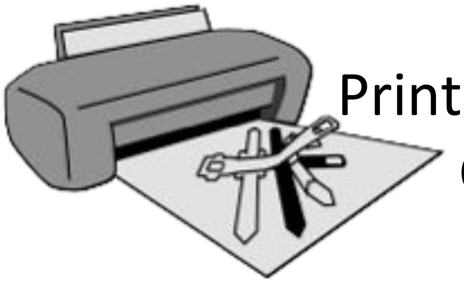

Collaborative Proposal: Printable Robots: An Expedition in Computing for Compiling Functional Physical Machines

Daniela Rus, Andre DeHon[‡†], Martin Demaine, Sanjeev Khanna[†], Sangbae Kim[§], Vijay Kumar[*], Wojcieck Matusik, Insup Lee[†], Martin Rinard, Rob Wood[η]

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[†]Department of Computer Science, University of Pennsylvania

[‡]Department of Electrical and Systems Engineering, University of Pennsylvania

[*]Grasp Laboratory, University of Pennsylvania

[η]School of Engineering and Applied Sciences, Harvard University

Vision

- Democratize access to robots (and other programmable machines)
- Wide-spread dissemination and availability of customizable affordable robots throughout society
  - Manufacturing
  - Education
  - Health care
  - Environment
  - Search and Rescue
  - Home applications
  - …

- Establish new user community and means to share
  - Designs
  - Experiences
- *If you can imagine it you can build it*
- Enormous potential for broader impacts

Expedition PIs

Wood

Rus

Kumar

deHon

Matusik

MIT, University of Pennsylvania, Harvard University

Demaine

Kim

Rinard

Lee

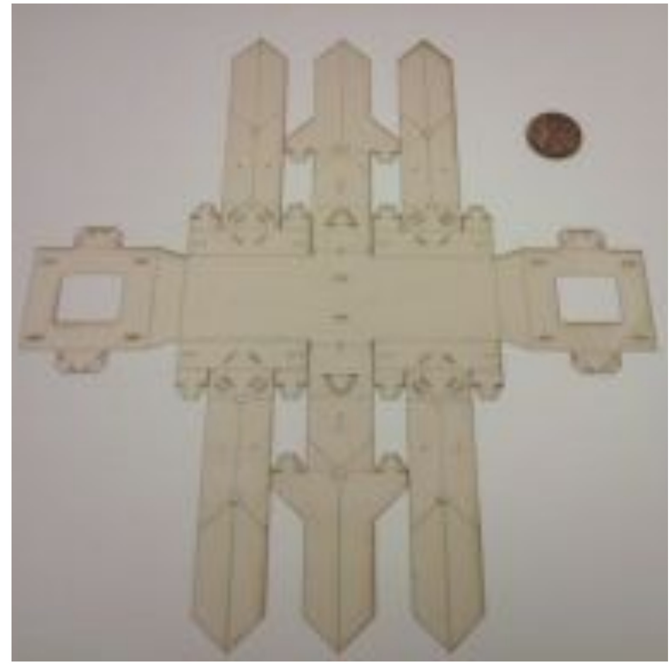
Khanna

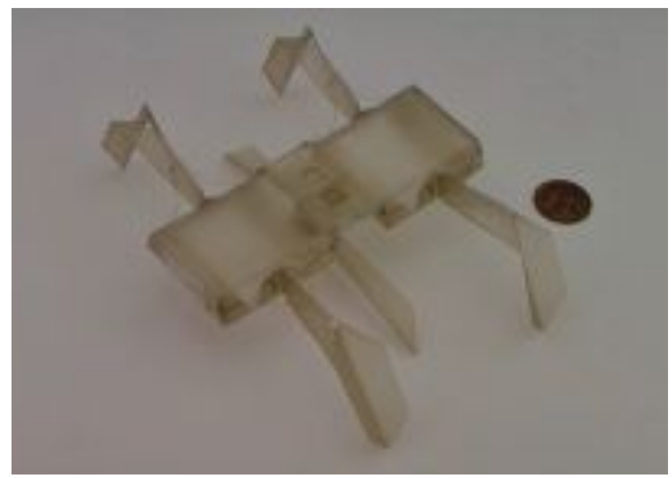
Our Vision and Science Quest

- To develop an end-to-end process that starts with specification and delivers a functional programmable device
- To establish the science of computation for programmable printable objects PPO

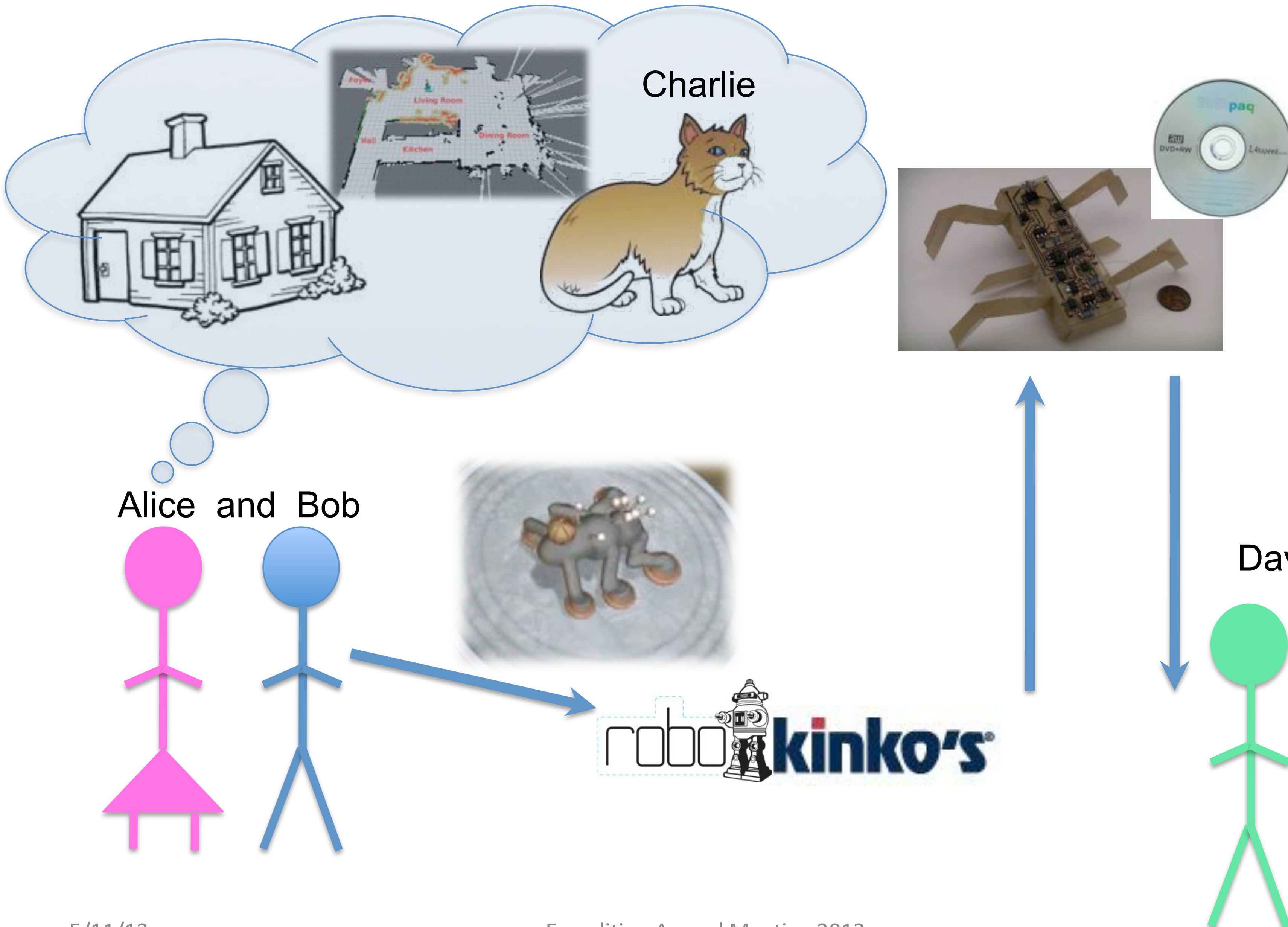
- H1: A unifying framework exists for specifying a general class of programmable objects: representations, a general architecture, and a expressive formal language
- H2: Given this framework, it is possible to automatically generate the hardware and software to realize the physical object?

- Results: will lead to a new industry and a new level of accessibility to PPOs and democratize robotics





Challenge: Computational Programmable Objects



PR App – from ideas to prototypes

Enabling

- *Hackers to produce physical prototypes**
- *Newbies to produce personal robots*
- *Middle-schoolers to print their own Lego modules*
- *Sharing of designs via PRInventory repository*

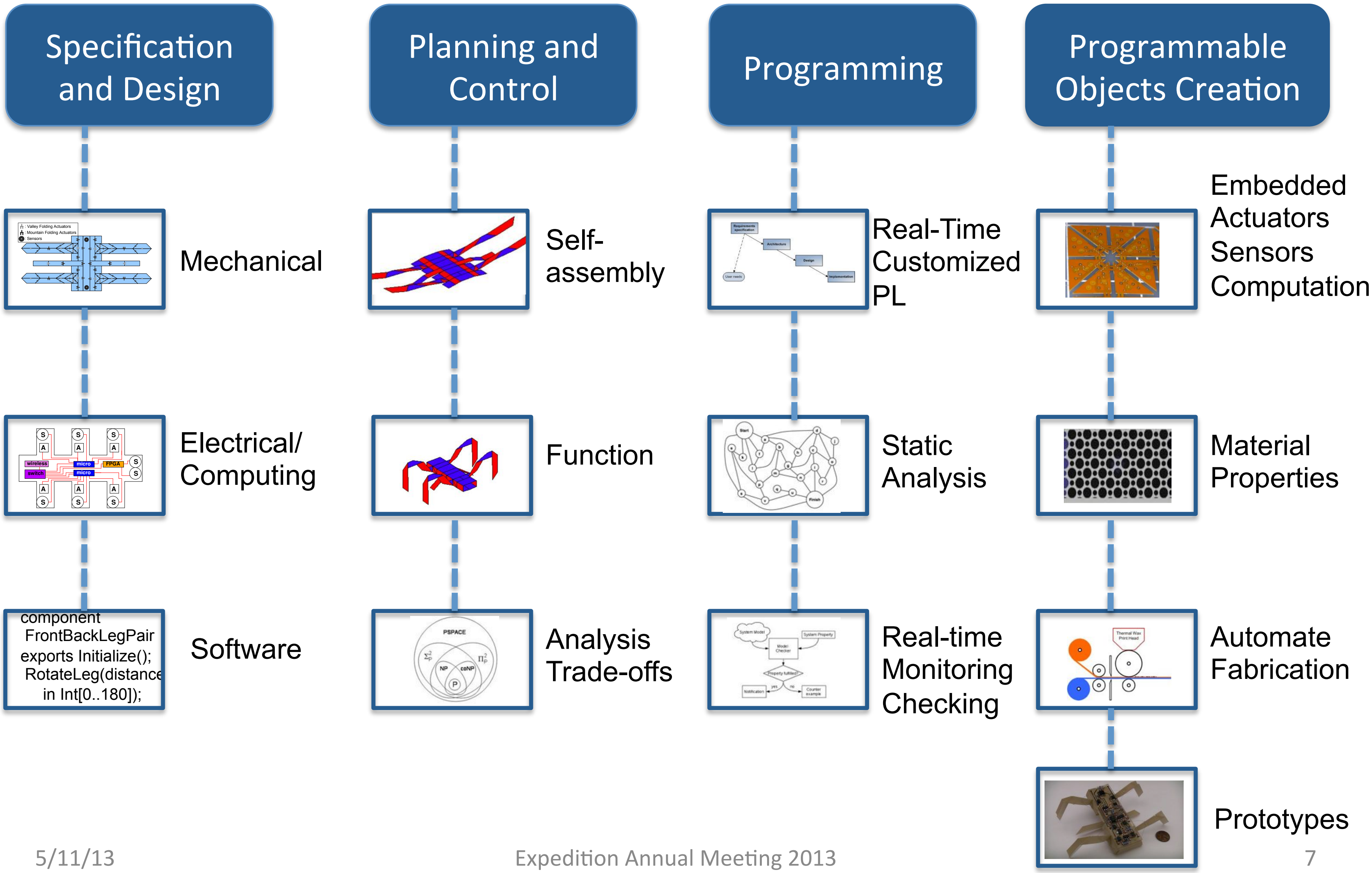
* Modeled after PennApps, a highly successful annual 48-hour hackathon run by students at Penn, http://teams.2011f.pennapps.com/

Specifying Design from Database of Components

Using Physics-Based Simulation to Verify Constraints

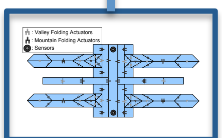
Video from Spore™, EA Games 2008

Multi-Disciplinary Research Pillars

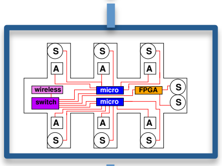


Multi-Disciplinary Research Pillars

Specification and Design



Mechanical



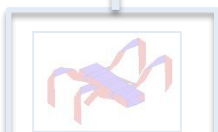
Electrical/ Computing

```
component
 FrontBackLegPair
exports Initialize();
 RotateLeg(distance
   in Int[0..180]);
```

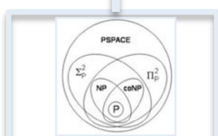
Software

Planning and Control

Self-assembly

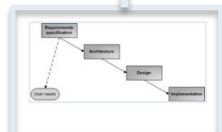


Function

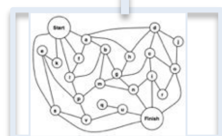


Analysis Trade-offs

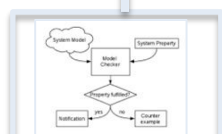
Programming



Real-Time Customized PL



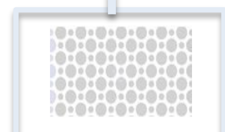
Static Analysis



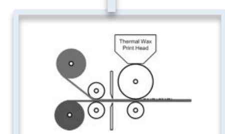
Real-time Monitoring Checking

Programmable Objects Creation

Embedded Actuators Sensors Computation



Material Properties

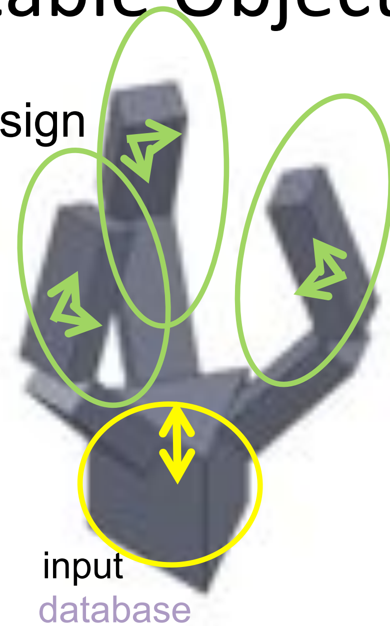


Fabrication

Prototypes

Programmable Printable Objects: Design

New Design



Database Search:

segmentation

+

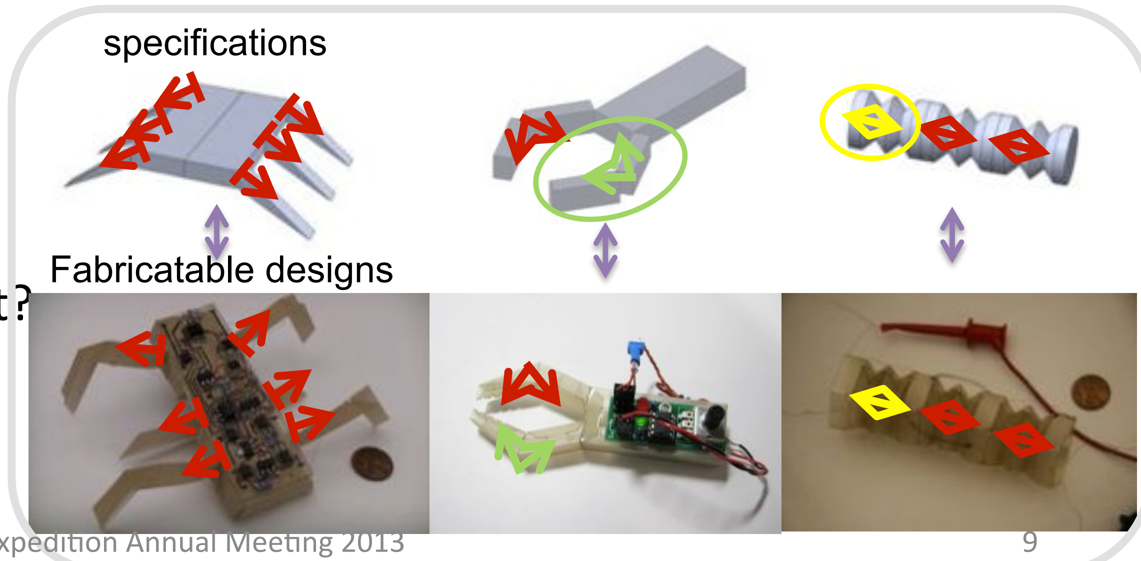
functionality matching

+

composition

Computation Challenges

- How do we design the geometry and material properties given the specified constraints?
- Given a *library of designs*, how do we segment, match function, and compose to get new designs?
- How do we optimize the parameters of the design?
- How do we accurately simulate and analyze object?



Library

Programmable Printable Objects: Design

Computation Challenges

- How do we design the geometry and material properties given the specified constraints?
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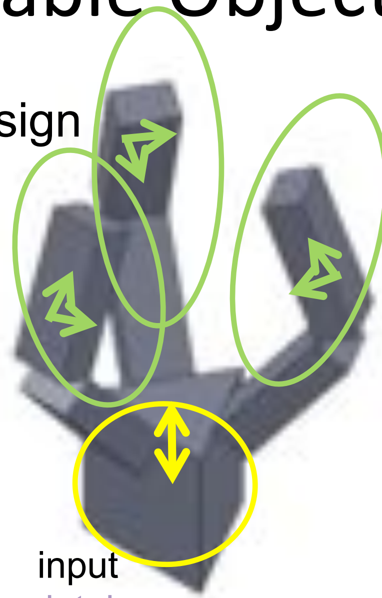
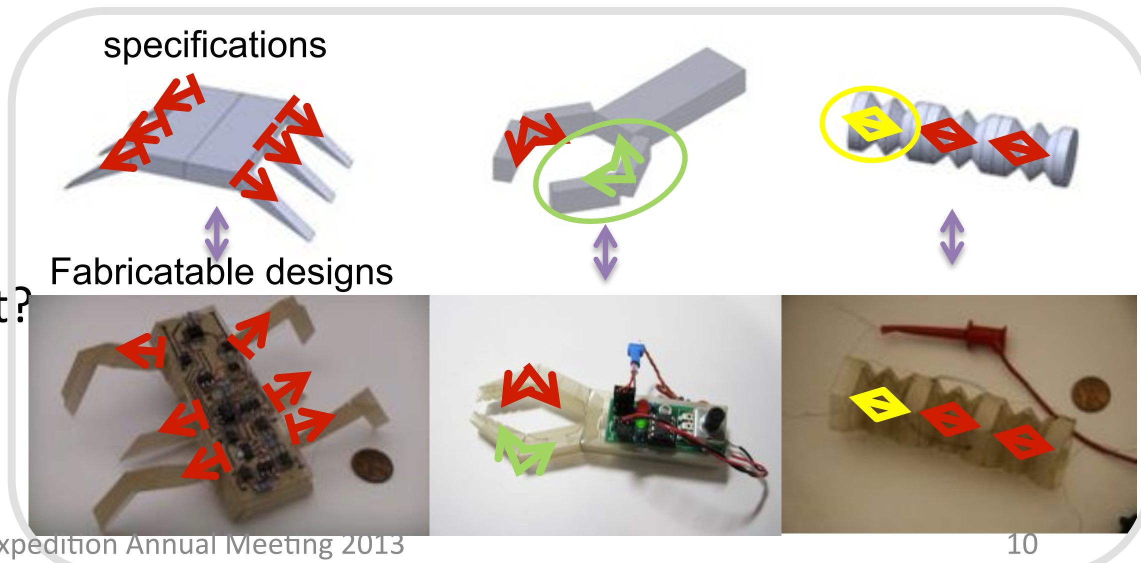


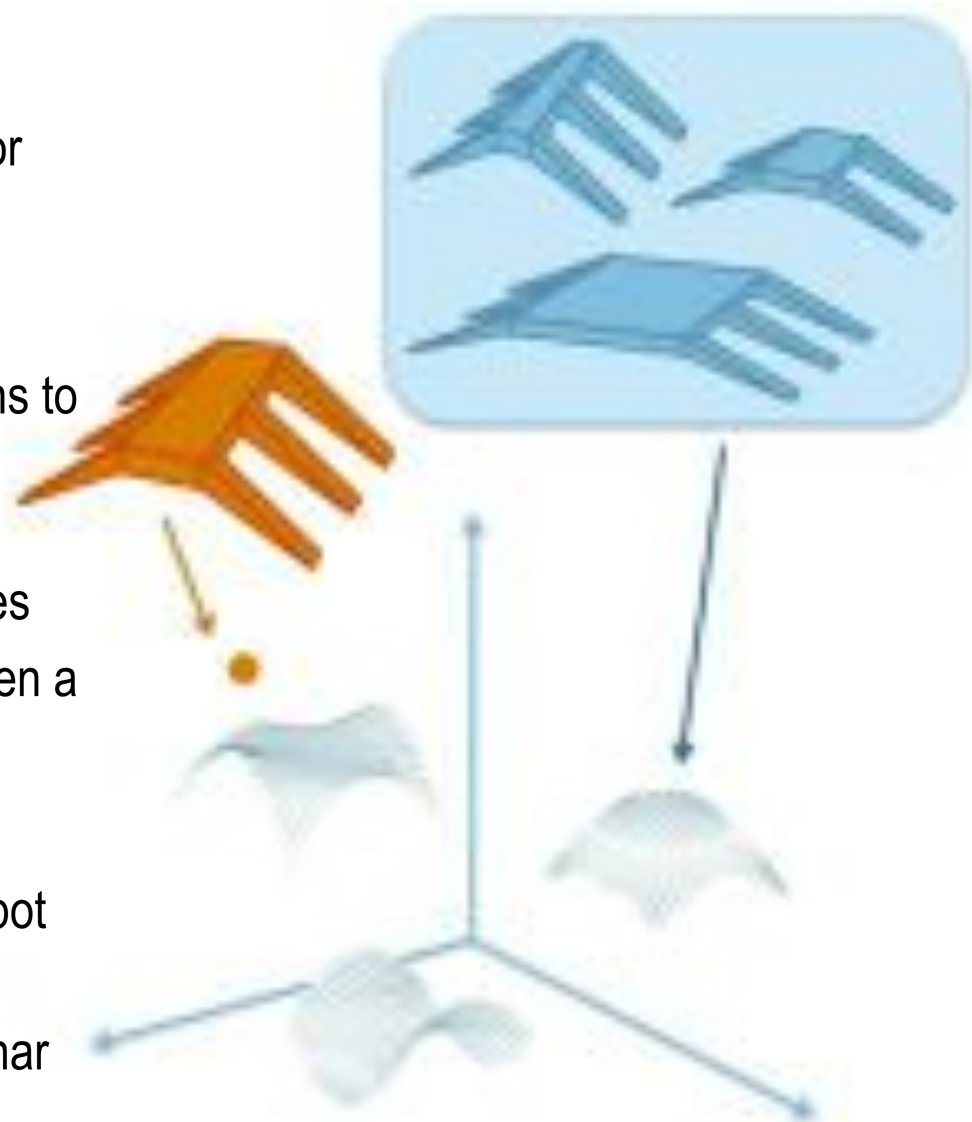
Database Search:



Library

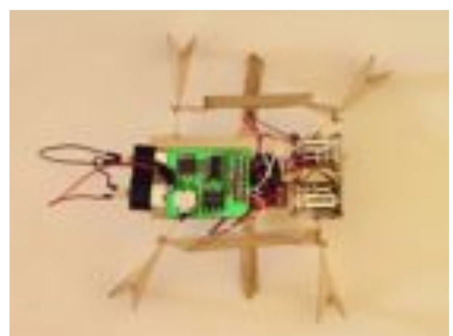
Design and Fabrication from Examples

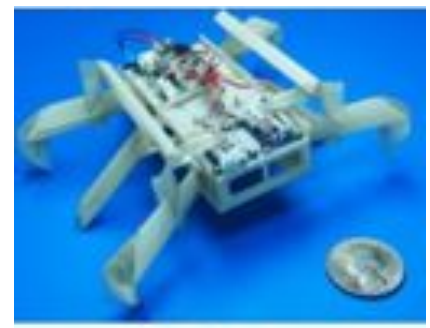
- Overview:
  - A data-driven method and system for creating fabricable designs
- Contributions:
  - Representing and converting designs to parameterized fabricable templates
  - A data-driven model consisting of a collection of parameterized templates
  - Computing an optimal match between a desired input our data-driven model
- Achievements due to EXP award:
  - Creation of an initial database of robot designs
  - Adapting our template model to planar foldable designs

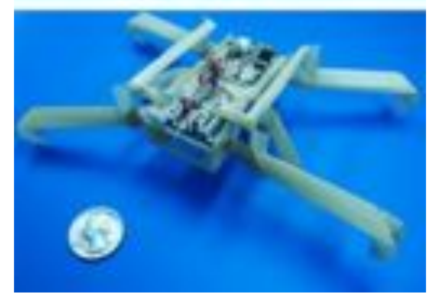


Template-Based Design of Printable Hexapod Robots

- Use a design template to tune parameters of a general legged robot design to specialized applications
- Varied actuation technology, body dimensions to instantiate hexapod robots and compared their capabilities
- Enabled through close collaboration between the Rus (MIT) and Wood (Harvard) groups

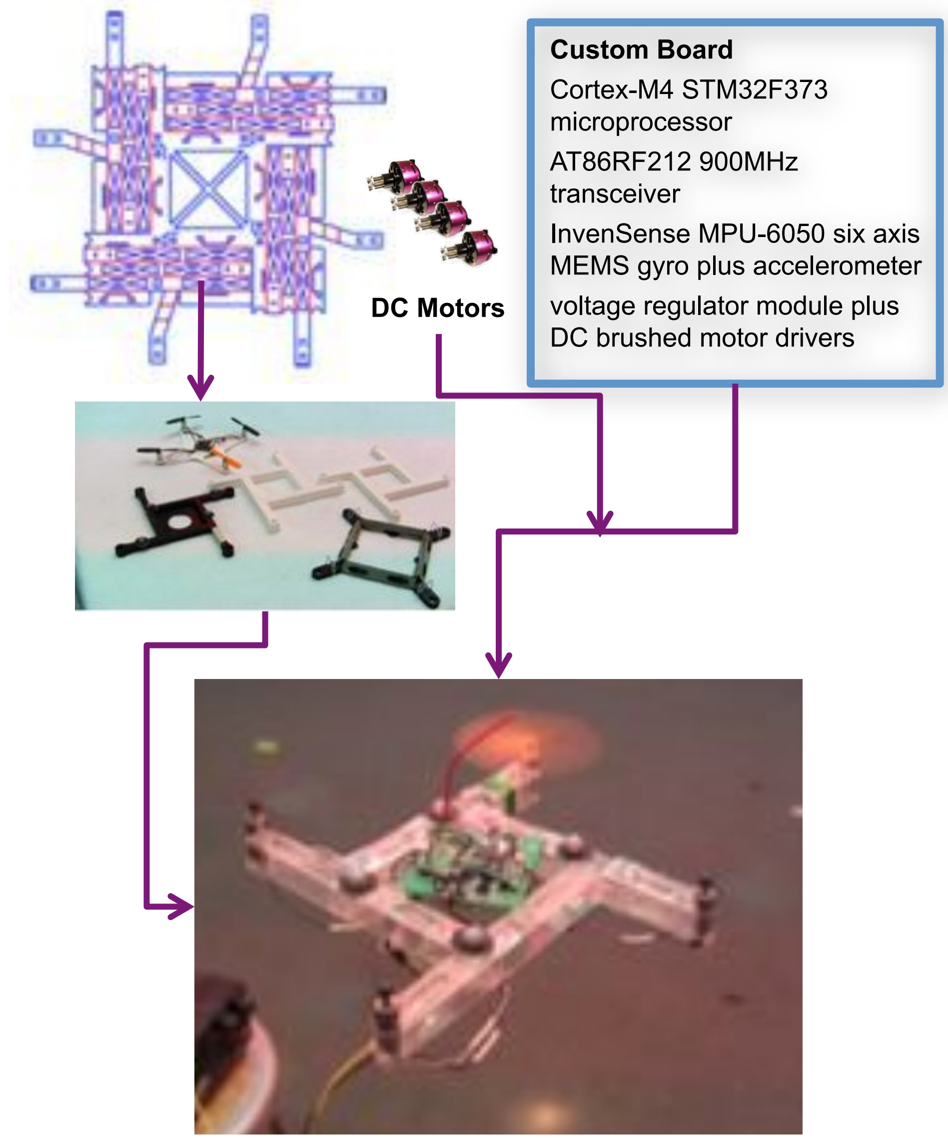






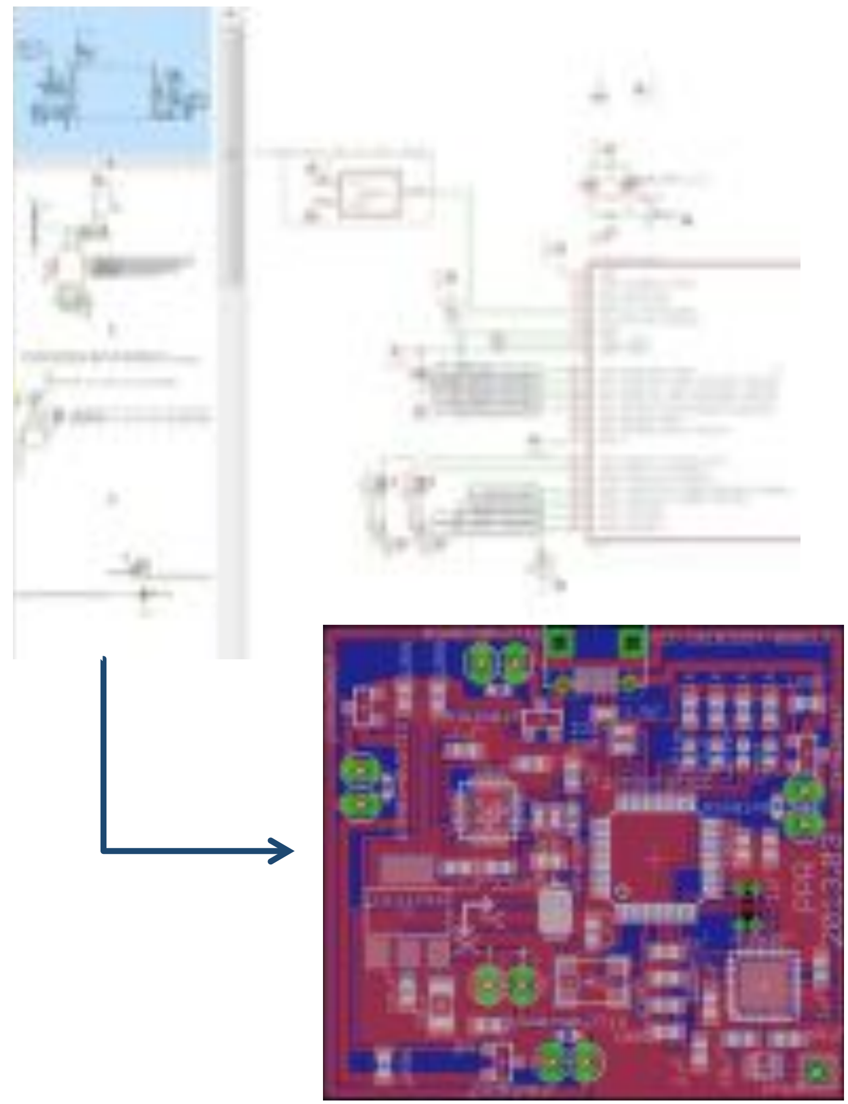
Mechanical Design by Computation

- Script for modular composable designs with connection and mounting components added automatically
- Lower the barrier to entry for design and manufacture of agile, autonomous robots
- Light-weight, low power, printed flying robot fabricated in 8 minutes
- Exciting collaboration and synergies between MIT and Penn
- Framework removes tedious fab steps and allows focus on software for function

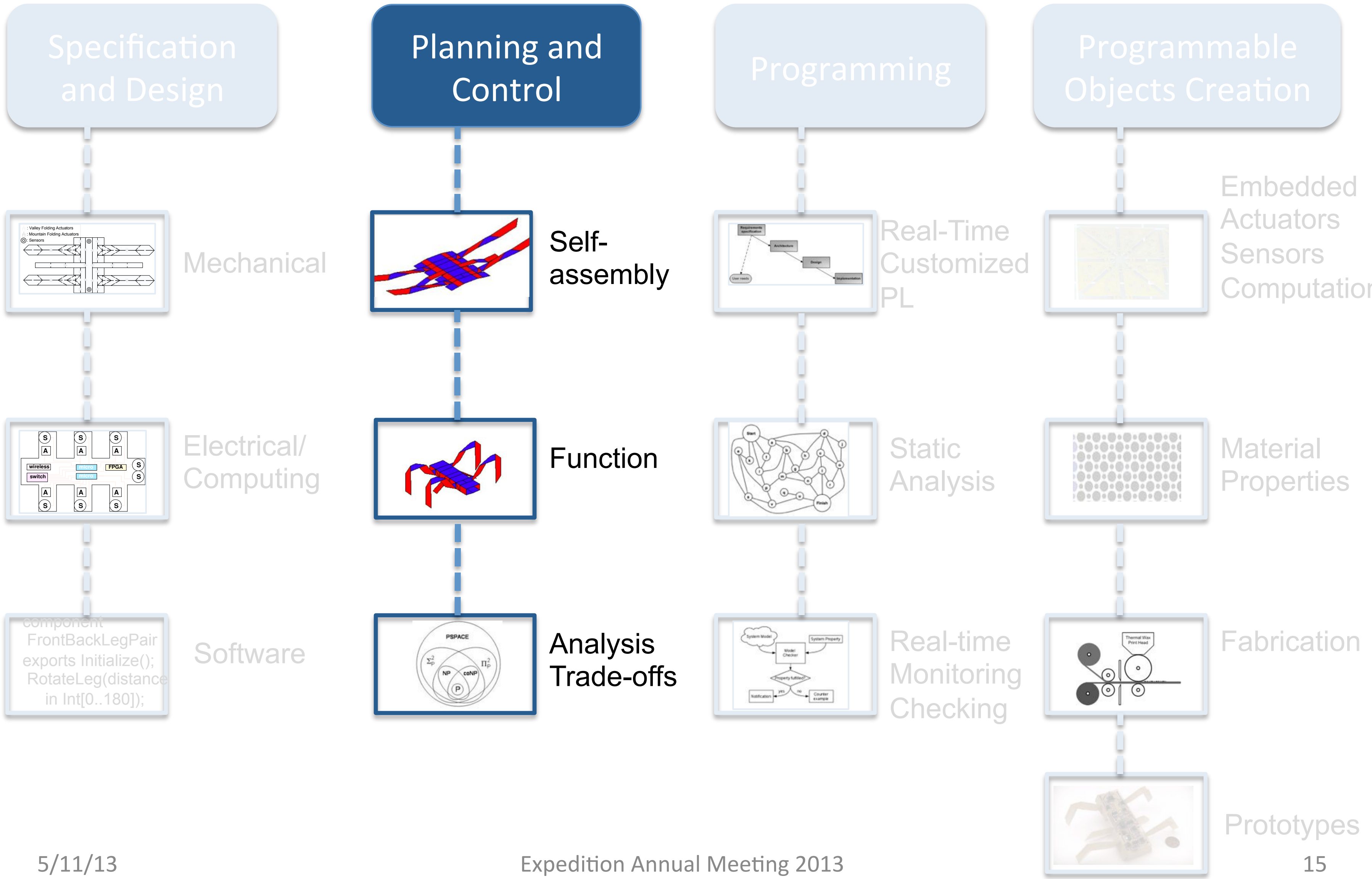


Electronics Database for Printable Robots

- Modular electronics allow experts' designs in novices' circuits
- Lowered barrier to entry and reduced PCB design time
- Idea conception to flying robot in less than one week, including fabrication and soldering time
- Enabled by weekly group brainstorming between Harvard, MIT, Penn

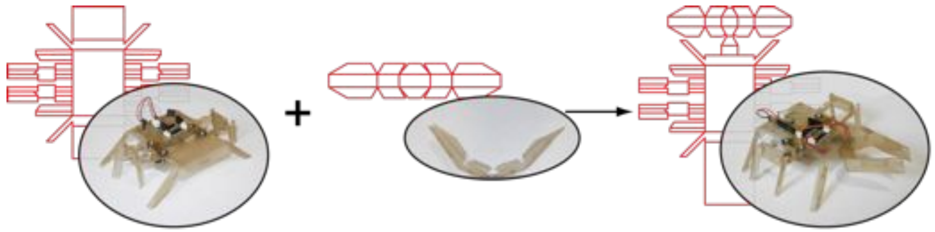


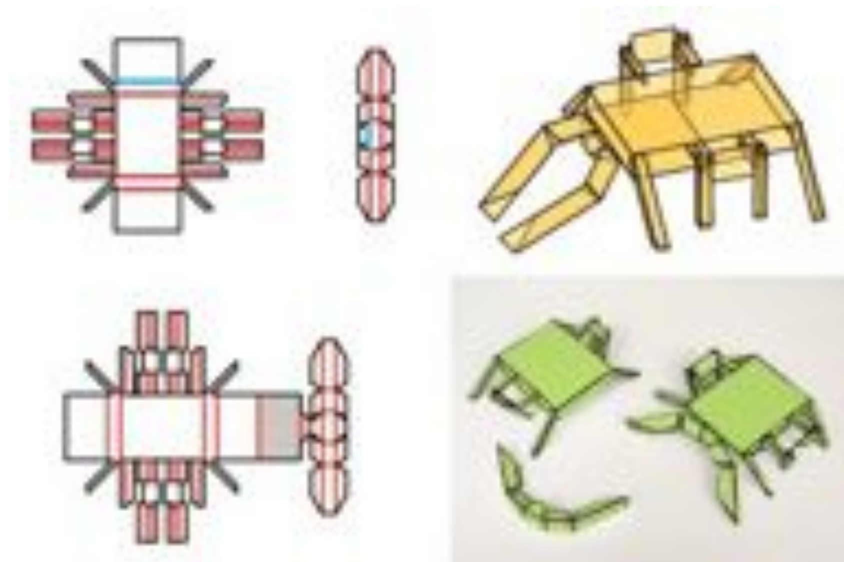
Multi-Disciplinary Research Pillars



Composing Robot Designs

- Algorithm for composing foldable submodules
- Given two surfaces in 3-D and their 2-D unfoldings, a surface consisting of the two originals joined along an arbitrary edge can always be achieved by connecting the two original unfoldings with some additional linking material
- algorithm to generate composite unfolding.
- Extensive algorithm verification
- Enabled by weekly brainstorming between Harvard, MIT, Penn teams





Universal Popup Mechanisms

- Any 2D polygon can be subdivided into a single-degree-of-freedom popup, with specified target angle
- Any orthogonal 3D polyhedron can be subdivided into a single-degree-of-freedom popup

[Abel, Demaine, Demaine, Eisenstat, Lubiw, Schulz, Souvaine, Viglietta, Winslow 2013]

Synthesizing Robot Designs

- Modular robots offer flexibility
- Selecting an appropriate module configuration for a task can be very difficult for a novice user
- Our algorithm merges two existing mechanism designs into an optimal new design that implements both functionalities
  - Synthesize new designs using a library of base designs.
- Designs topologies represented as graphs
  - Kinematic and physical constraints represented as properties of each node (joint) and edge (link)
- Problem formulated and enabled by Inter-disciplinary discussions between Harvard, MIT, Penn teams during weekly project meetings

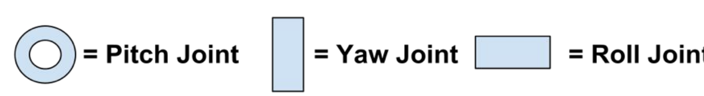
(A) Four-fingered gripper design

+

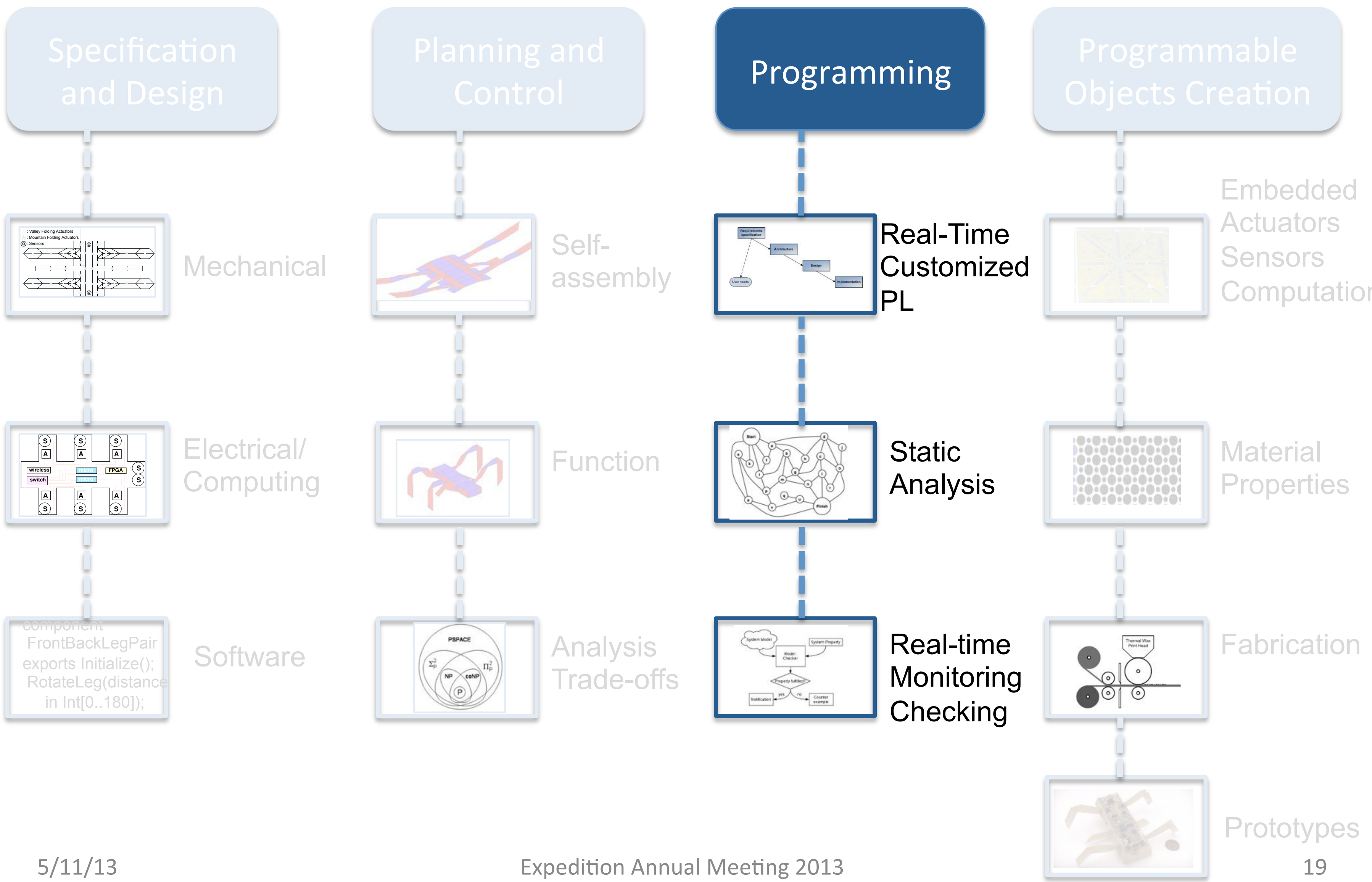
(B) Four-legged walker design

=

Merged design embeds both (A) and (B)



Multi-Disciplinary Research Pillars



REACT:

React Event-driven Asynchronous Concurrent Turing-complete

- High-level, event-driven language
  - Designed to work with robots
- Unified sequential conceptual model for distributed reactive programs.
  - Programs free of concurrency bugs by construction
- Rich tool set
  - Amenable to formal analyses and automated testing
- Support for a concrete robot programming toolkit (e.g., ROS)

ROSLab

- Objective: *Development of a Simplified High-Level Programming Language for Robotic Applications*.

♦ ***ROSLab*** **(based on ROS) allows to program a robot with blocks and links in a GUI interface**

♦ **It offers:**

- **A simple, intuitive, and fast way of programming;**
- **No need to know specific C++/ROS semantics;**
- **C++/ROS code generation;**
- **Formal analysis of implemented algorithms.**

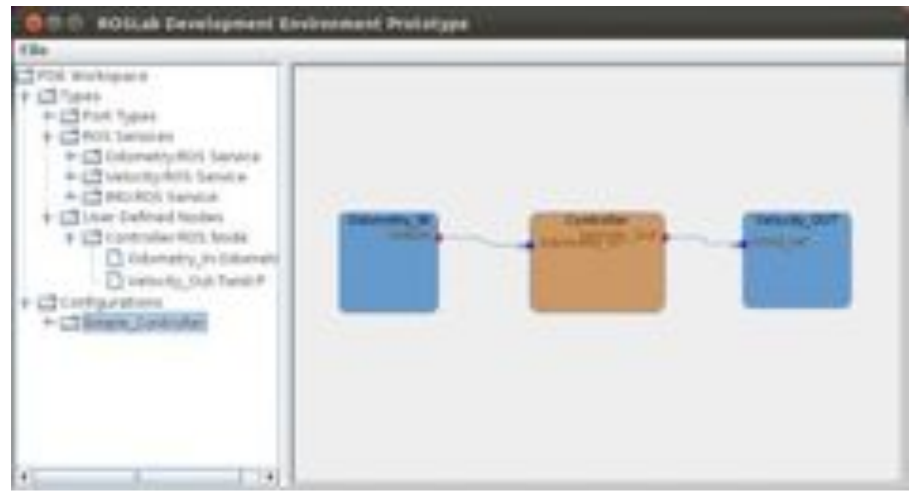
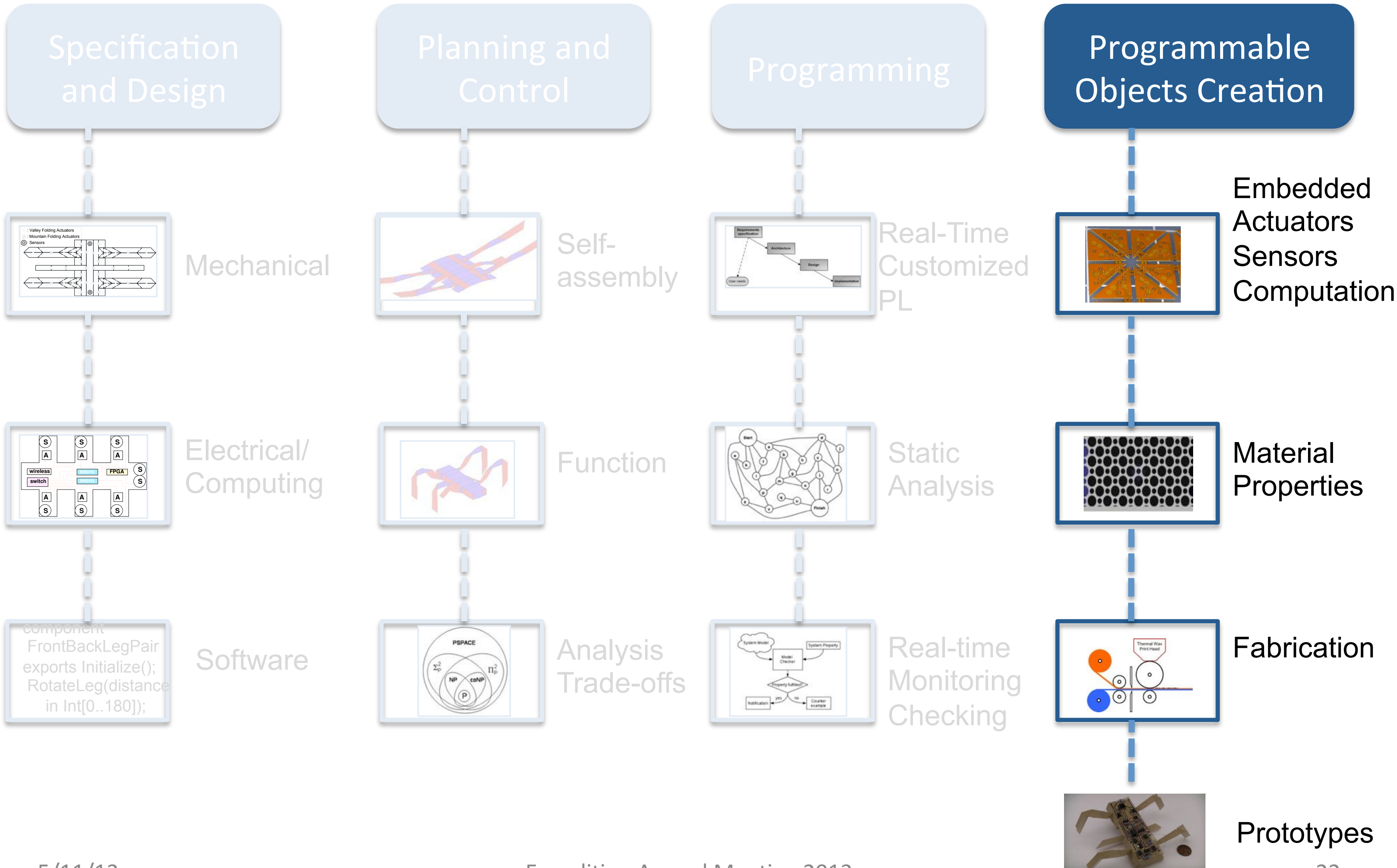


Figure: Example of an application written in ROSLab. The left hand side menu displays a list of sensors, actuators, and controller nodes that a user can define and utilize for specific robotic applications. On the main Workspace (right) three blocks are shown: a controller that receives as input messages from an odometer sensor and sends command velocities to an actuator as output.

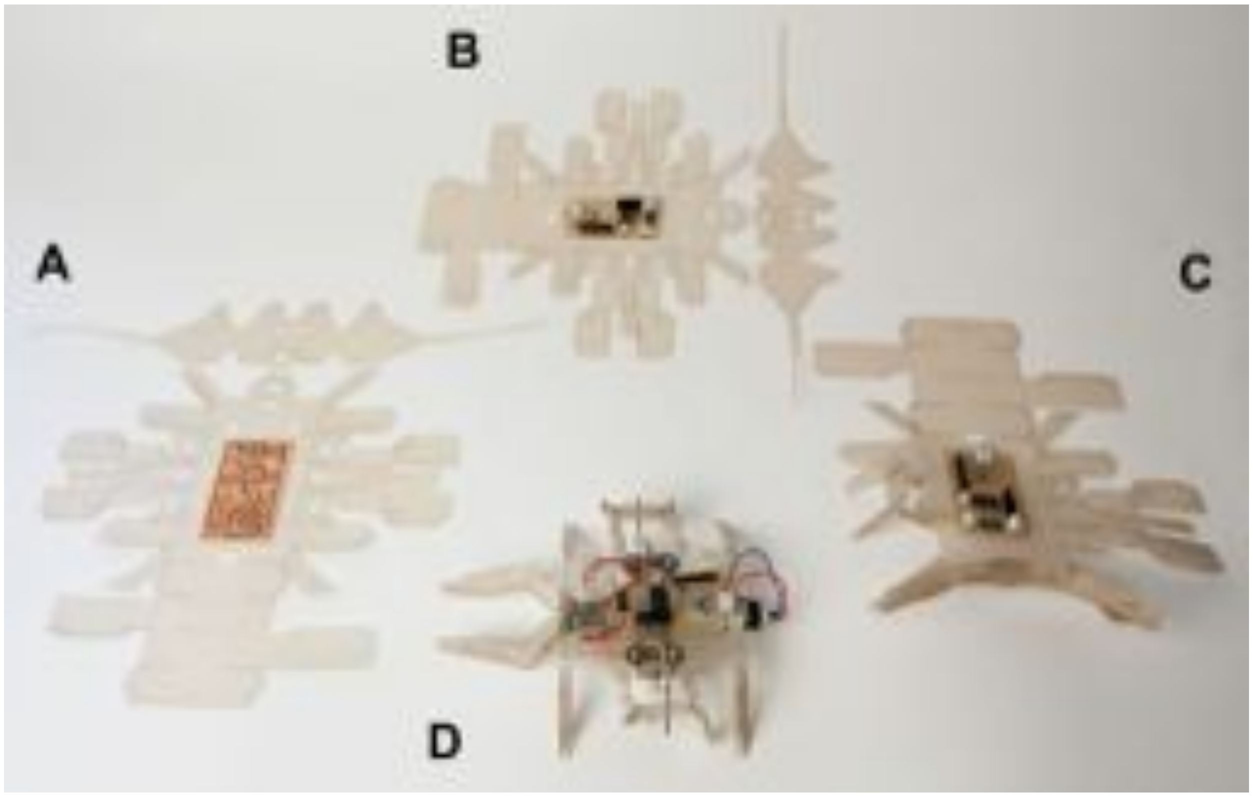
Multi-Disciplinary Research Pillars



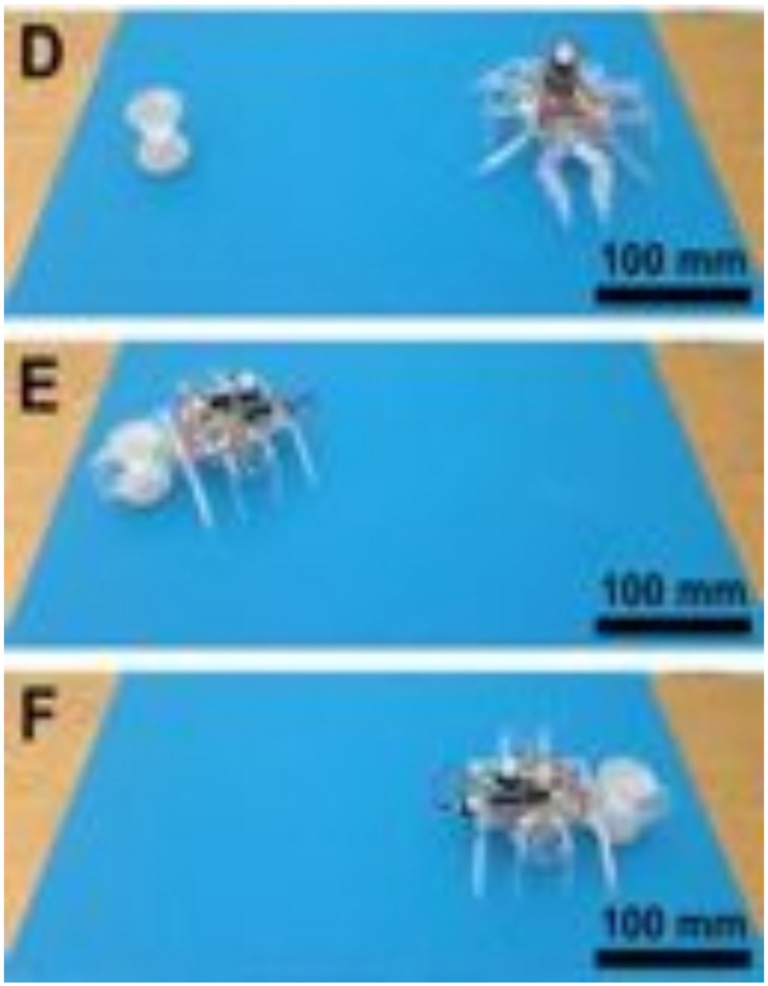
Mobile Manipulator Through Composition

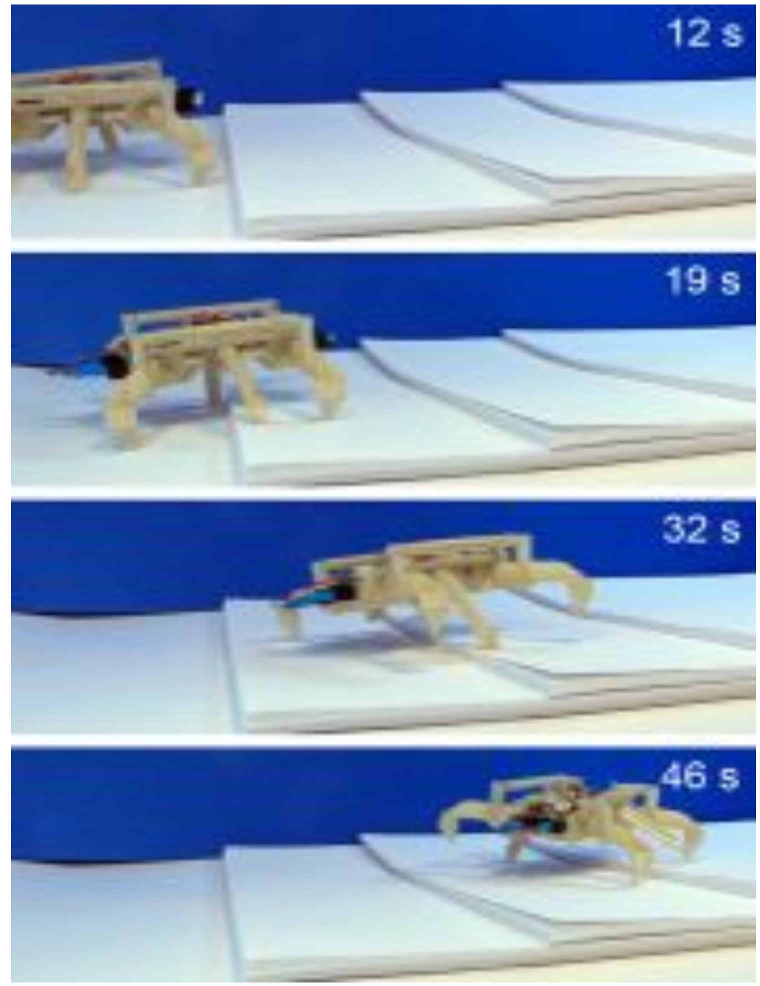
- Printable robots aims to automatically generate robot designs by combining seed modules
- Demonstrated this approach, and the generality of print-and-fold fabrication, by composing gripper and legged robot designs into a mobile manipulator
- Project enabled by insights in origami design, and mechanical and electrical fabrication composed from teams at MIT and Harvard

Printable/Programmable Objects
"Fetch Insect"



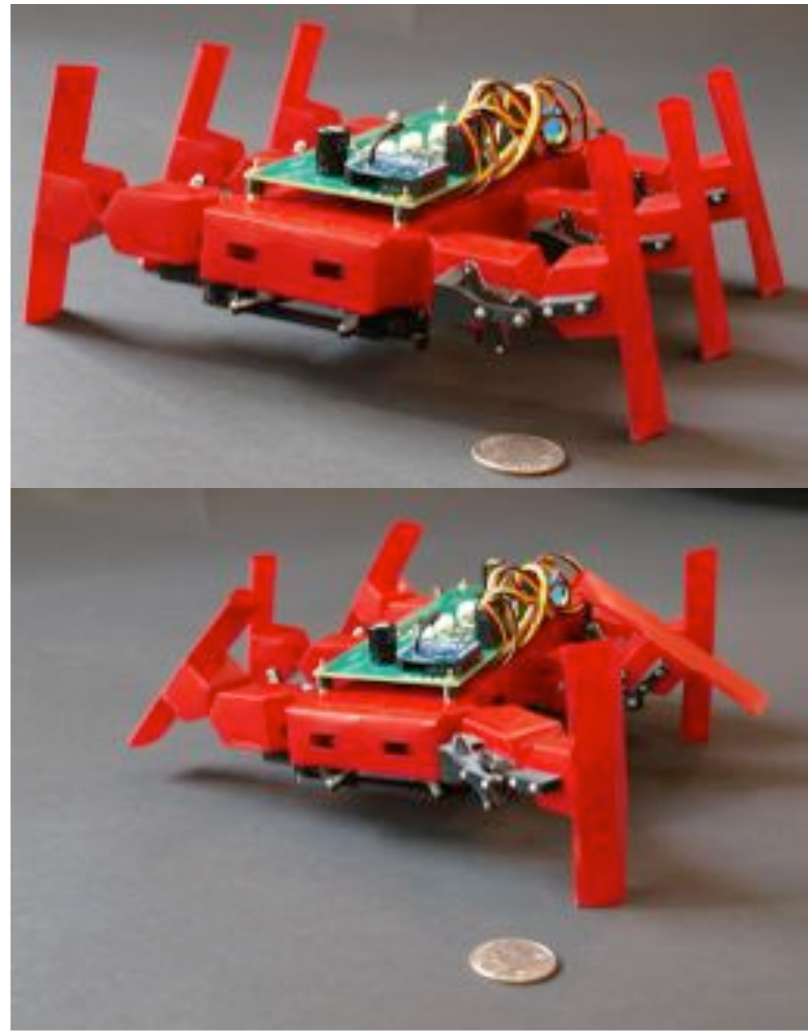
Example: Printable/Programmable "Fetch Insect"





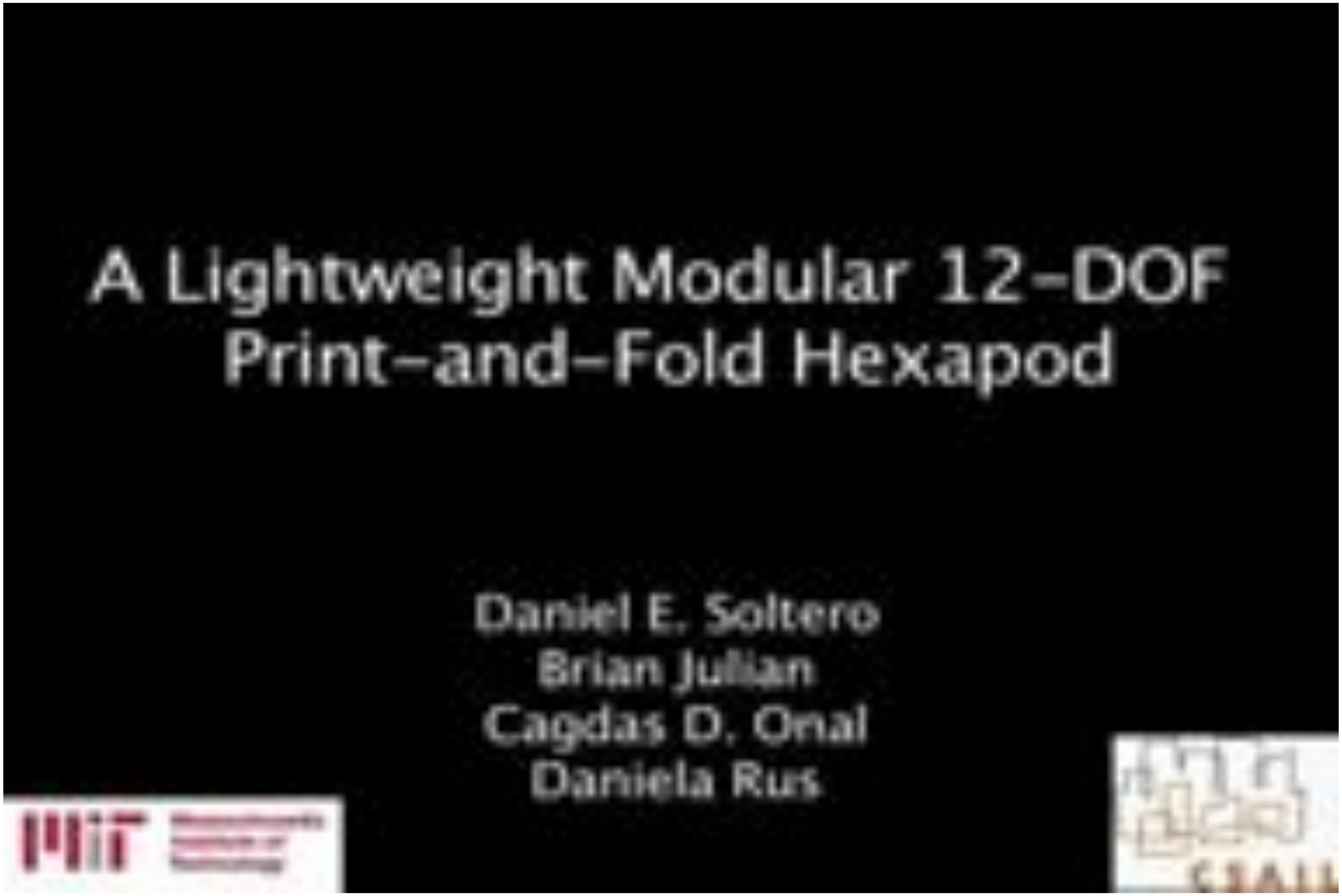
A Lightweight Modular 12-DOF Print-And-Fold Hexapod

- Designed and built a team of printed hexapods and navigation control support
- Performance comparable to complex commercial product
- Fully autonomous hexapod created completely out of planar fabrication techniques
- This robot addresses some of the performance limitations of Fetch Ant



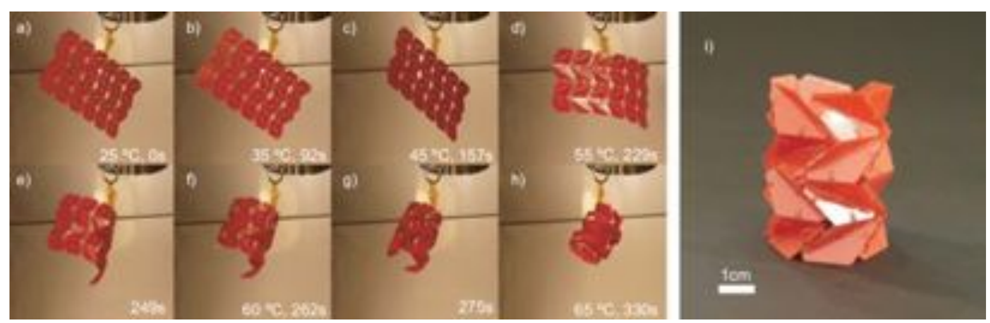
Video:
http://people.csail.mit.edu/soltero/PrintAndFoldHexapod.mov

Fire Ant: Fabrication and Function



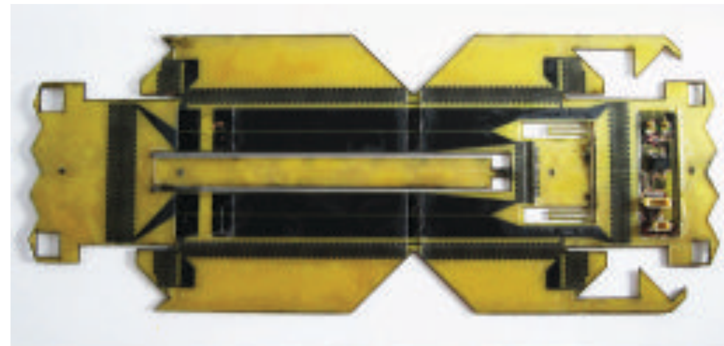
Printable Self-Folding Laminates

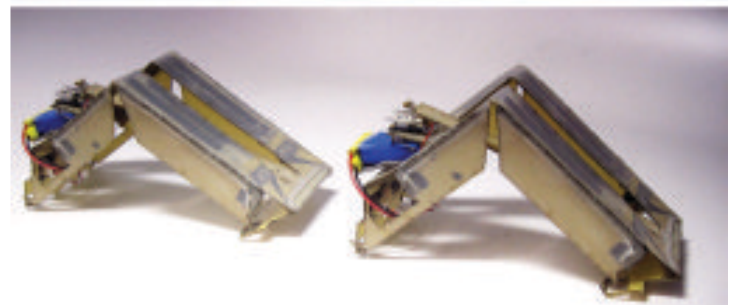
- 2-D composites with embedded shape memory polymers self-assemble into 3-D structures via folding
- Demonstrated the self-folding of a range of complex structures with bi-directional folding
- Demonstrated self-folding under uniform heat using contractive sheet sandwiched between crease pattern with
- Variety of materials and approaches identified using complimentary facilities and expertise in Harvard and MIT groups

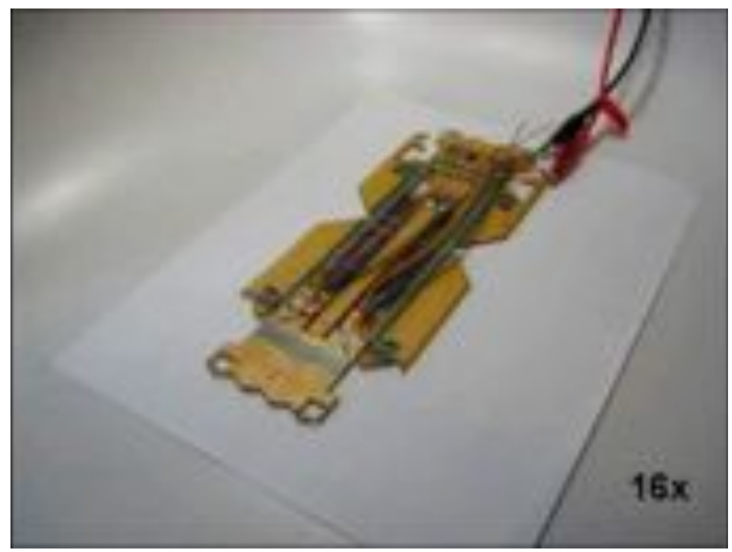


Robot Self-Assembly by Folding

- Printable shape memory polymer composites self-fold into functional machines for autonomous assembly and deployment
- Designed and tested a robot that locomotes with an inchworm gait
- Project inspired by complementary expertise of collaborators at Harvard and MIT







Broader Impacts: Education and Outreach

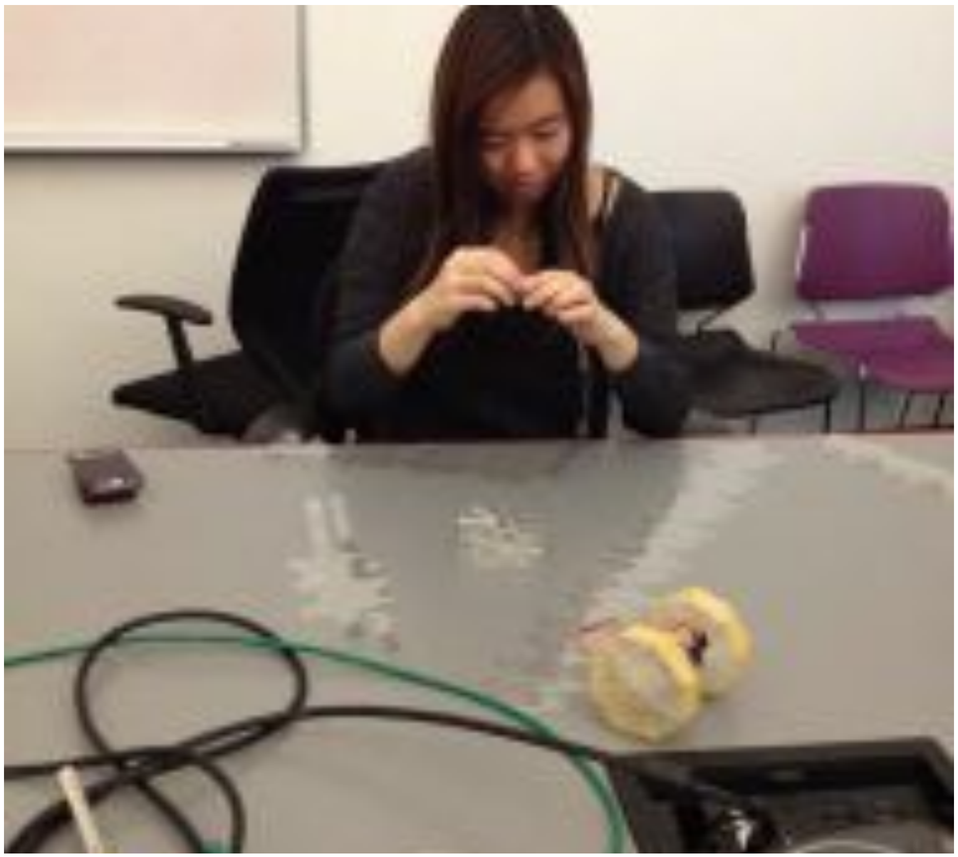
- Goal: inspire students of all ages, researchers, and the population at large to pursue careers and innovate in computer science and engineering
- Business plan competition
- Courses, online materials (roboticscourseware.org), workshops
- Projects for k-12: if you can imagine it you can build it
  - Adding printable components to go beyond First Lego League Competition
  - CTY curriculum for computation that interacts with the physical world
- Outreach to the general public through art
- Outreach to the developing world: grasping modules for MIT wheelchair

First Lego League

MIT CTY workshop

Pilobolus-MIT performance

Education and Outreach Year 1 Achievements

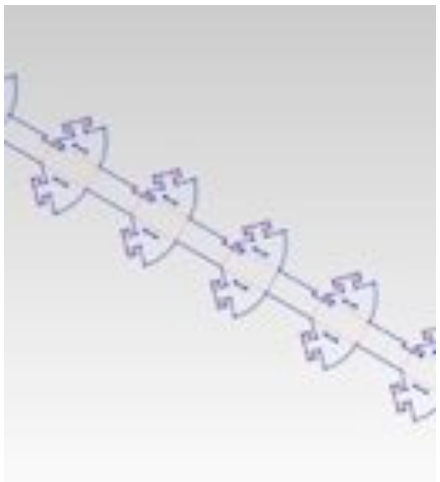


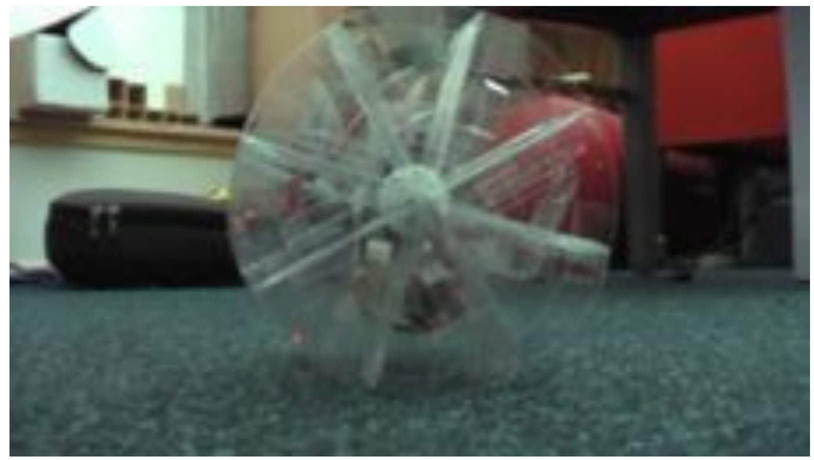
- Summer 2012: 12 UROPs, 2 highschool interns
- Summer 2012: 3D printer donation to Weston Middle School (school chosen by raffle, donation using discretionary funds)
- September 2013: MIT-SEG winner in the $10 robot AFRON competition
- October 18-19 2012 Umbrella Project at PopTech
- November 29 Printable Robots Workshop, Weston Middle School
- January 2013 Harry Huchra (Commonwealth)
- Spring 2013: 6.S080 Invention through Computation (Demaine, Rus, Hoberman)
- May 19 2013 Umbrella Project at MIT
- Over 20 tours to middle schoolers including for National Robotics Week
- Kumar's group volunteers and judges for 2013 FIRST LEGO championship

SEG: A Printable Low-Cost Educational Robot

- AFRON Design Challenge: Creating an educational robot kit for students in developing regions
- A fully-functional programmable mobile robot that costs $14 suitable for 'one robot per child' goal
- Integration of undergraduate researchers in the design and development of printable robots
- One Robot Per Child

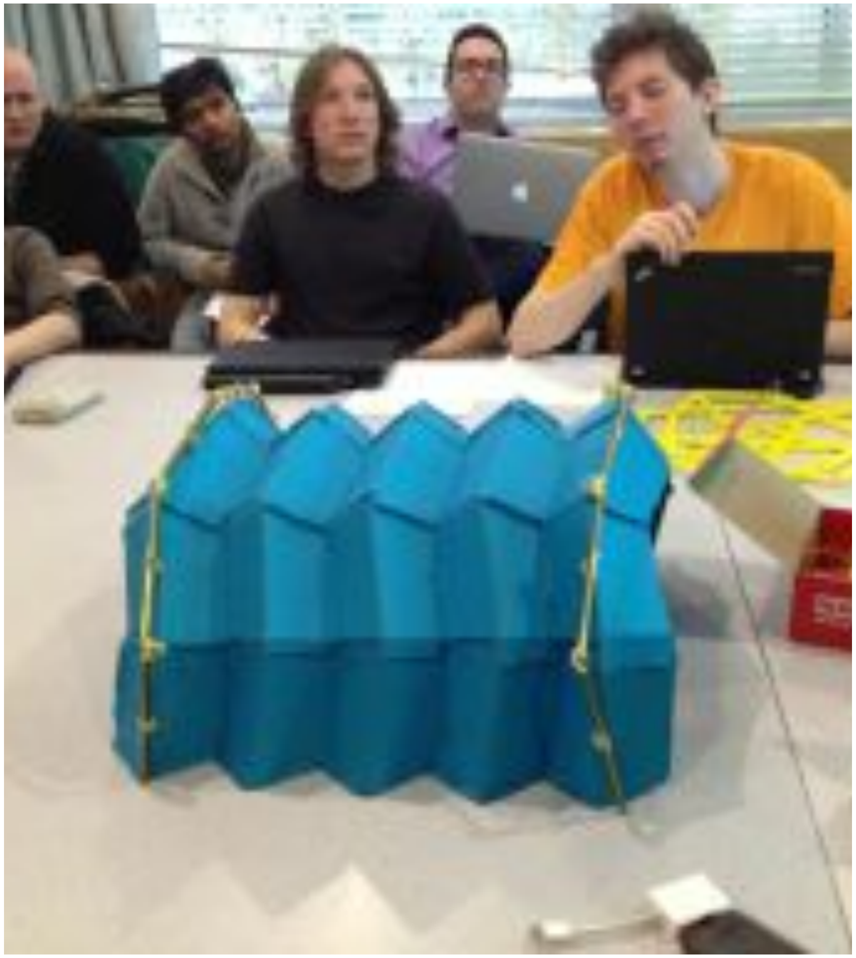
MIT SEG Details





MIT-SEG Robot: One Robot Per Child

6.S080 Mechanical Invention through Computation



Year 1 Achievements: Middle School Curriculum

3D printer donation to Weston Middle School
Module for teaching Finite State Machines

Year 1 Achievements: Umbrella Project@PopTech

Working Together

- Weekly meetings
- Rotate focus topic across the 4 research pillars
- Integration scenarios
- Platform: the database
- In-person meetings: September 2012, May 2013

Connections to Other Expeditions Projects

- Harvard: microfabrication
- Penn: verification
- Berkeley: AFRON

Long-term Societal Benefits

- Science-base for computation that interacts with the world
- Mass customization
  - bring flexibility to manufacturing
  - enable rapid customized assistive devices
  - enable teaching tools for hands-on learning
  - create a new industry and its associated jobs
  - One Robot per Child
- Broad access to printable functional objects
- New user community will share designs
- Foldable objects will revolutionize transportation
- New sensors, actuators, materials, processes
- Real-time programming languages with run-time checks

- Impact other fields: materials science, physics, chemistry

RoboKinko's will democratize access to smart devices