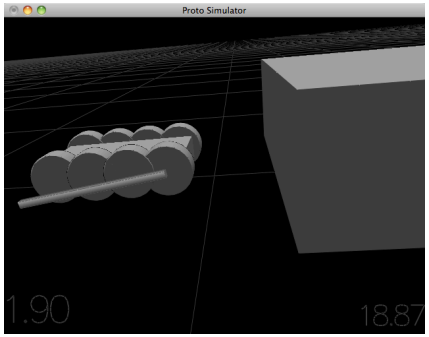


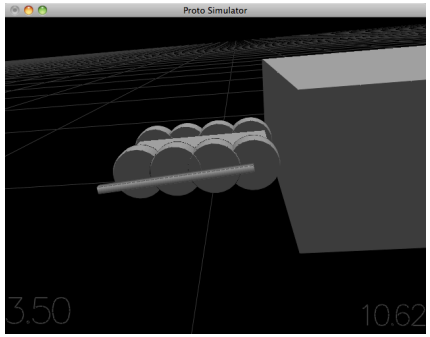


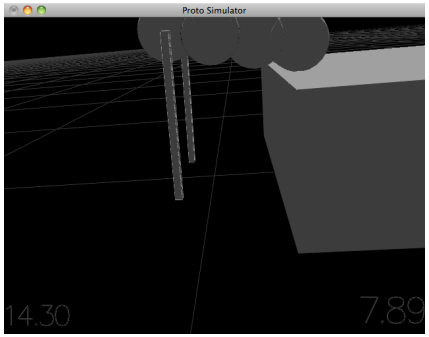


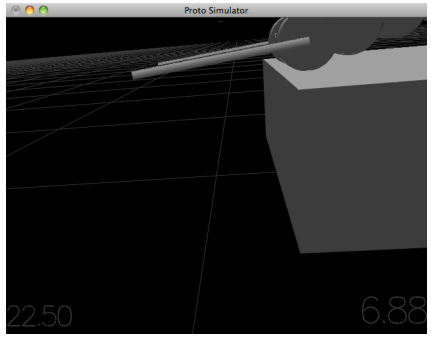


Simulation after changes:









Higher step → longer flipper, longer body, bigger motor

How Hard is it to Change Flipper Length?

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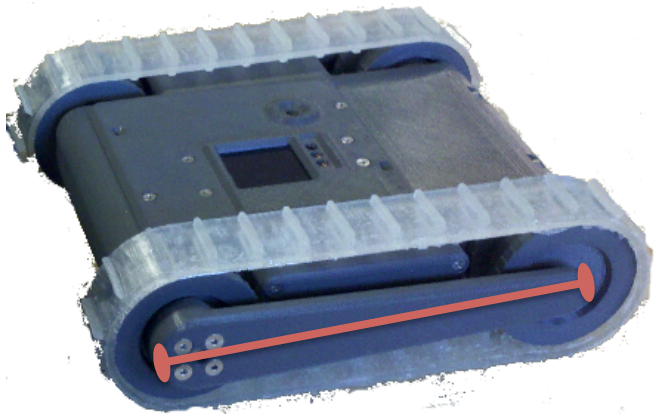

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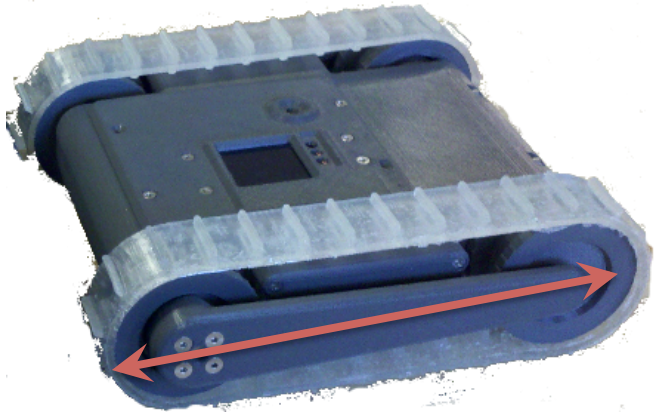
Does it grow from the center?



How Hard is it to Change Flipper Length?

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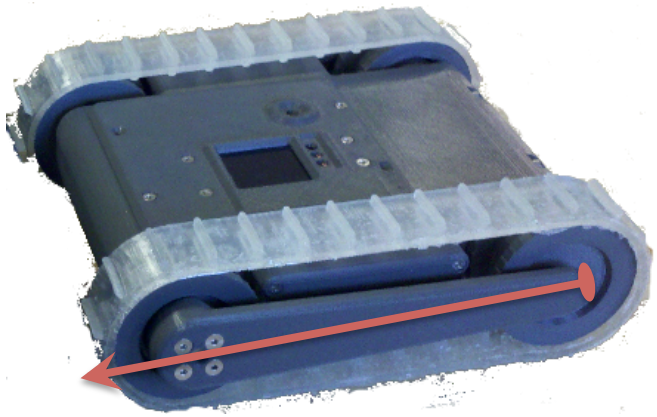
Does it grow from the center? the front?



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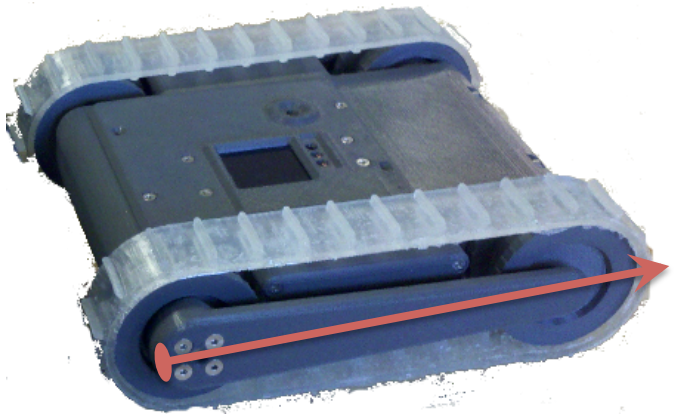

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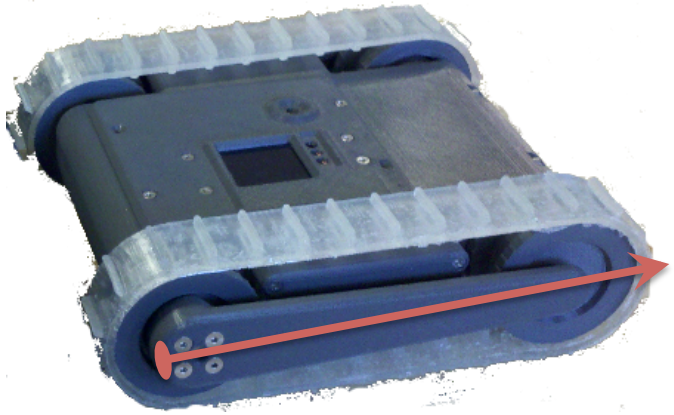

Functional blueprints control the key attributes…

… but our designs have many others!

A Complex Transformation…

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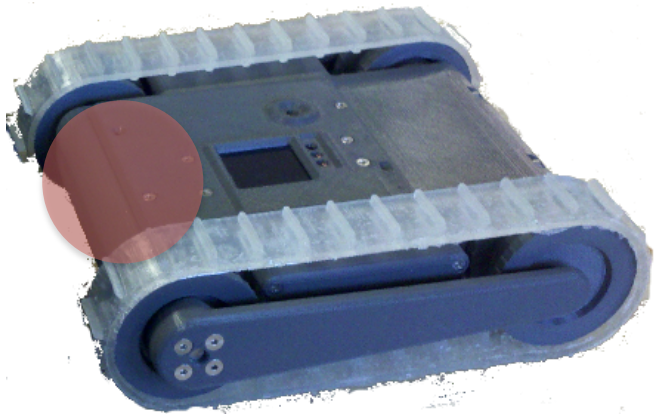
- Both flippers are driven by one servo…



A Complex Transformation…

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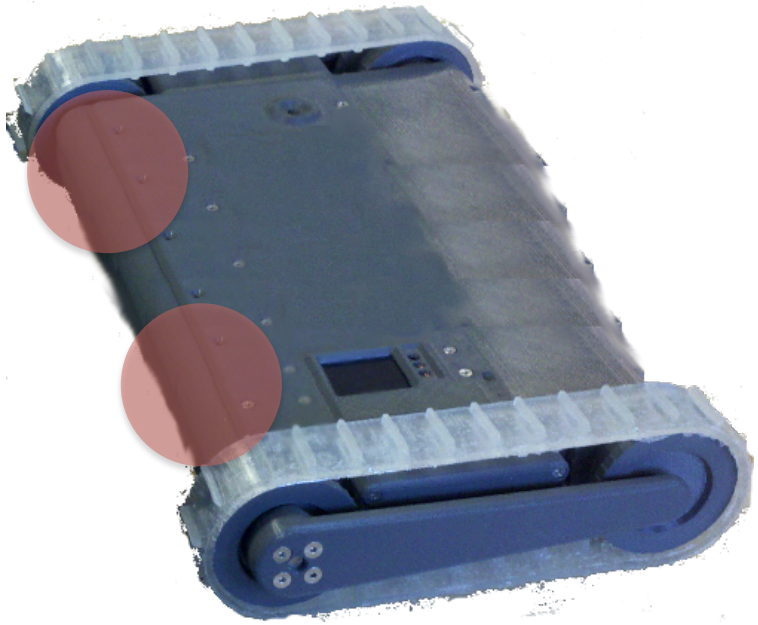
- Both flippers are driven by one servo…

  … what if the robot widens to need two?



Solution: Developmental Program

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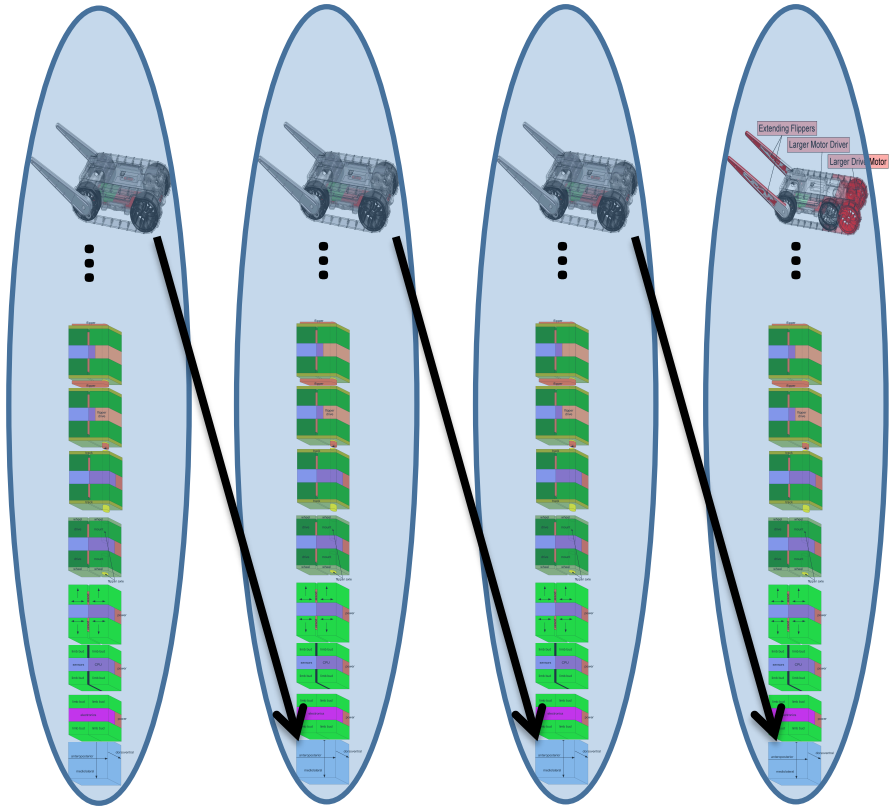
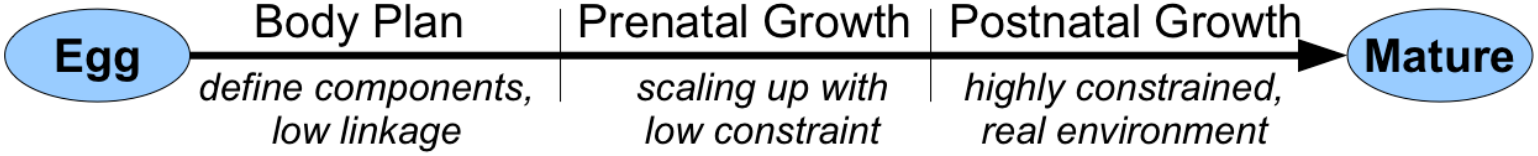
A developmental program constrains geometric relationships between components

- Reduced dimensionality
- Greater design flexibility





Developmental Primitives

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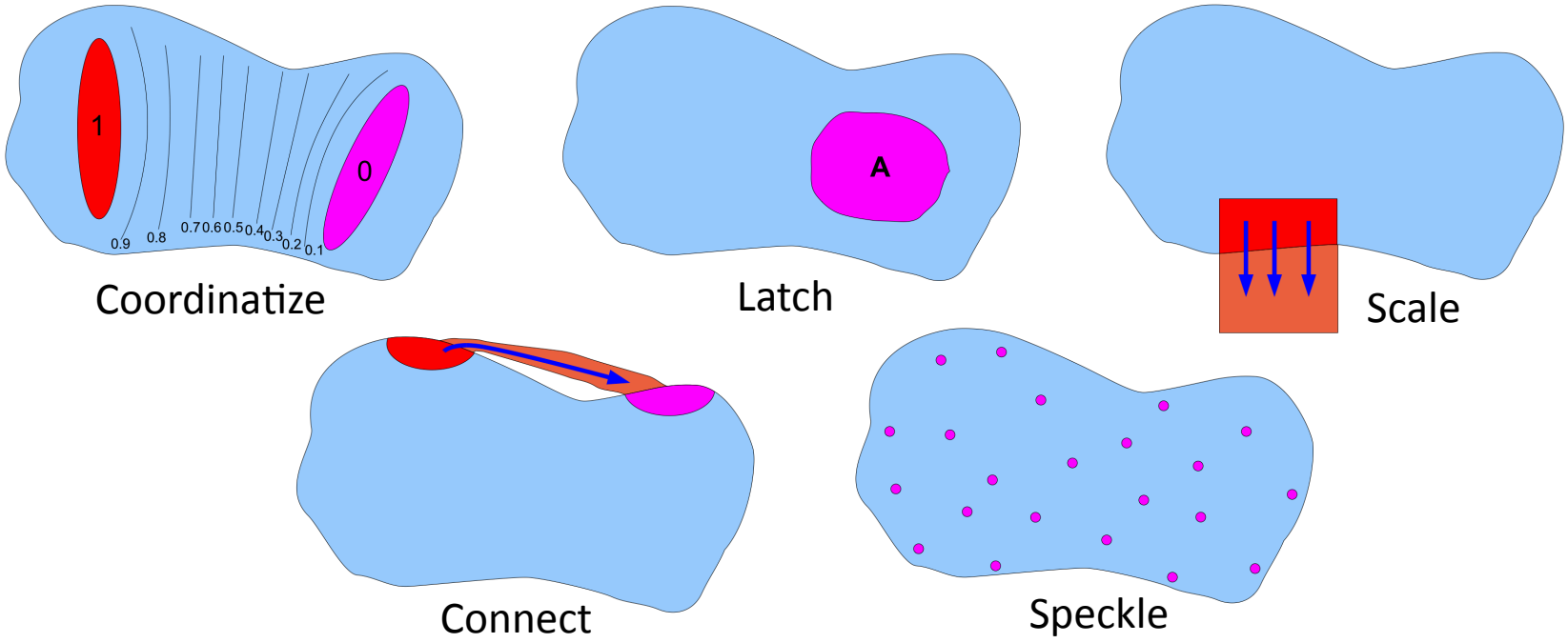
We begin with 5 manifold operations:



Each based on a key animal development pattern.

How far can we get with just these?

Developmental Program for Body Plan

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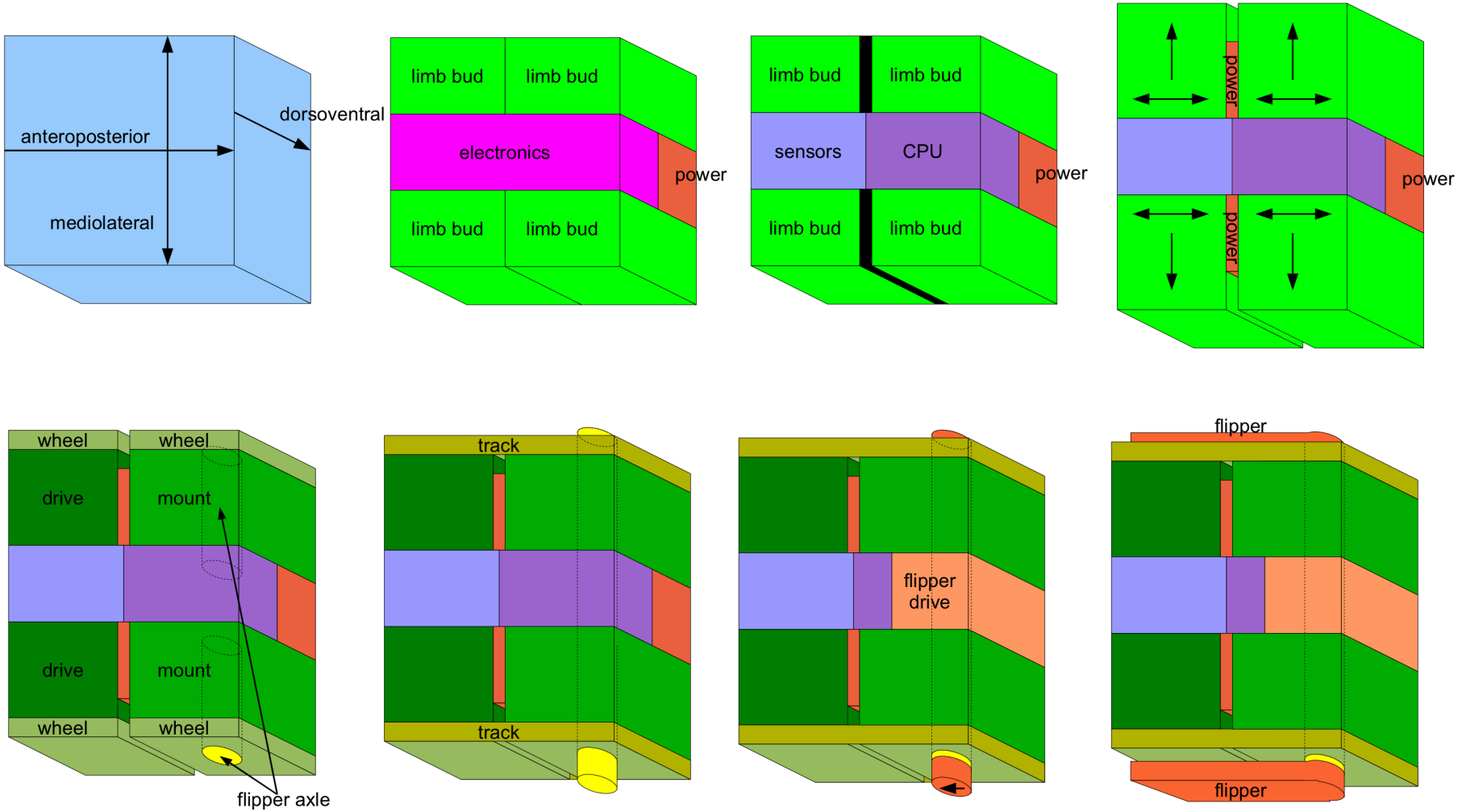

Final size: ~2mm

Next: prenatal growth

Body Plan Dictates Family of Variants

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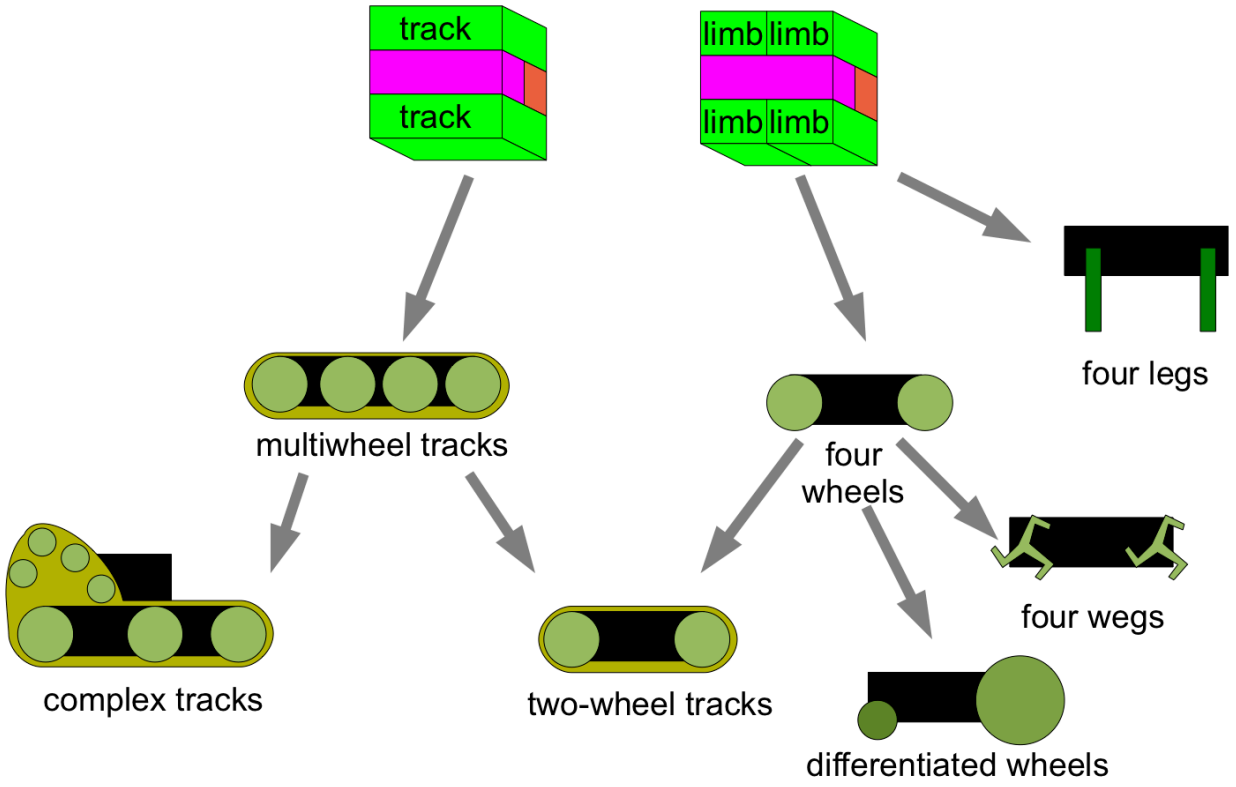

- The sequence of development for a body plan implies a prioritization of major design features, selecting a family of more accessible variants

Other Alternative Body Plans

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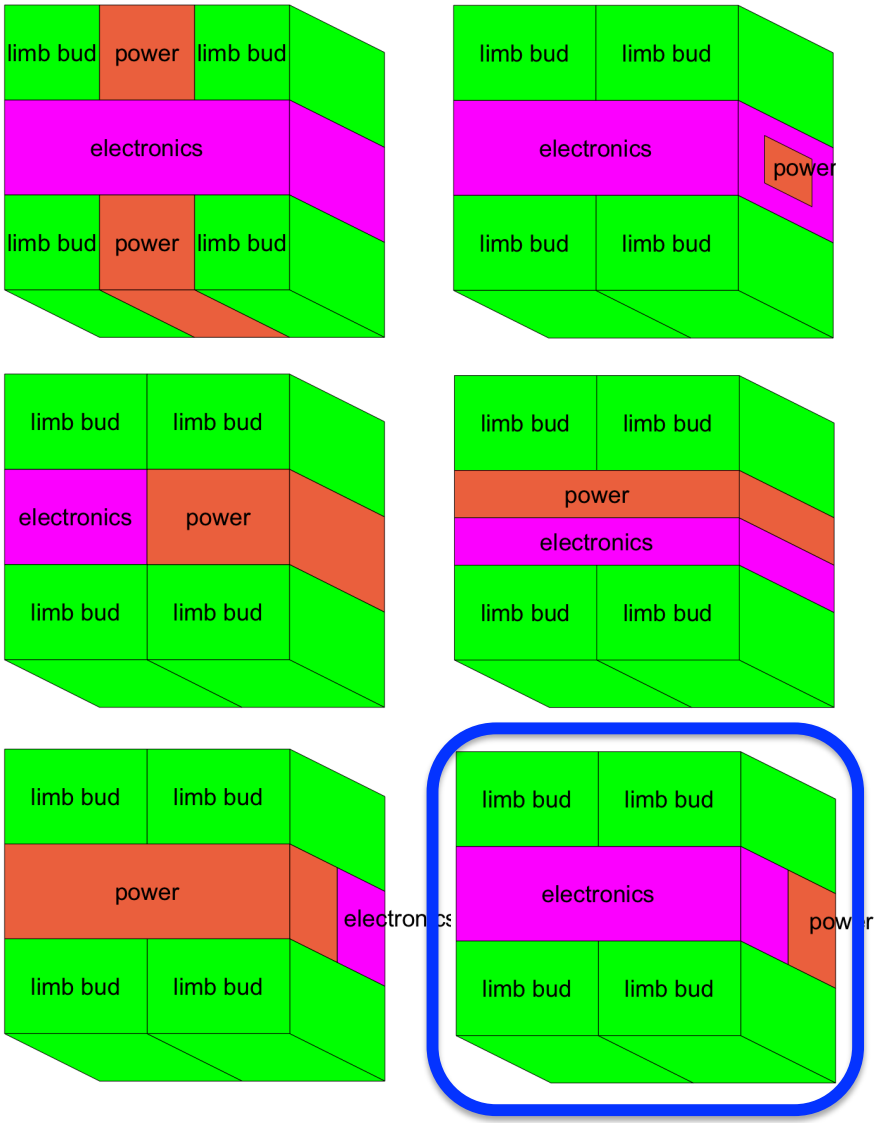

- Symmetric power or electronics splits a unified component
- Nested body adds ill-motivated complexity
- Of the asymmetries, ventral power also implies a preferred low center of gravity

Other Key Developmental Decisions

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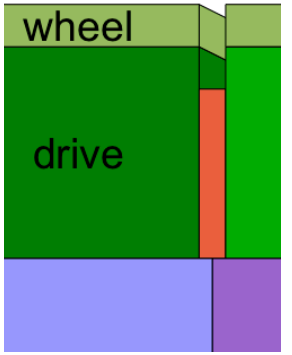
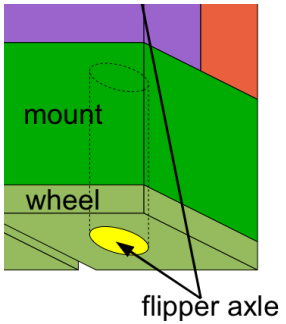
- Wheel attachments: packaged component with a “base limb” included within wheel
- Flippers: based on wheel axles ensures flipper/wheel structure integrity, but makes them hard to separate





Program Representation: Manifold Rules

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Precondition:	Tissue = egg Anteroposterior > 0.5 Mediolateral > 0.33
Effects:	Latch(limb-bud)

Precondition:	Tissue = egg Anteroposterior < 0.5 Mediolateral > 0.33
Effects:	Latch(limb-bud)

Precondition:	Tissue = limb-bud
Effects:	Coordinatize(Proximodistal)

Precondition:	Tissue = limb-bud Proximodistal exists
Effects:	Scale(Proximodistal,1.5) → Latch(limb)

Precondition:	Tissue = limb Proximodistal > 0.8
Effects:	Latch(wheel)

Precondition:	Tissue = limb Proximodistal < 0.8 Anteroposterior < 0.5
Effects:	Latch(drive)

Precondition:	Tissue = limb Proximodistal < 0.8 Anteroposterior > 0.5
Effects:	Latch(mount)

- Parallel application, continuous manifold evolution, conflict resolution by actuator blending
- Benefits: implicit relations, easy to modify/insert

Program Representation: Manifold Rules

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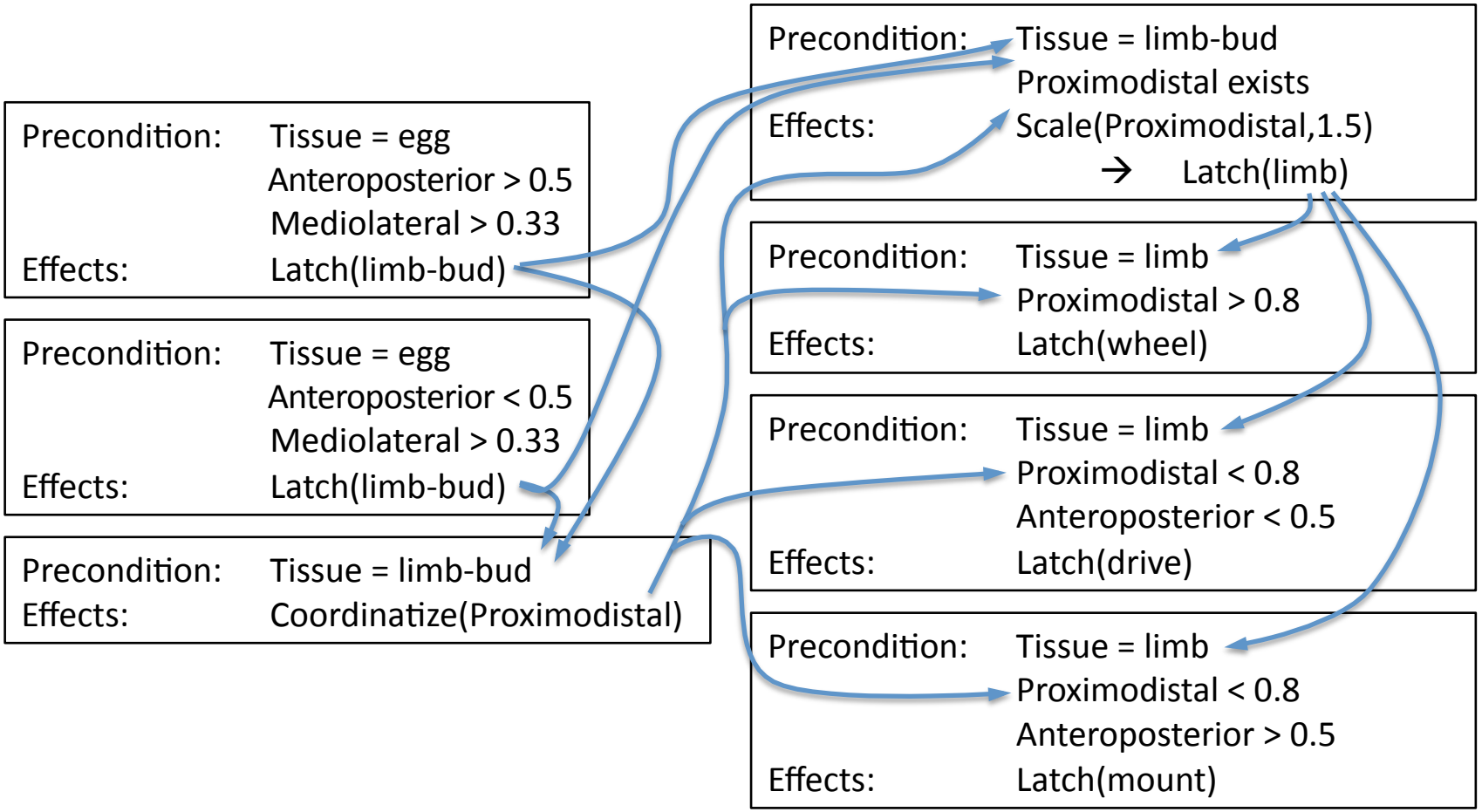

- Parallel application, continuous manifold evolution, conflict resolution by actuator blending
- Benefits: implicit relations, easy to modify/insert

Details: Packaged Components

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Approach: interpolate across parts from a "Component Model Library"

Details: Wiring

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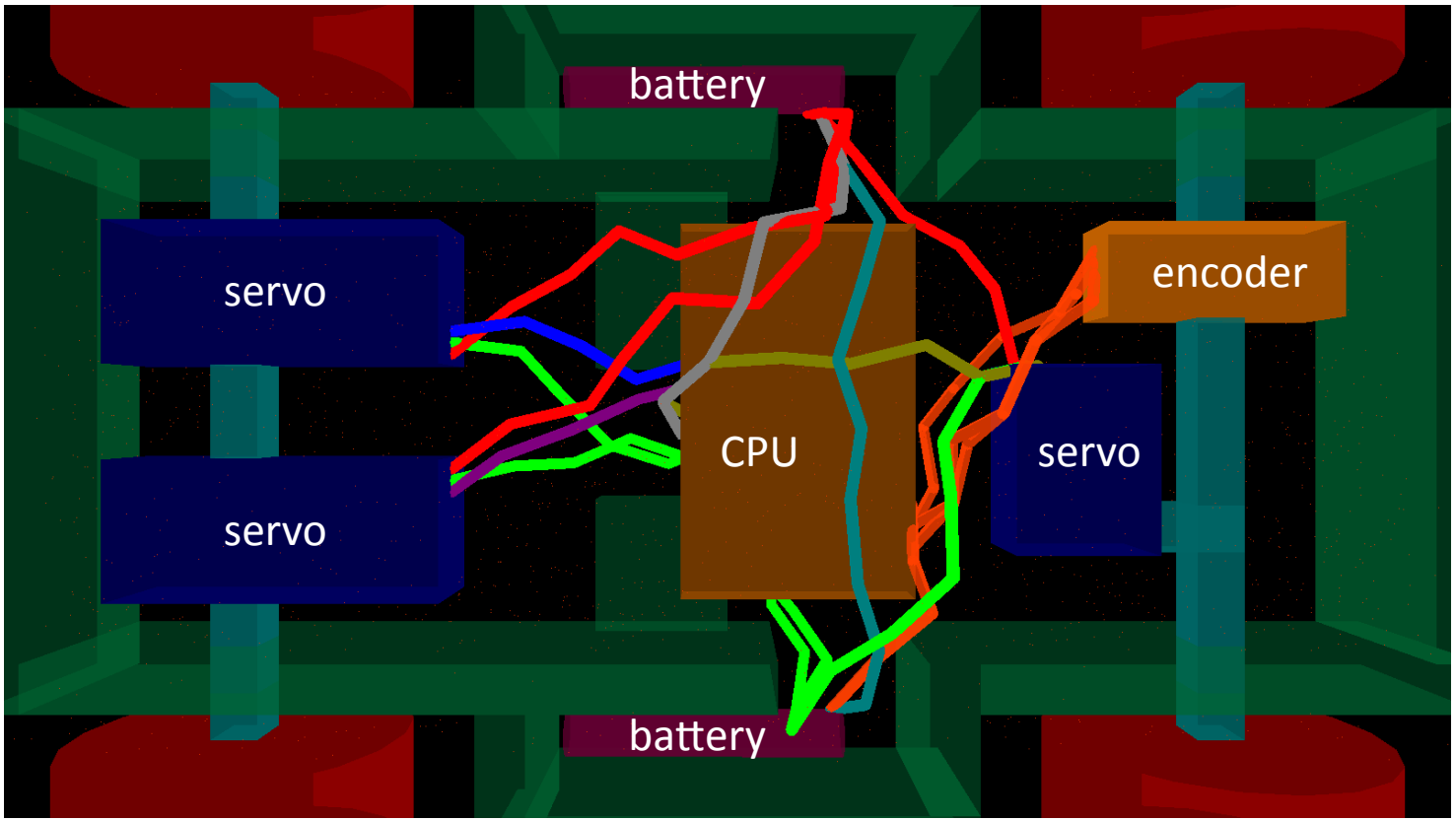
- Chemotactic model:



Contributions & Next Steps

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- Functional blueprint concept adapted for electromechanical design
- Development sets implicit structural relations
- Initial developmental models for miniDroid

Next: full simulation, integration with FBs

Goal: development of novel structures

Project Team:

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