A Morphogenetically Assisted Design Variation Tool

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Brittleness of Electromechanical Systems

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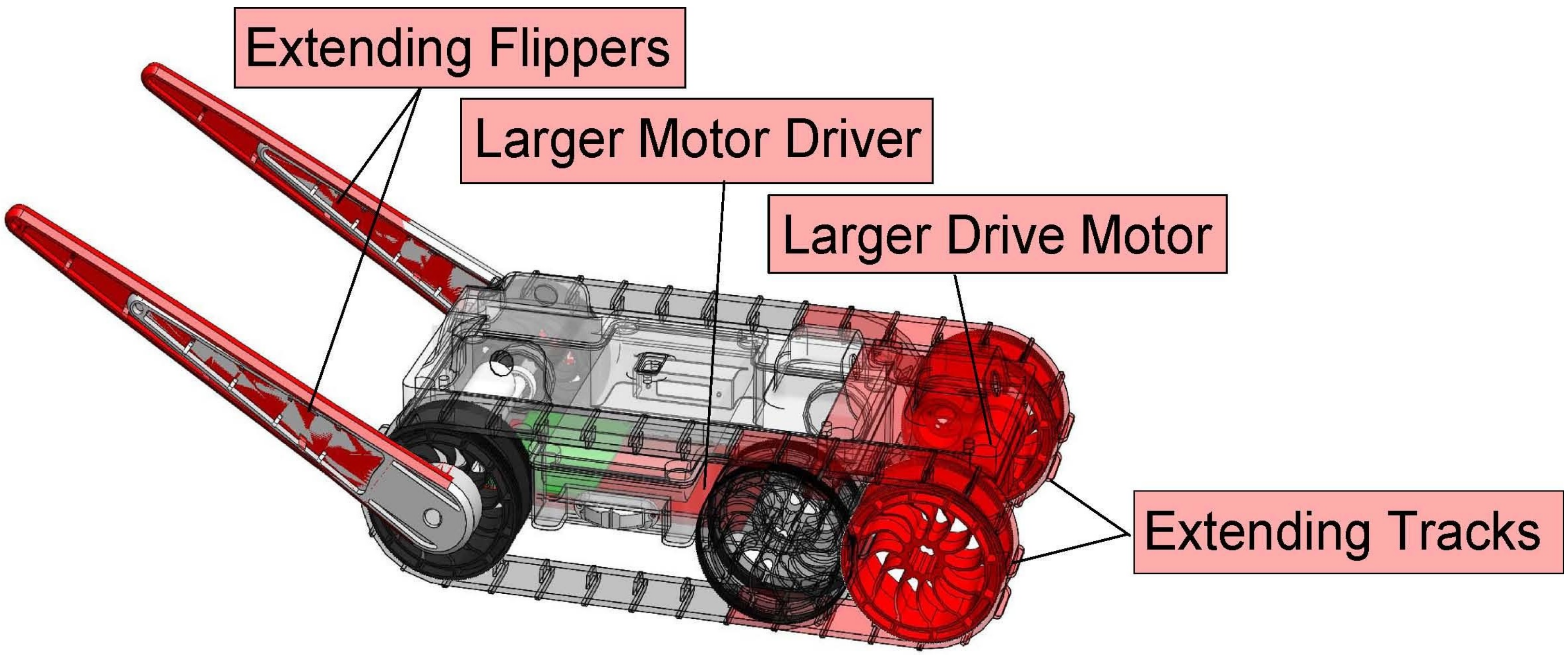
Even "simple" robots require careful design of many interacting components…



Once a system is constructed, difficult to modify design

miniDroid

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Design Variation Tool

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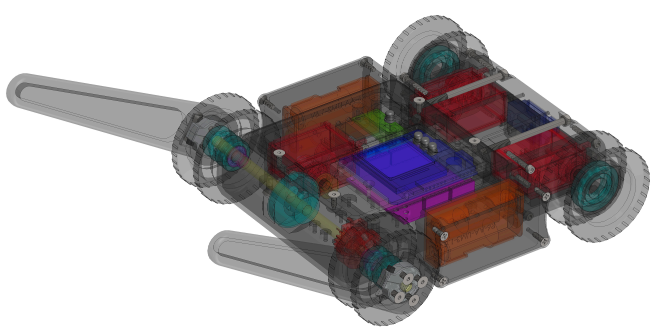
- Goal: design adaptability in engineered systems. When a design element is modified, the rest of the design automatically adjusts to compensate.
  - Enable users who are novices at electromechanical design to create functional design variants
- Idea: inspired by biology where animals adapt gracefully as they grow using ***feedback loops*** to make changes that maintain the integration of the organism as a whole



Functional Blueprints: Stress Functions

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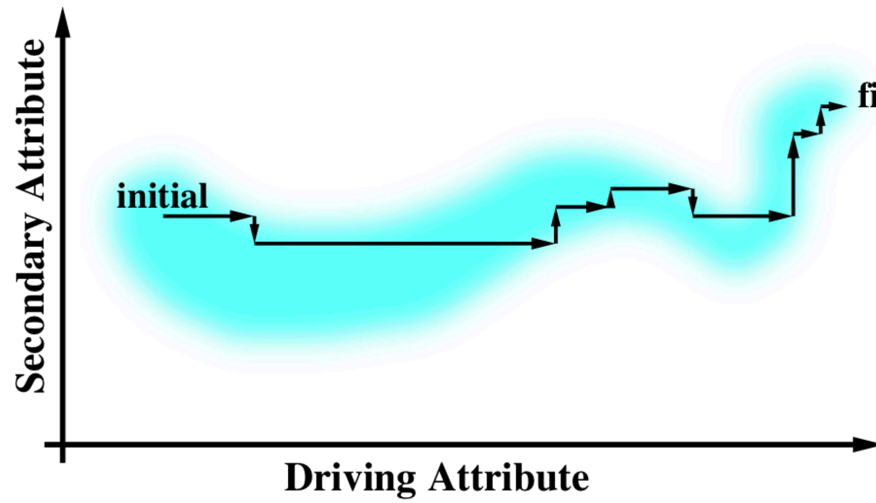
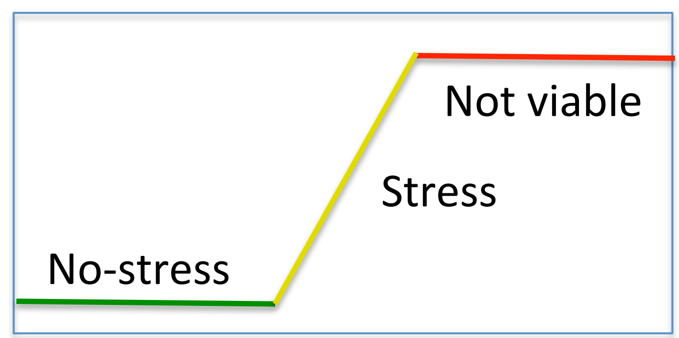
- Idea: keep the design always working, navigate through viable space



- Stress functions define viable and non-viable space



Functional Blueprints (FBs)

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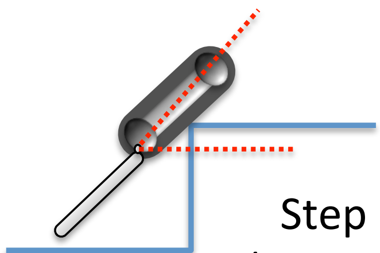
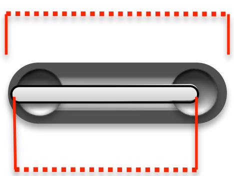
Examples:

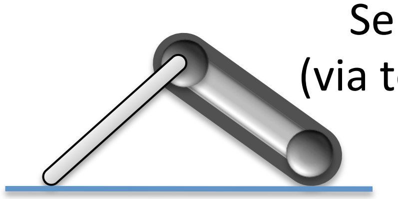


Step Climbing
(via ascent angle)



Flipper/Body Ratio

Self-Righting
(via torque/mass)



Inspired by regulatory processes in natural morphogenesis

FB requirements:

- Initial viable design
  - always maintain design viability
- Behavior that degrades gracefully
  - detect when design elements start to become problematic
- Metric for stress degree & direction
  - Stress used as a coordination signal among different subsystems
- Incremental adjustment program

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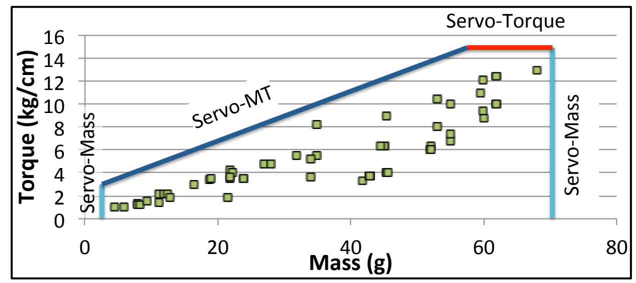
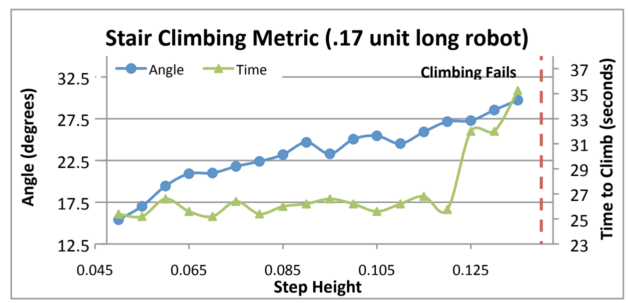
Types of Functional Blueprints

- **<u>Closed-Form FBs</u>:** stress evaluated analytically using equations provided by domain expert
  - FB constraining robot body's length-to-width ratio
- **<u>Quantized-Component FBs</u>:** for choosing from libraries of fixed component variants
  - *Servo* FB constrains the torque and mass of servo motors
- **<u>Simulation-Driven FBs</u>:** for evaluating complex non-closed-form functions
  - *Climb* FB maintains a miniDroid's ability to climb and is evaluated through a ROS simulation
- **<u>User-Command FBs</u>:** temporary FBs that incrementally shifts a design or evaluator parameter towards the specified value





MADV Architecture

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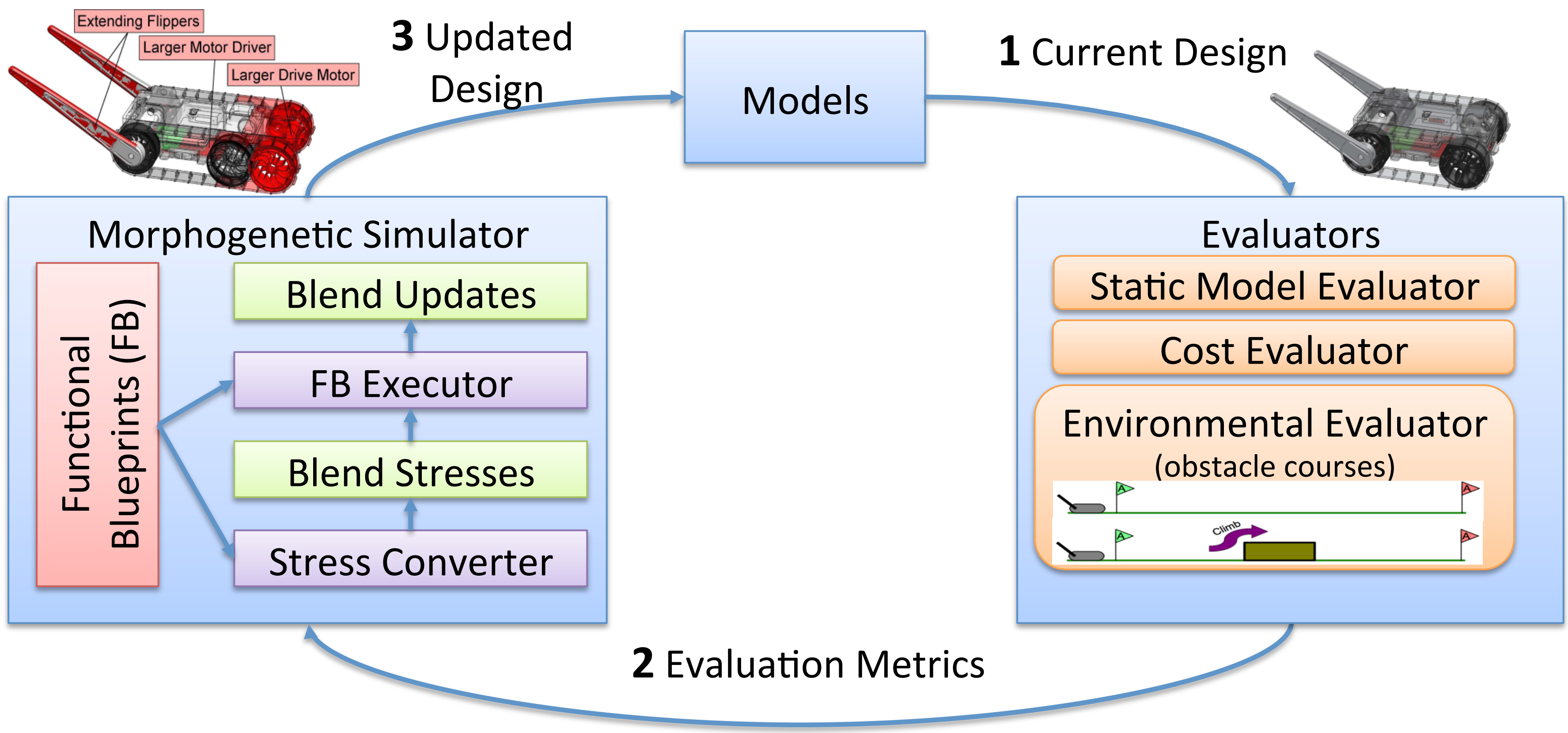

- Evaluators measure how well a design accomplishes its goals. Input: design parameters. Output: evaluation metrics
- FBs blend evaluation metrics from multiple evaluators and convert them to stresses.
- FBs incremental programs calculate update for design parameters, resulting in a new design variant that is still viable

miniDroid Case Study

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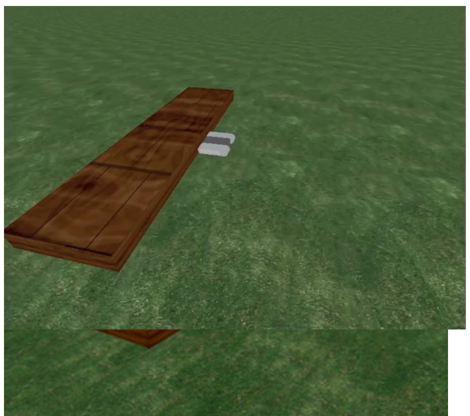
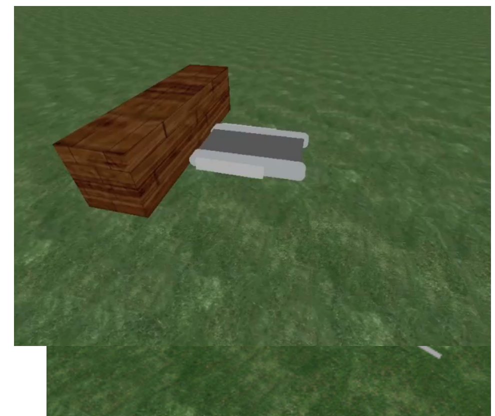
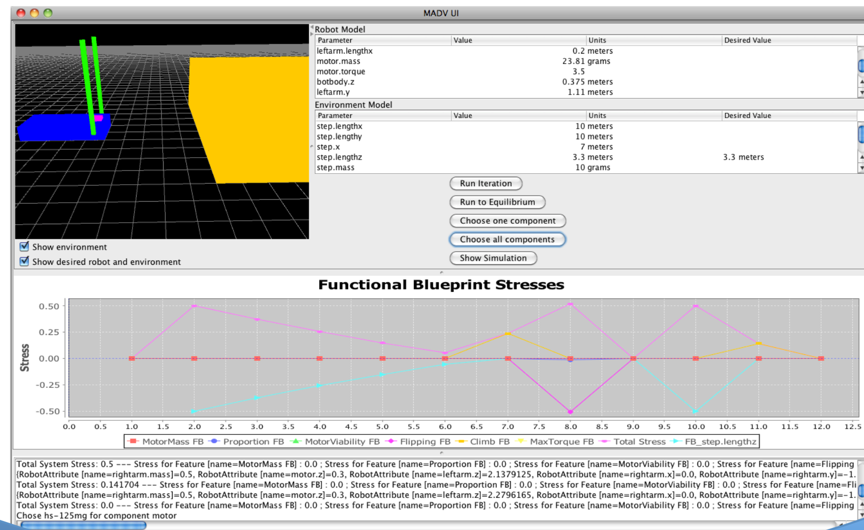
Original miniDroid climbs over a 10cm



Goal: a variant to climb over a 55cm step





- Selected subset of critical miniDroid functions
  - e.g., climbing over obstacles, flipping over
- Identified 7 key design parameters affecting these functions
- 8 FBs for evaluating these functions

miniDroid Case Study

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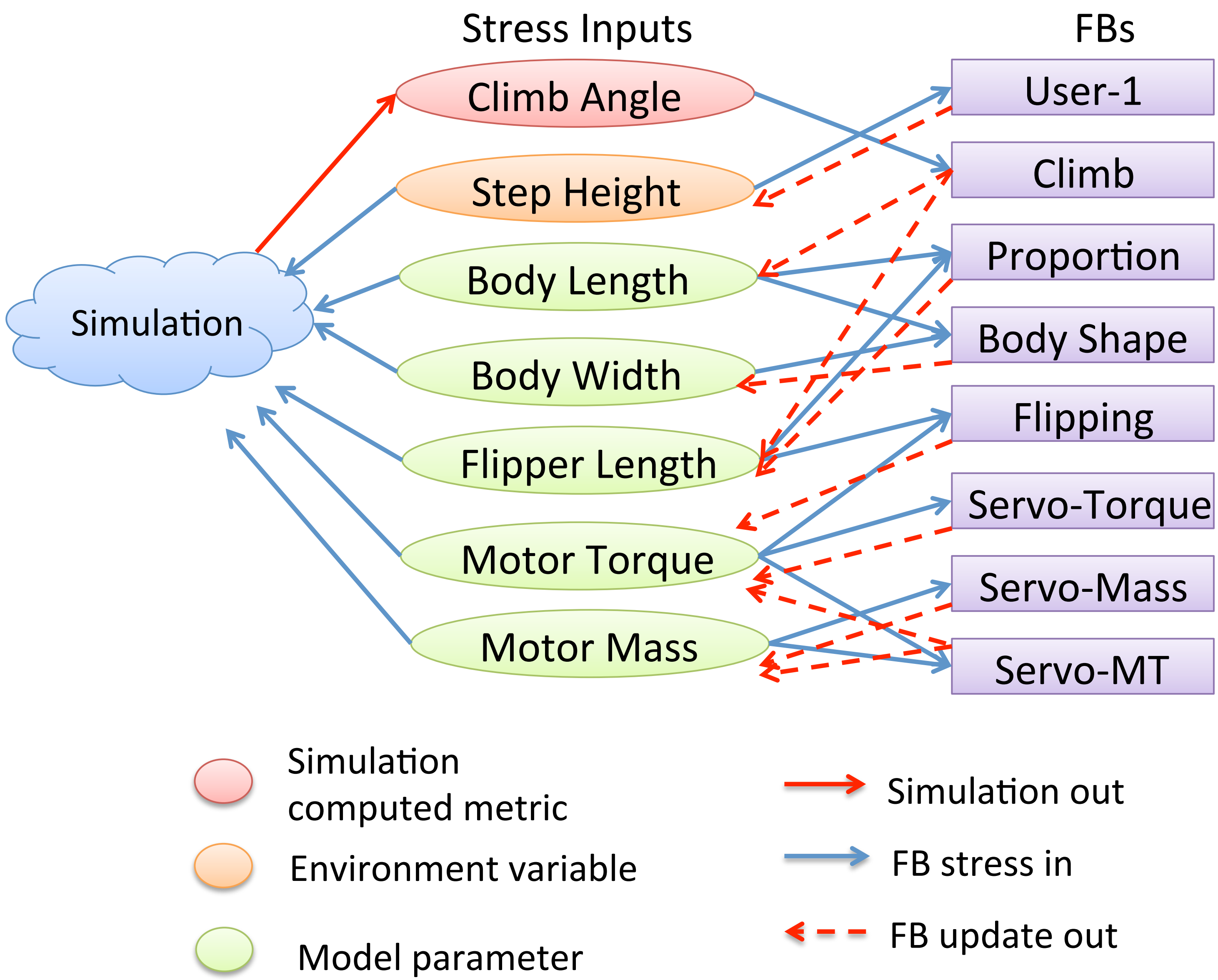

Stress & Parameter Changes

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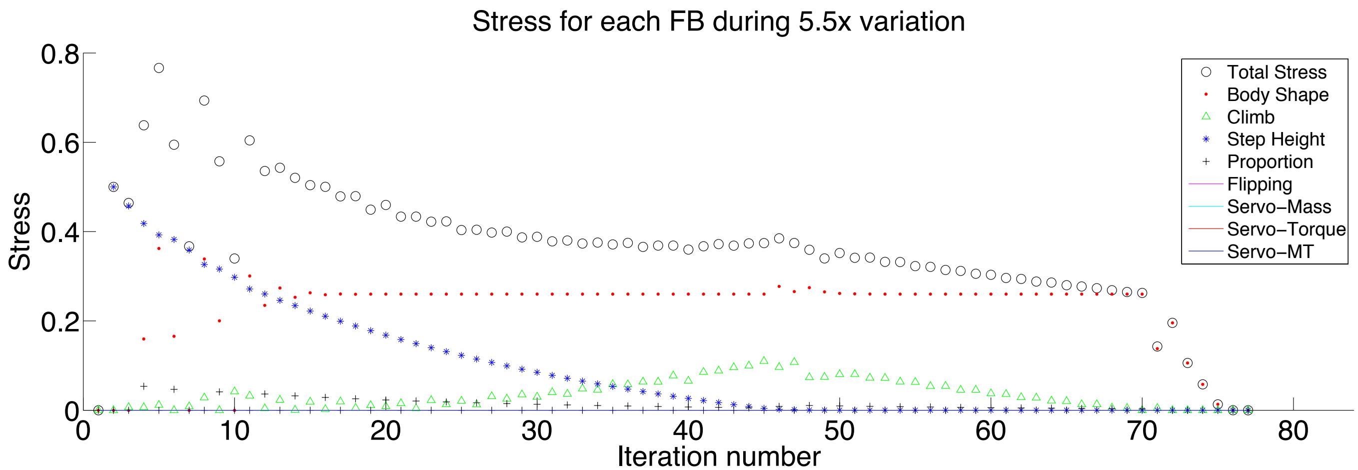
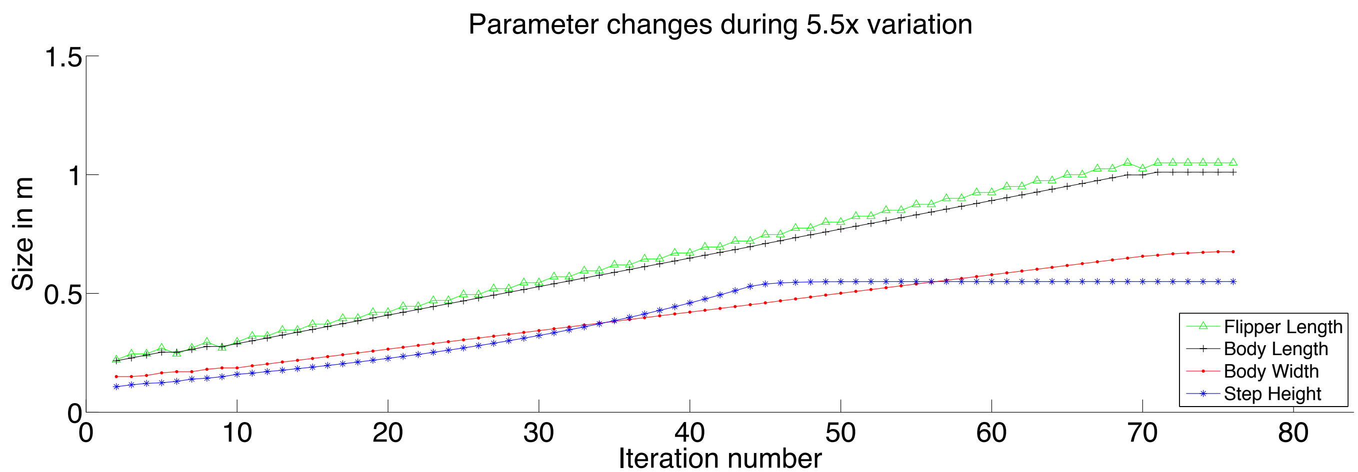
MADV achieves goal in 75 design iterations

All intermediate designs are functional





Generalizability and Scalability

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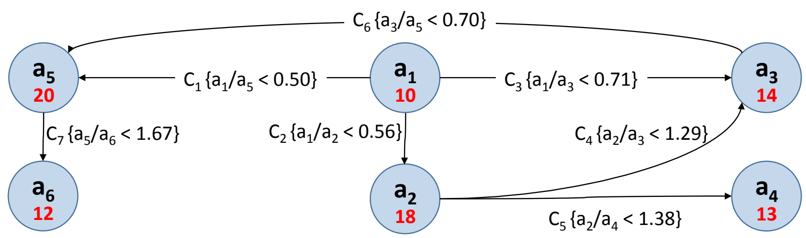
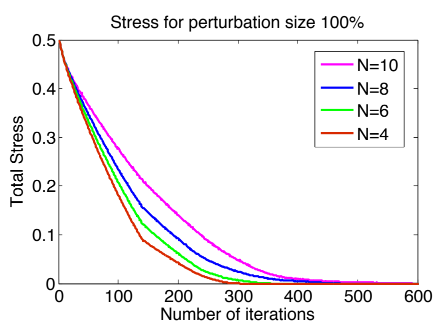
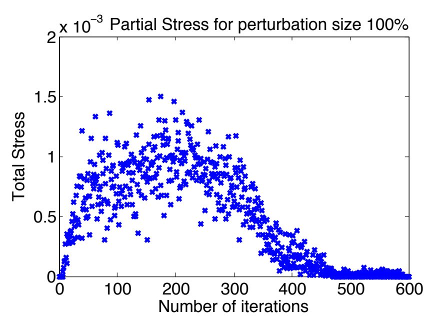
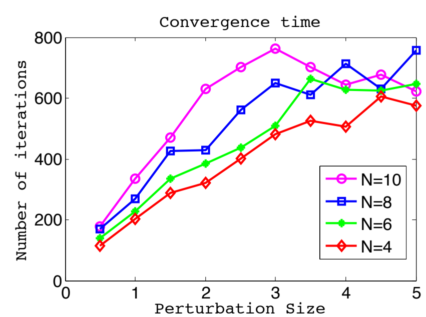
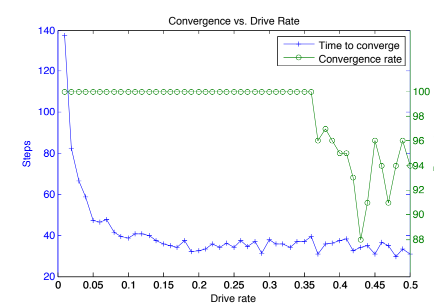
- Scalability: more detailed miniDroid model developed in 3 hours: 112 parameters and 111 FBs
- Generated random networks of abstract FBs and design attributes:











Comparison vs. Genetic Algorithms

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- Two GA fitness functions, max 1000 iterations:
  - FF1: function of distance between desired and initial solution and sum of constraint violations
  - FF2: functions of stress inputs used by FBs
- Results:
  - FBs more focused, fewer iterations, closer to initial design, lower final stress
  - Solved problems 280x faster, 100% convergence rate
  - FBs explore less of the design space

Perturbation size 1	| Initial - Final |	# Iterations	Time (s)	Stress	Convergence
Functional Blueprints	**22**	**310**	**0.01**	**0**	**100%**
GA w/o stress (FF1), pop 50	48	756	0.12	0.65	35%
GA w/ stress (FF2), pop 50	80	714	0.52	0.2	40%
GA w/o stress (FF1), pop 500	55	714	2.65	0.14	40%
GA w/ stress (FF2), pop 500	88	323	2.8	0.05	85%

Usability & Extensibility

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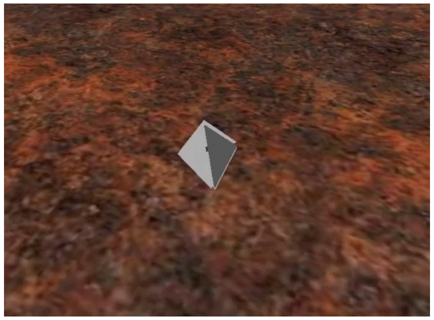
Our implementation of the MADV architecture is reusable and extensible

- Code base is highly modular
- FBs, parameters, and evaluator settings are specified in XML files
- Evaluators are Java objects allowing problem-specific evaluation (e.g., via RPC to rigid body simulators)
- Reused blueprints for Mars lander



Summary

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- Design variant tool created that uses Functional Blueprints
- miniDroid case study: 5.5x variant
- Functional blueprints are generalizable, scalable, and reusable
  - Random FB networks
  - Mars lander

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Code posted