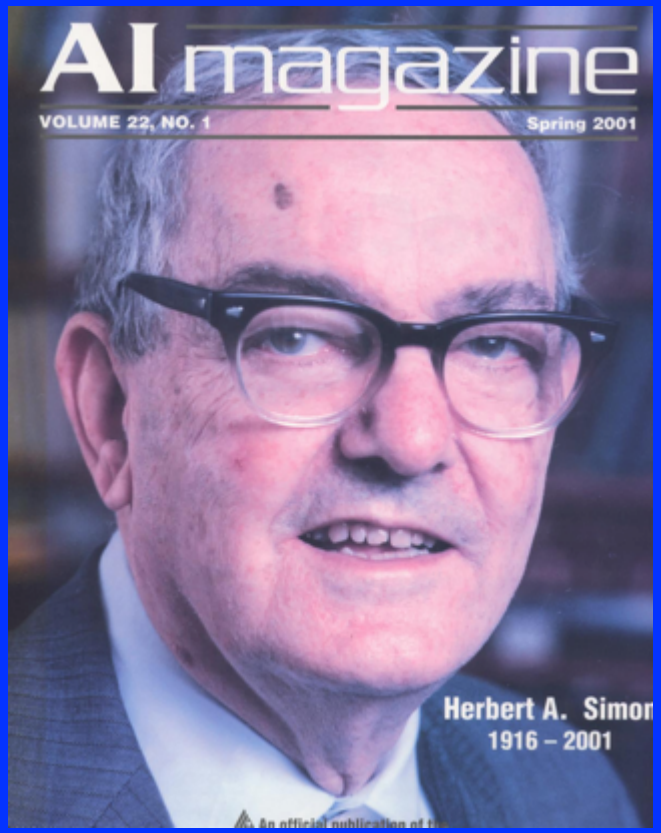


Self-Reconfigurable Robots, Digital Hormones, and Surprise-Based Learning

Wei-Min ("wingman") Shen
Polymorphic Robotics Laboratory
Information Sciences Institute (ISI)
Computer Science Department (CS)
Center for Robotics and Embedded Systems (CRES)
University of Southern California
http://www.isi.edu/robots



Forecasting the Future or Shaping it?
October 19, 2000

Our task is not to *predict* the future; our task is to *design* a future for a sustainable and acceptable world, and then to devote our efforts to bringing that future about.

Professor Herbert A. Simon
Nobel Price Laureate
A Founder of Artificial Intelligence

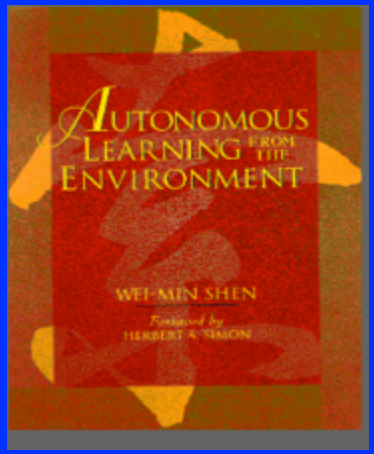
Prof Wei-Min Shen http://www.isi.edu/robots

Self-Reconfigurable Modular Robots
(System of Systems)

Surprise-Based Learning







Polymorphic Robotics Lab

http://www.isi.edu/robots

- Our Research
  - ***Self-Reconfigurable Systems***, including robots, UAVs, agents, structures, networks, bio-models, …
- Funding Agencies
  - Government: DARPA, NASA, NSF, AFOSR, ARO, NavLab
  - Industry: Chevron, Motorola, …
- Awards
  - Navigation Robots: AAAI Robotic Competition (1996)
  - First RoboCup World Championship (1997)
  - Best Paper at SAB Conference (2002)
  - USC Research Awards (2003)
  - Robotic Contiguous Challenge Award, ICRA (2008)
  - Best Paper at 26th Army Science Conference (2008)









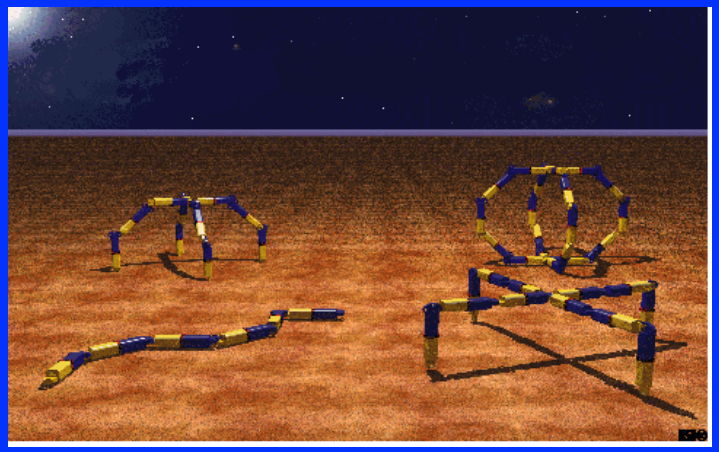
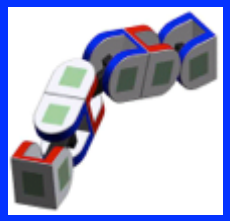
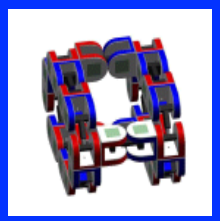








Self-Reconfigurable Robots

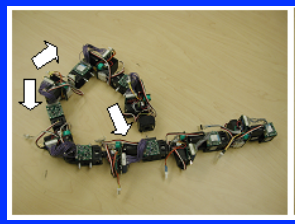
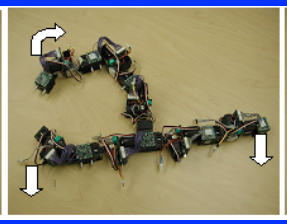
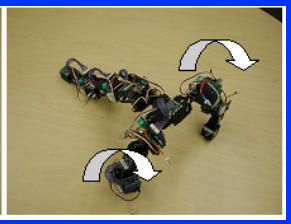













Introduction Movie



SuperBot Vision for Space

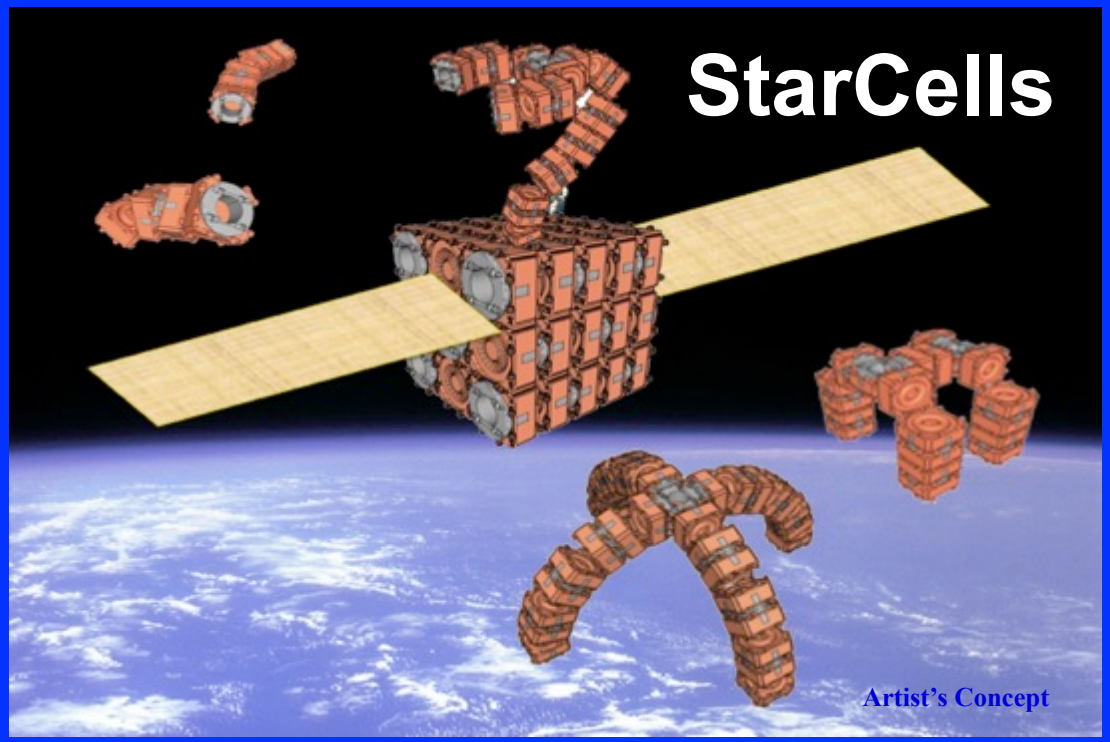
Modular, Multifunction, Self-Reconfiguration

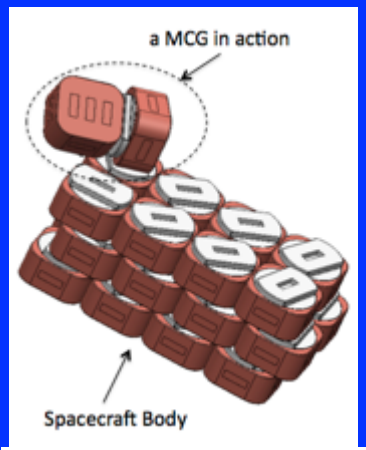




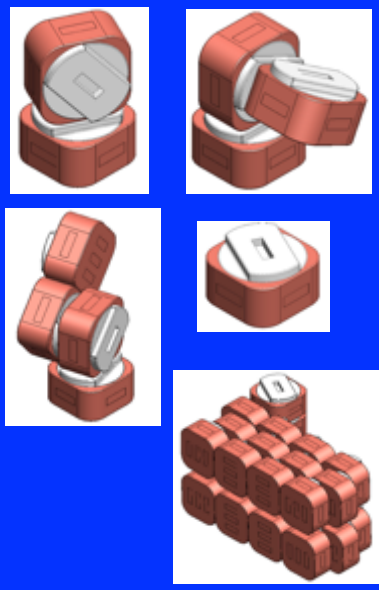


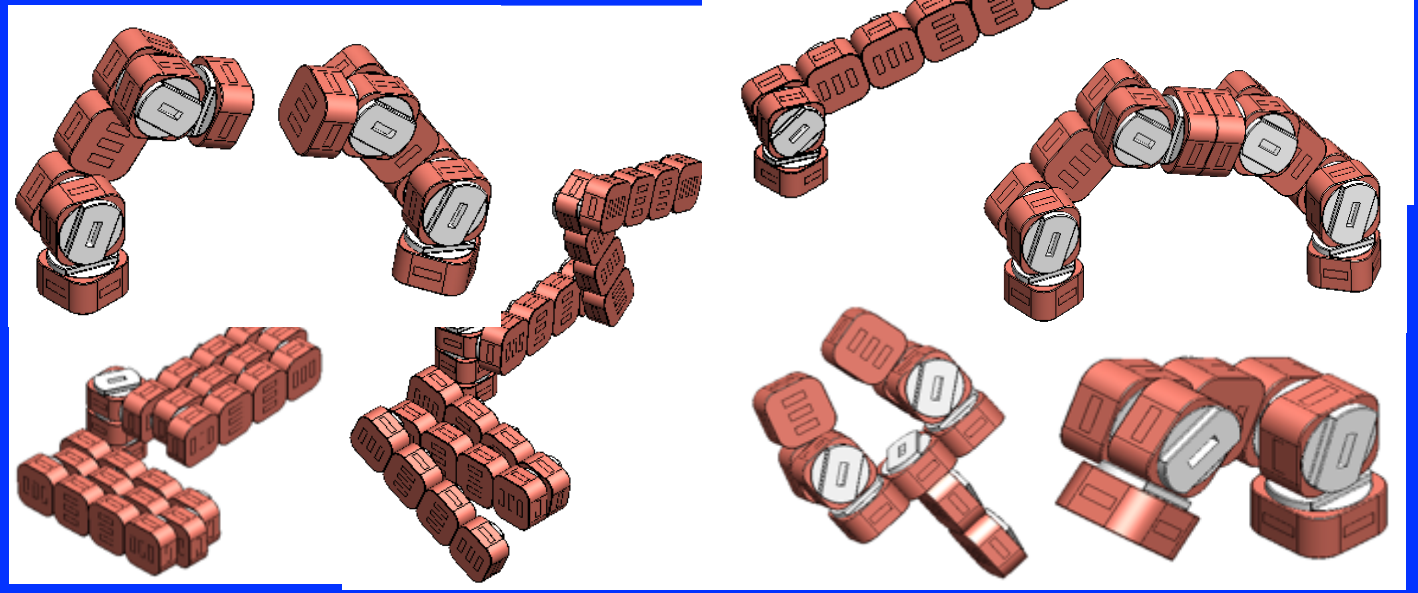
StarCells



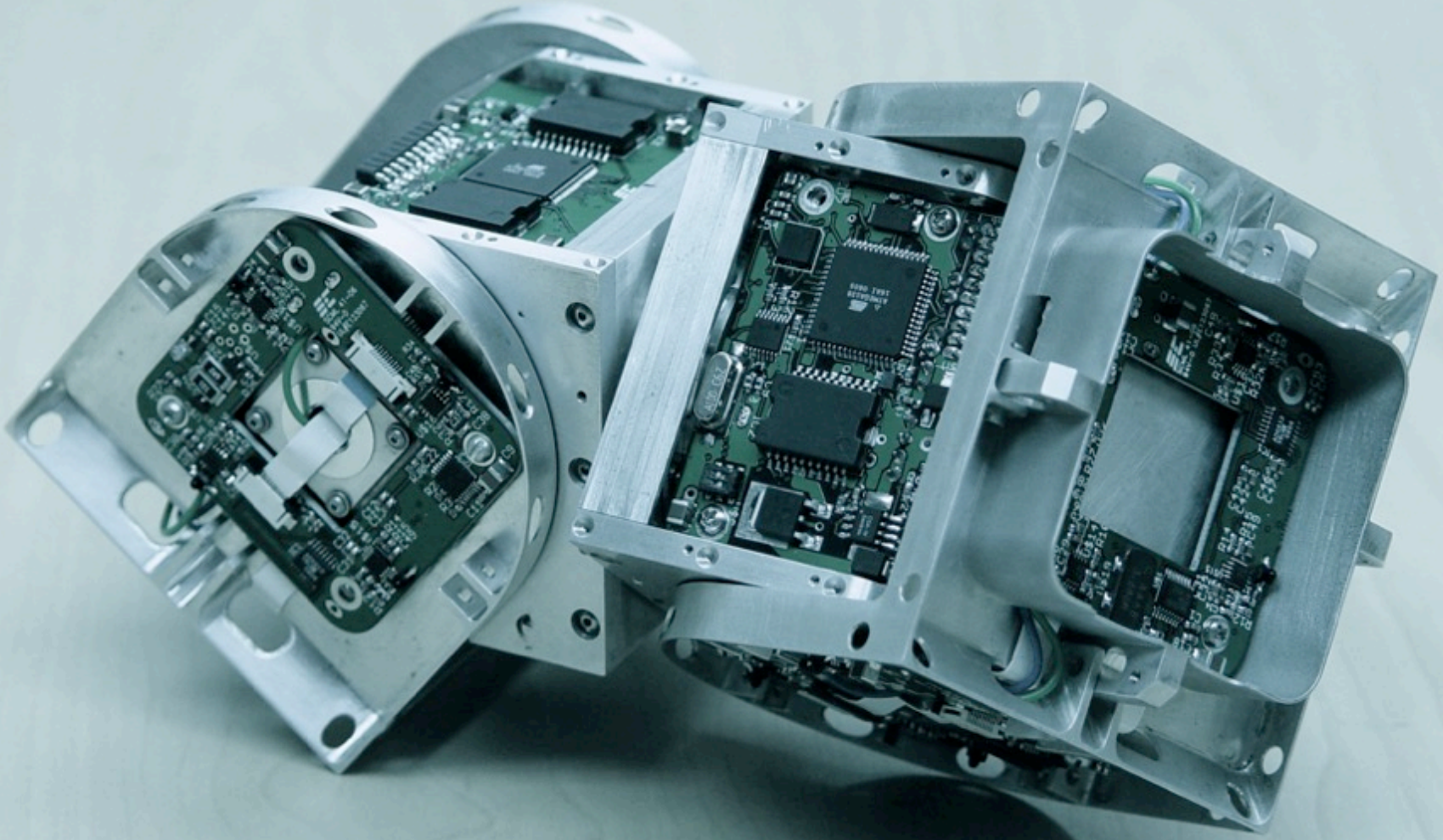








Approved for Public Release, Distribution Unlimited



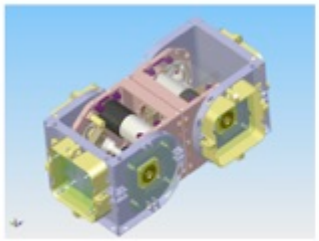
SuperBot: Key Concepts

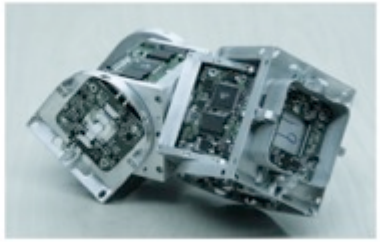
Invention
- Development of connectable modules with onboard power, connectivity, motion, sensing, and intelligence

Key Features
- Capable of operating with other similar modules to morph into multi-shapes and multifunctional self-reconfigurable robots

Applications
- High-risk environments, such as space, underwater, nuclear sites, military, civilian, and reconfigurable/flexible manufacturing

"SuperBot" module specification
- 3-DOF rotational mechanism
- 6 connectors for reconfiguration
- Onboard batteries (7.4v 1.6Ah)
- 2 micro-computers (Atmage128)
- Communication by 4x6 infrared
- 3D gravity sensors
- 4x6 Proximity sensors
- Radio remote control
- Real-time operating system
- C programming environment
- Distributed control
- Topology-triggered behaviors



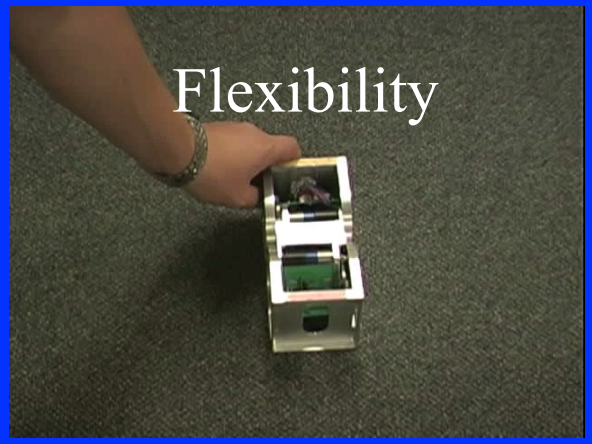



Dr. Wei-Min Shen, www.isi.edu/robots/, shen@isi.edu, 310-448-8710

Key Inventions & Patents

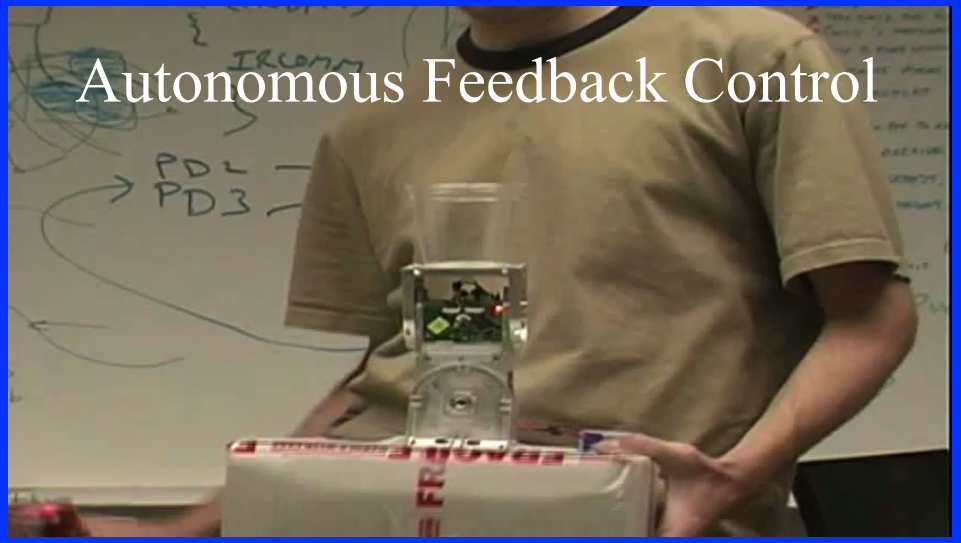
- Mechanical mechanisms
  - 3D reconfigurable modules
  - Self-healing connectors (US Patent)
  - Multiplex thrusts (US Patent)
- Electronic Components
  - Power Sharing, local and global communication
  - Multifunctional Mechatronics Architectures
- Intelligent Control Software
  - Digital hormones (US Patent)
  - Surprise-based Learning and Adaptation
  - Self-reconfiguration on-line planning
  - Self-assembly and self-healing

Single Module Autonomous Robots











Possible Configurations

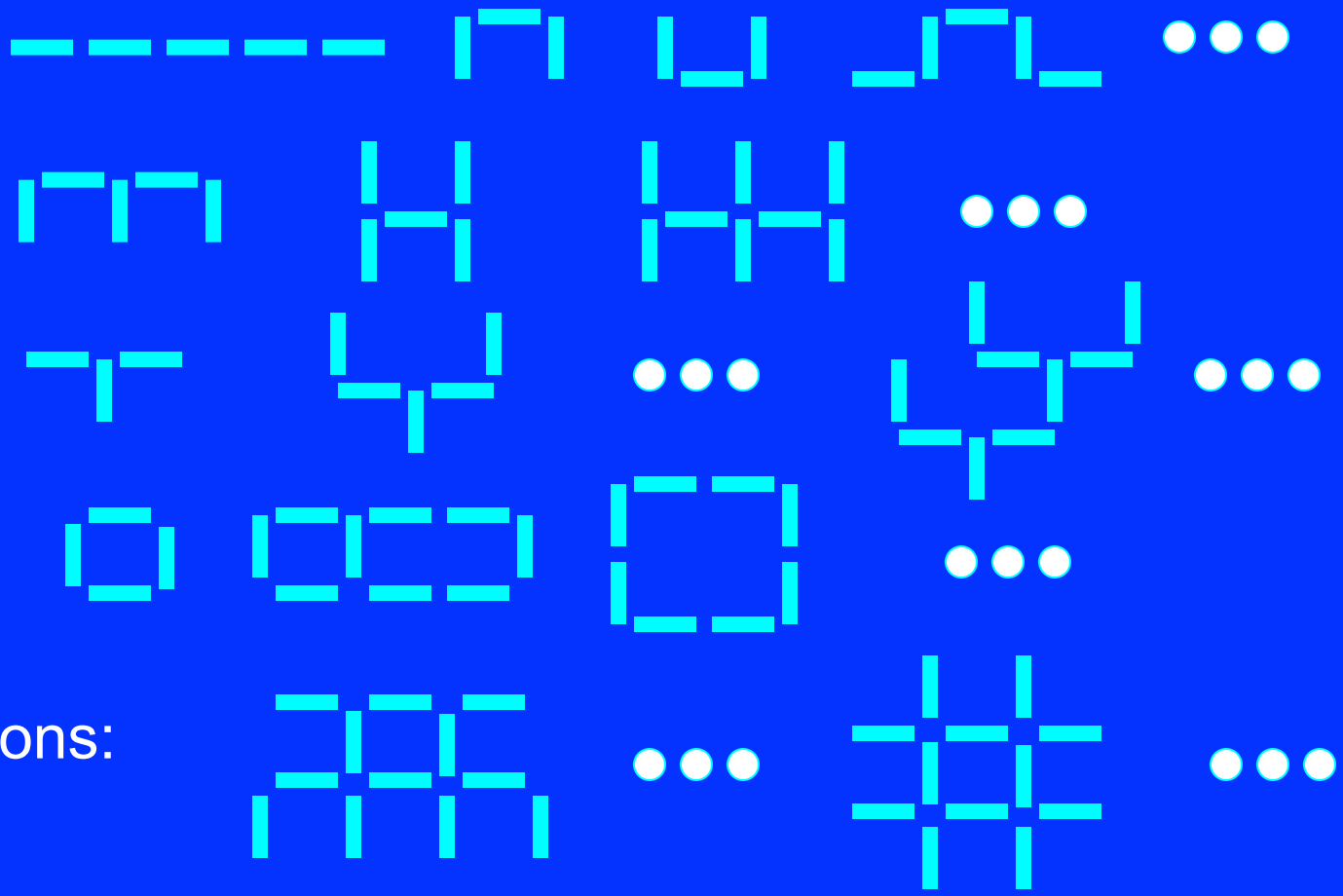
Chains:

Legs:

Trees:

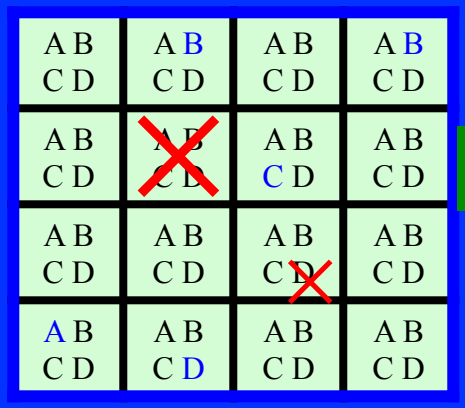
Loops:

Combinations:

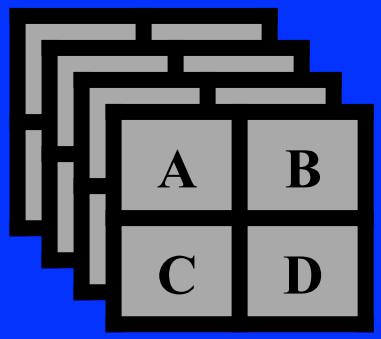


Resilience for Autonomy, Endurance and Mobility

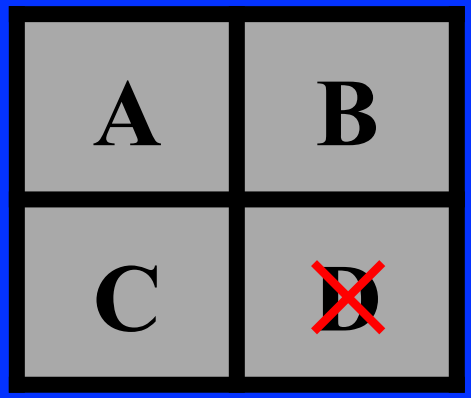
- Flexible Capabilities (✔)
- Reduced Cost (✔)
- Risk Reduction (✔)
  - One fails, there are others
- Failure Resilience (✔)
  - One wrong, all compensate
- Lifetime (longer)



Modularization



Pure Redundancy

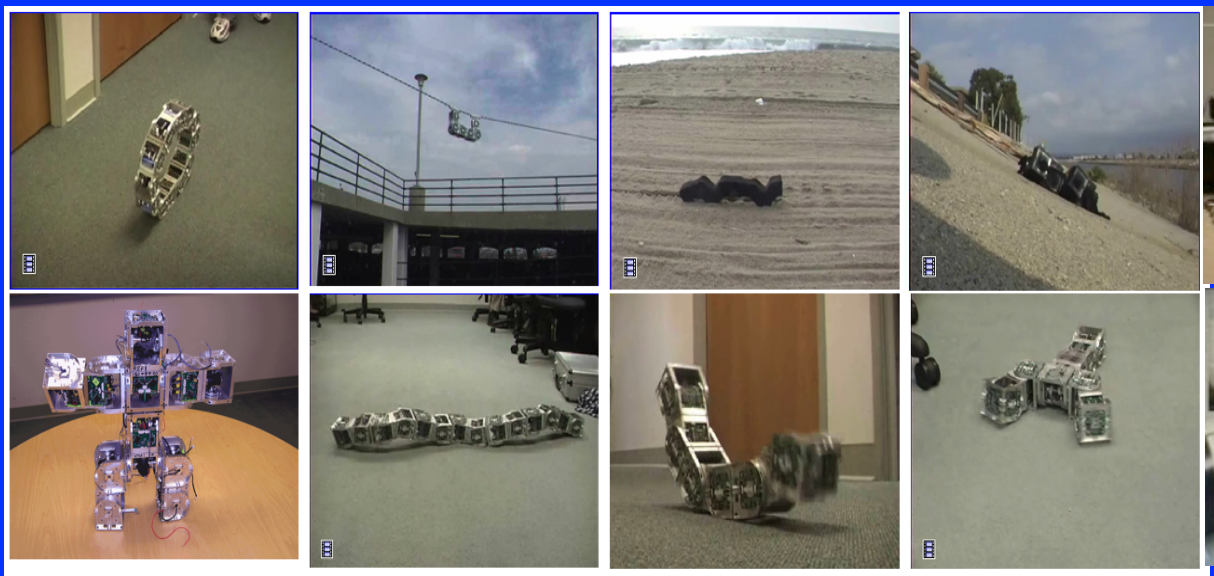


Monolith

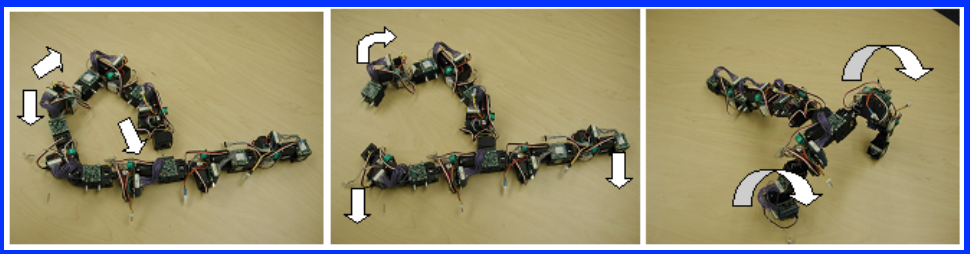
Modules in Configurations



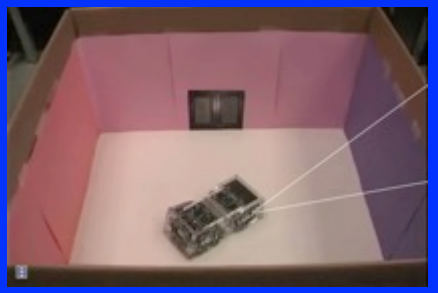
Multifunction, Reconfiguration, Distributed Control, & Learning







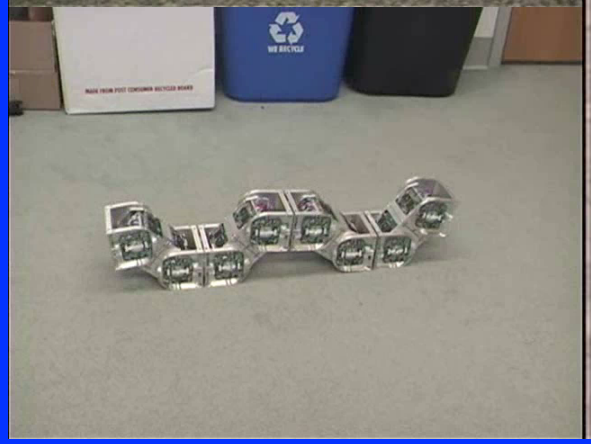




Dr. Wei-Min Shen, www.isi.edu/robots/, shen@isi.edu, 310-448-8710

Caterpillars on Beach







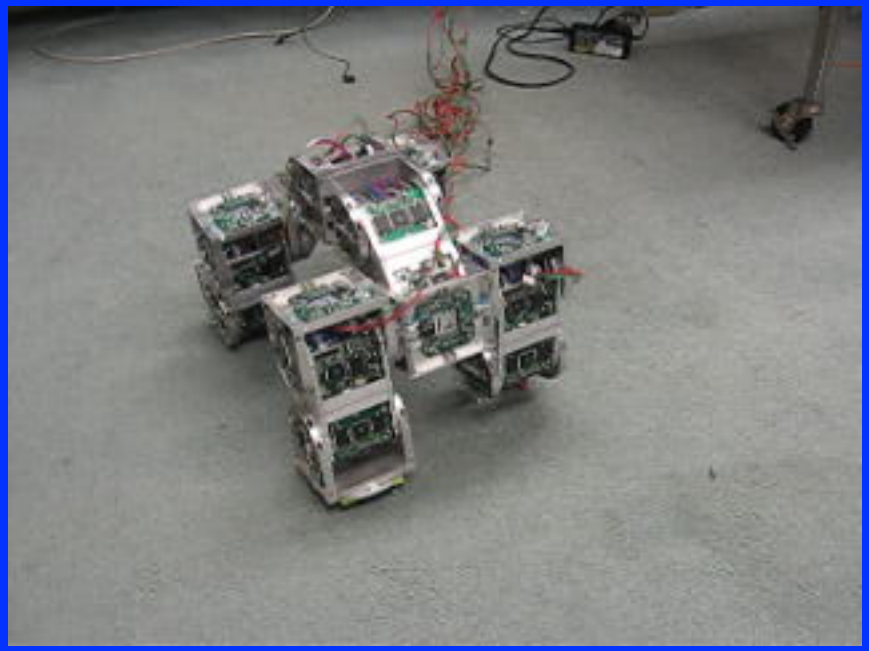
Locomotion Forms

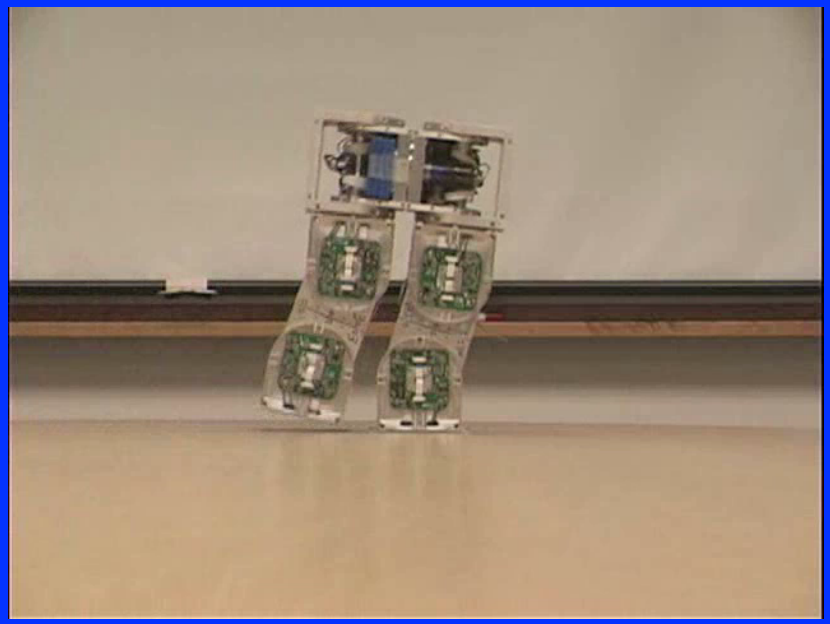






Walking with Legs





Digging and Burying



Going through Pipes



Crawl up Steep Slopes



Sand Dune Experiments

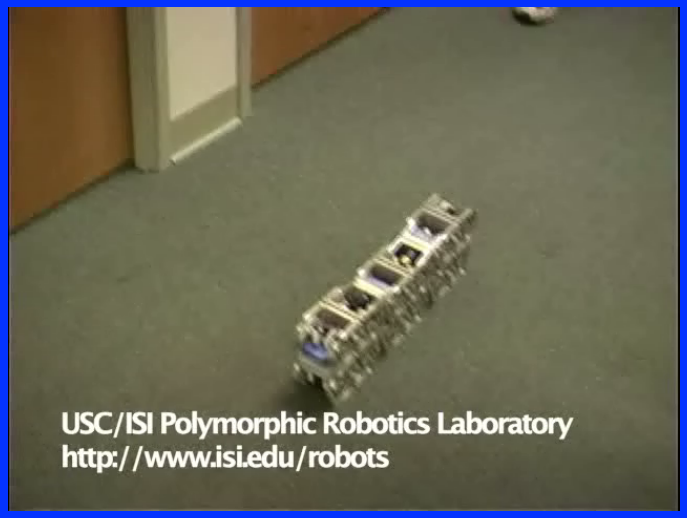


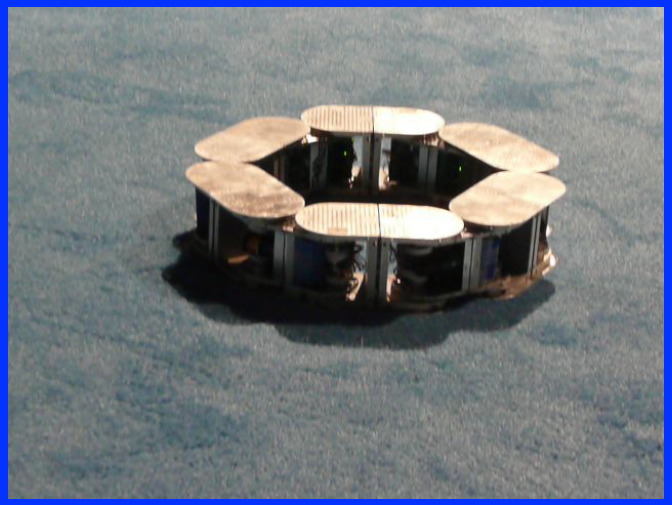






Rolling, Recovering, & Turning





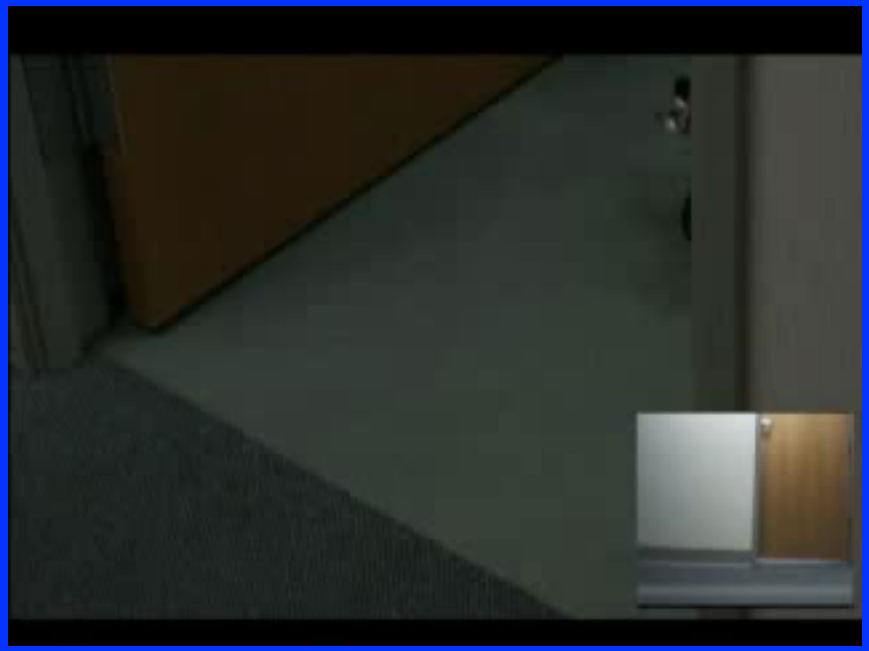


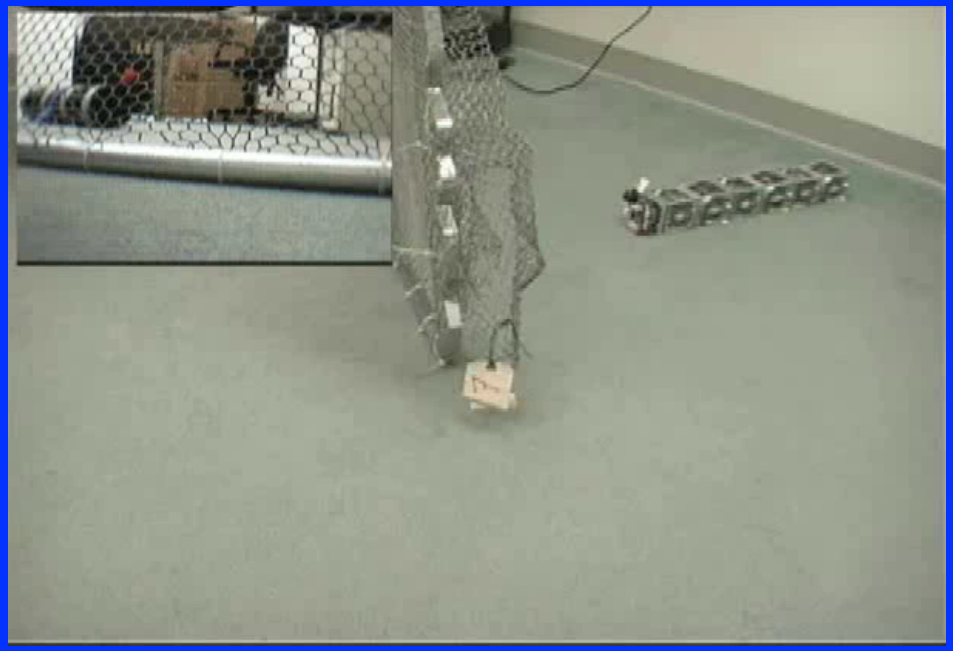
Climbing Ropes





Tele Operations





Roller Skates and Payload





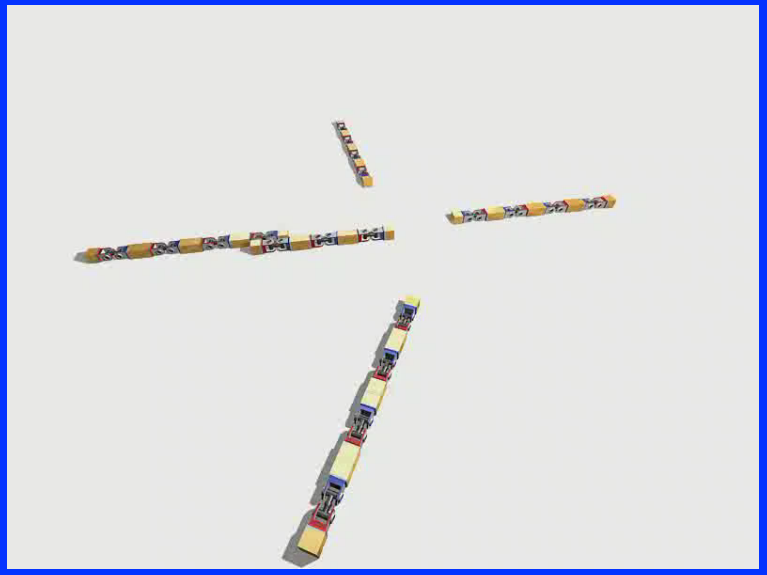
Rolling on Disks

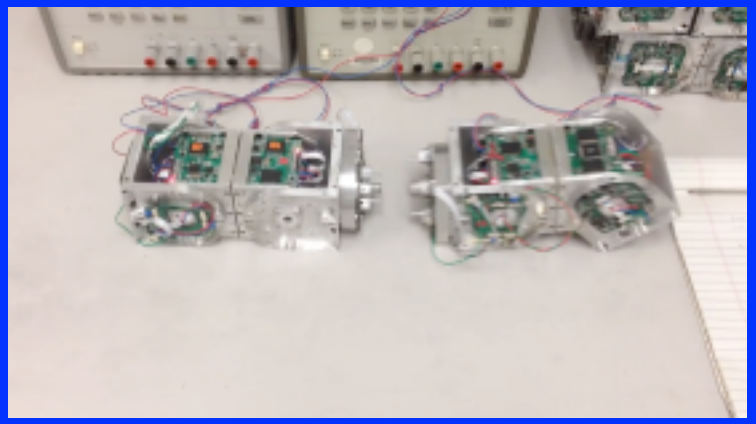


Self Reconfiguration

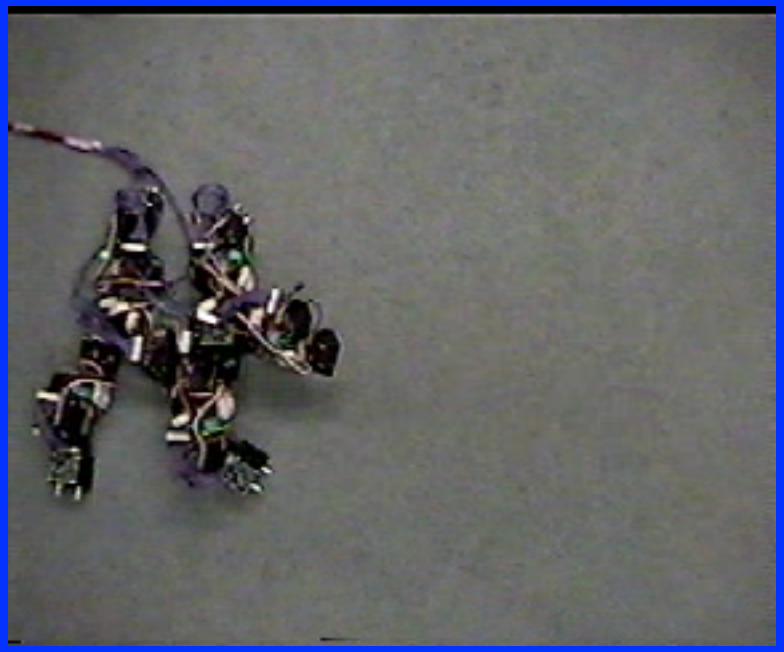








Resilient to Shape Changes





Infrastructure Inspections



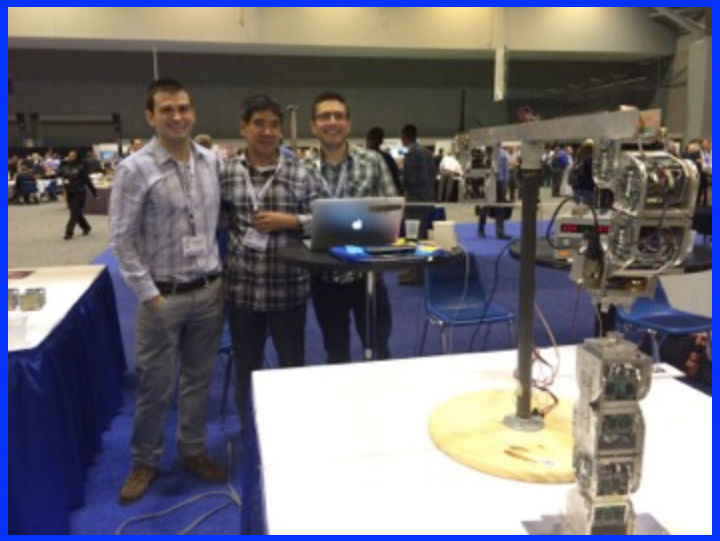


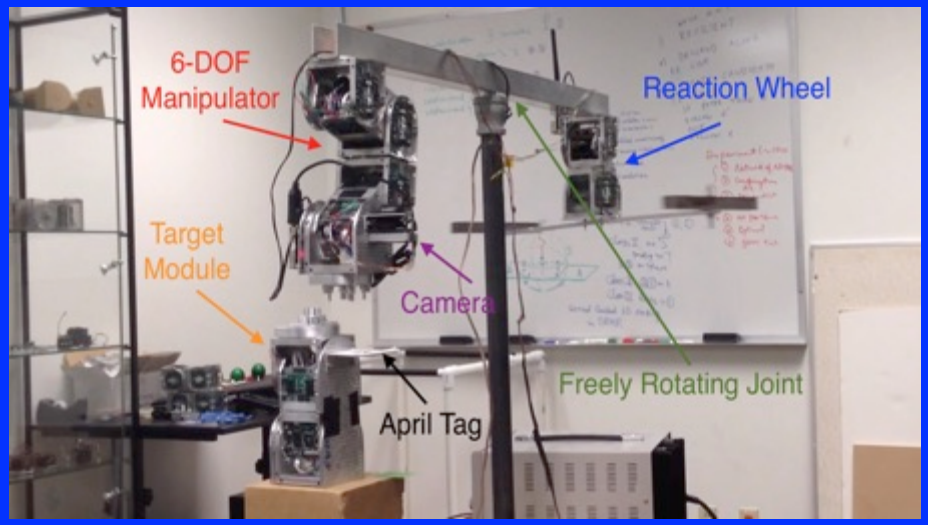


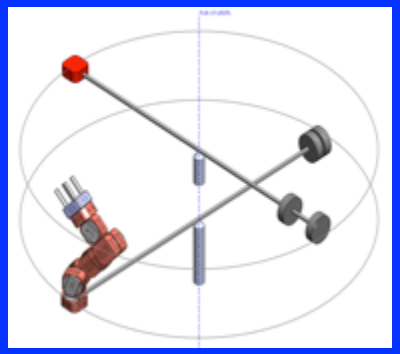


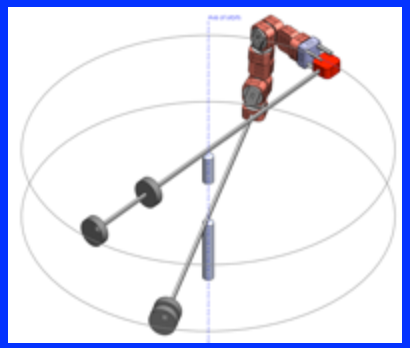
6D Autonomous Docking (in ~0G)

Featured at DARPA Wait-What Forum 2015

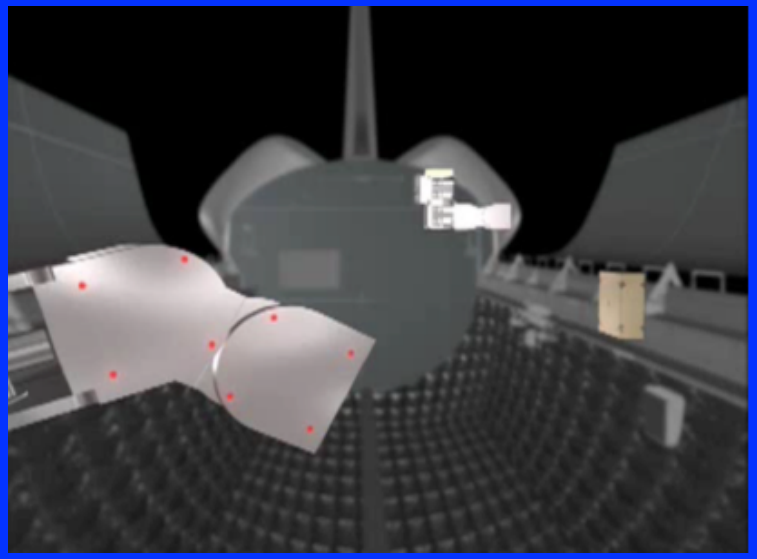


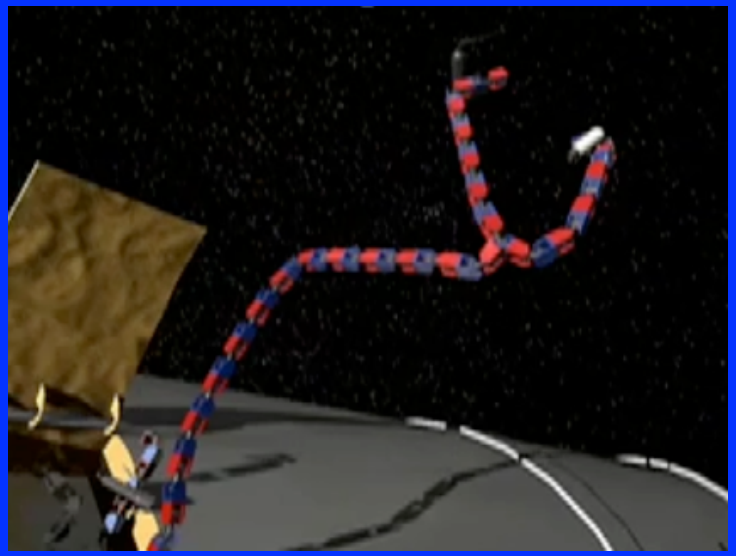


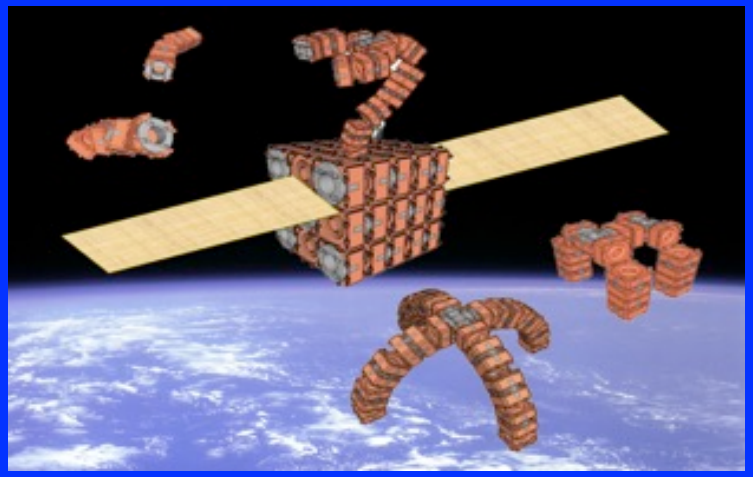


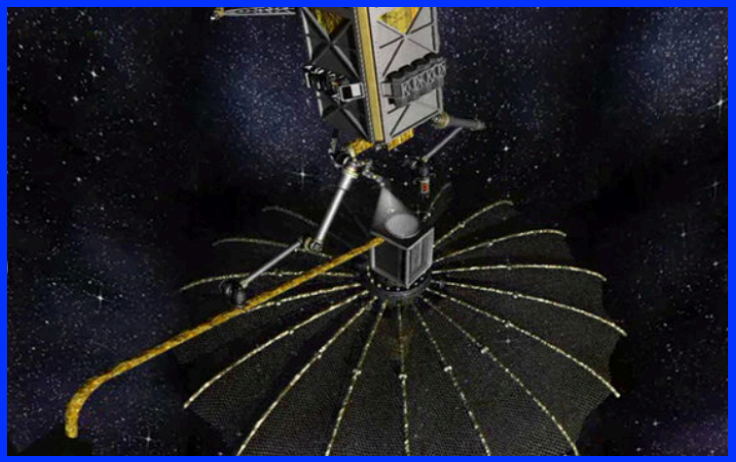


Future Operations in Space









Research Challenges

- How to make modules?
  - Modularity, nano, fluid, ...
- How to control a configuration?
  - One structure but many uses
- How to adapt configurations?
  - Many structures, adaptive









Advantages

Flexibility, Reusability,
Repair-ability, Low-cost, …

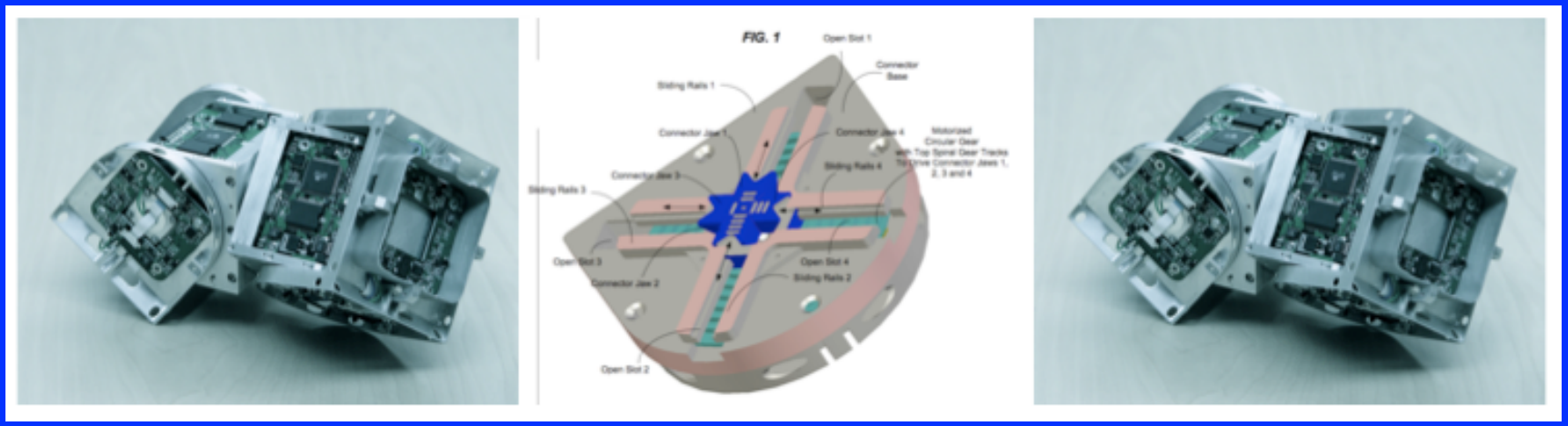
Challenges in Systems

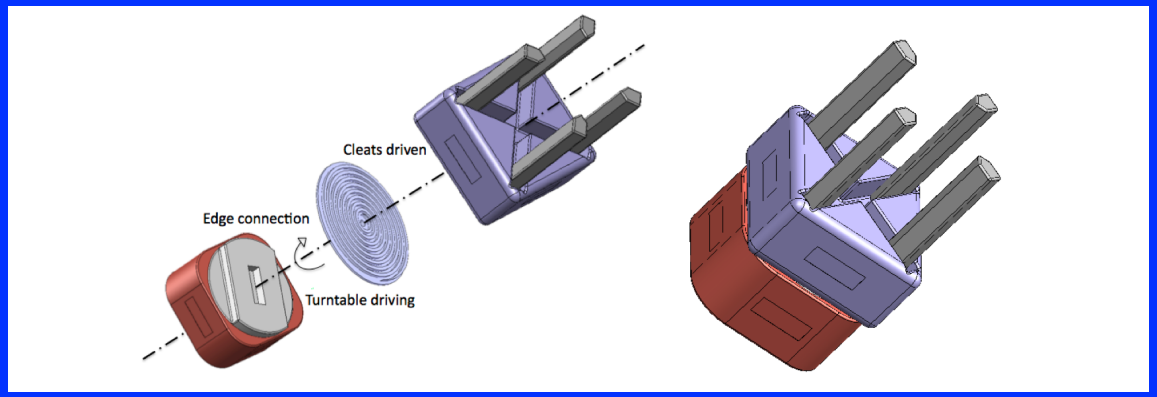
- **Challenges in Mechanics**
  - Modularity
  - Homogeneous and/or heterogeneous modules
  - Flexible, connectable, strong, small/large, …
  - Robust, durable, replaceable, ...
- **Challenges in Electronics**
  - Sensors, actuators, communication, control, interferences, collaboration, ...
  - Real-time operating system
  - Programming environment
  - Debugging facilities
  - Power sharing
  - Integration of all these!
- **Challenges in Connectors**
  - Genderless
  - Single side connectable/releasable
  - Thin but strong profile (no back-drive)
  - Efficient when connected and disconnected
  - Support multi-orientation engagements
  - Tolerant to misalignment
  - Communication
  - *Power sharing*
  - *Dirt tolerant*
- **Challenges in Intelligent Control**
  - Intelligent behaviors
    - Mobility adaptive to tasks/environment
    - Maneuverability adaptive to tasks/environment
  - Adaptive shapes and structures
    - Higher level challenges for AI & Robotics
    - Self-organization
    - Self-healing
    - Reconfiguration deciding, planning, execution
  - New theory for self-reconfigurable systems

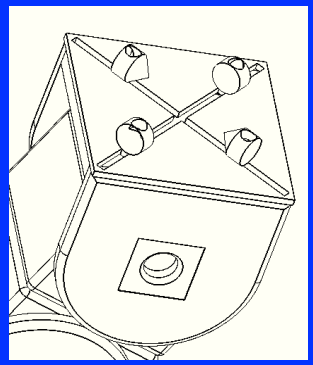
Challenges in Connectors

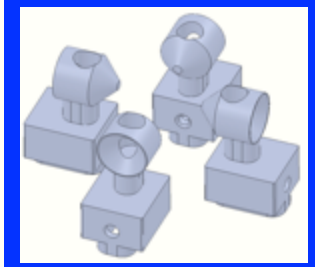
- Genderless
- Strong mechanical torque and endurance
- Data communication
- Power sharing
- Thin profile <15mm
- Dock-able between variable sizes
- Single side operational and releasable
- No back drive
- Efficient power consumption for connect/disconnect
- Multi-orientation engagements
- Tolerant to misalignment during docking process

SINGO Connectors
(US Patent 8,234,950)









Challenges in Distributed Control

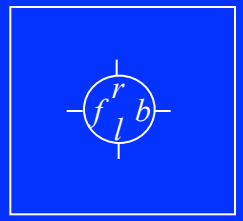
- Distributed among all modules
  - No “fixed brains” or single-point-failures
  - Free from any unique global names or identifiers
  - Discover topology and negotiate tasks
  - Change behaviors by topological locations
- Dynamic network topology
  - Endure unexpected changes in the network
- Asynchronous
  - Collaborate without any synchronized or global clocks
- Scalable
  - Function with any size and shape
- Adaptive
  - Perform complex tasks in different environments
  - Recover from component failures and self-repair
  - Autonomous learning for unexpected situations and tasks

"Digital Hormones" (US Patent 6,636,781)

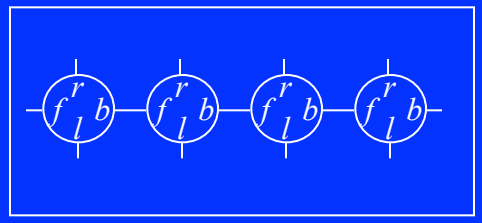
- Content-based messages
  - No addresses nor identifiers
  - Have finite life time
  - Trigger different actions at different sites
- Floating in a global medium
  - Propagated, not broadcast
  - Different from *pheromones*
    - Internal circulation, not external deposit
- Preserve local autonomy for individual sites
- Could modify module behaviors (as RNA)

Configuration Representation

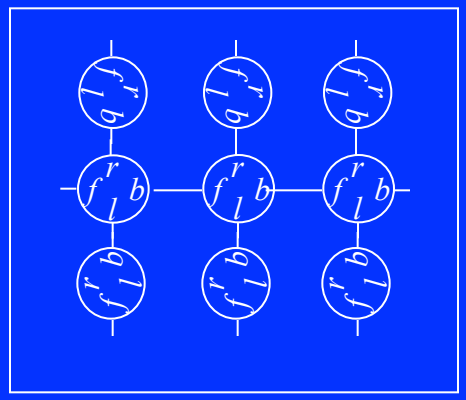
One module

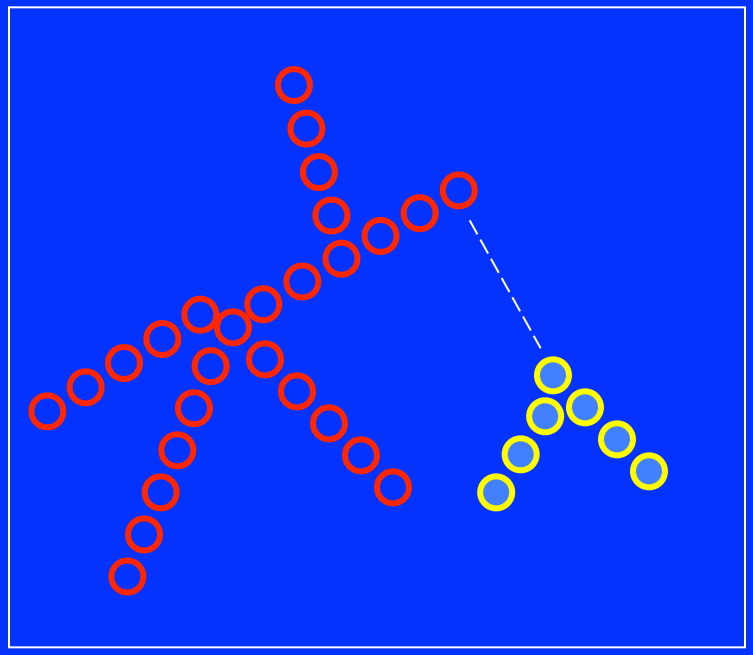


A Snake



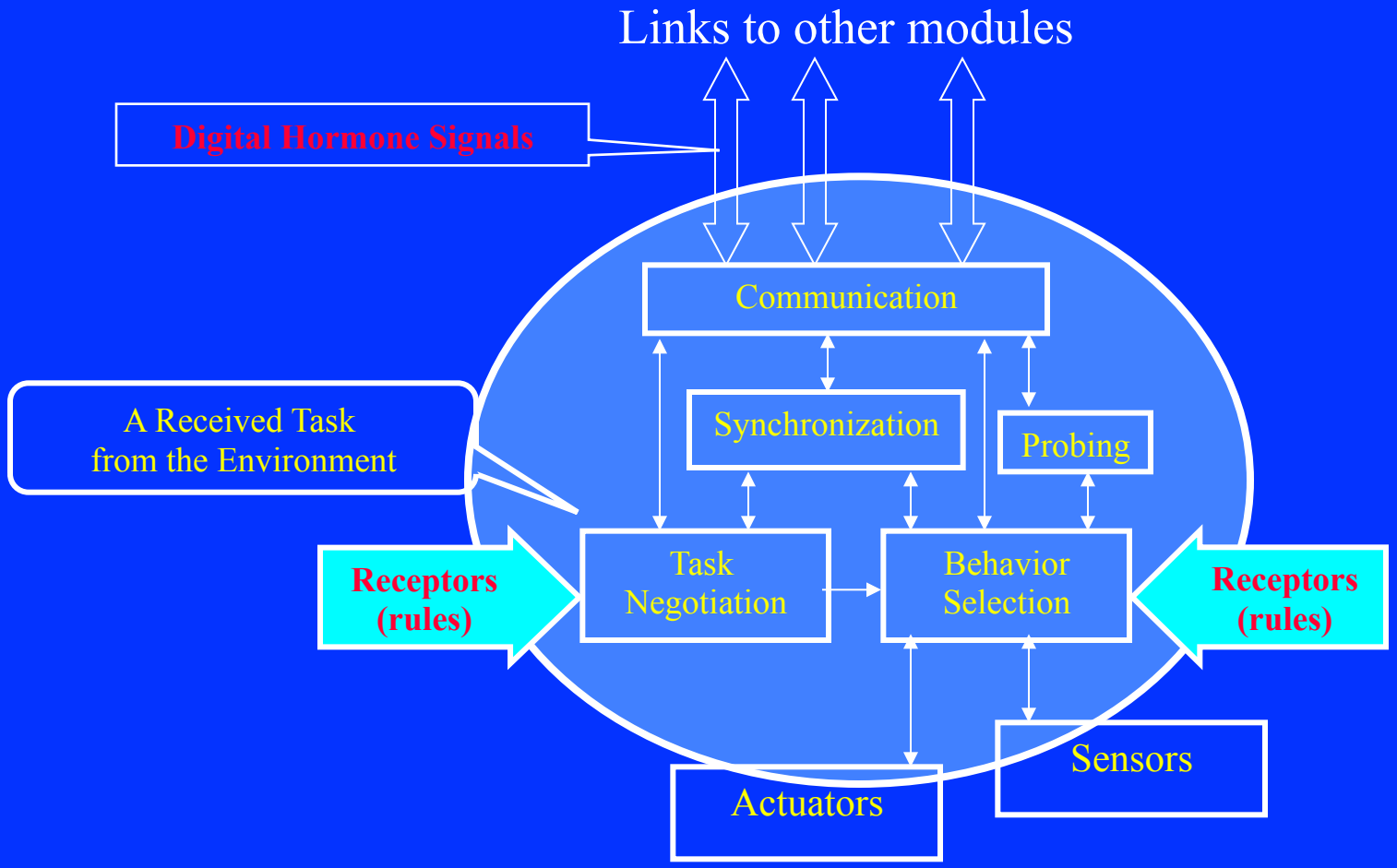
A 6-leg insect





Communication between two separate creatures

Internal Control Architecture

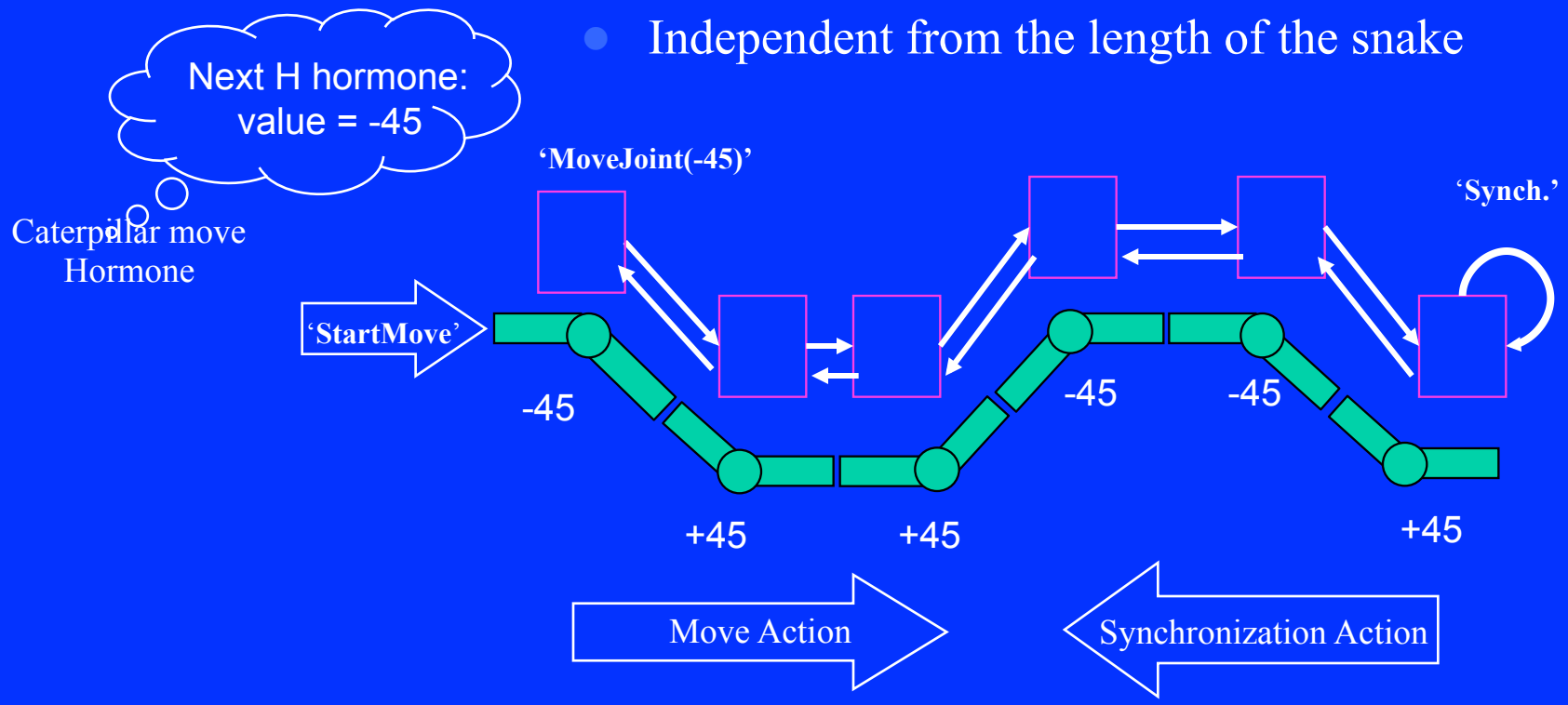


The Uses of Digital Hormones

- Communication in dynamic network
- Cooperation of autonomous robotic modules
  - Locomotion
  - Reconfiguration
  - Synchronization
  - Global effects by weak local actions
  - Conflict resolution (multi hormone management)
  - Navigation
- Configuration adaptation (vision, telescope, ...)
- Self-healing systems

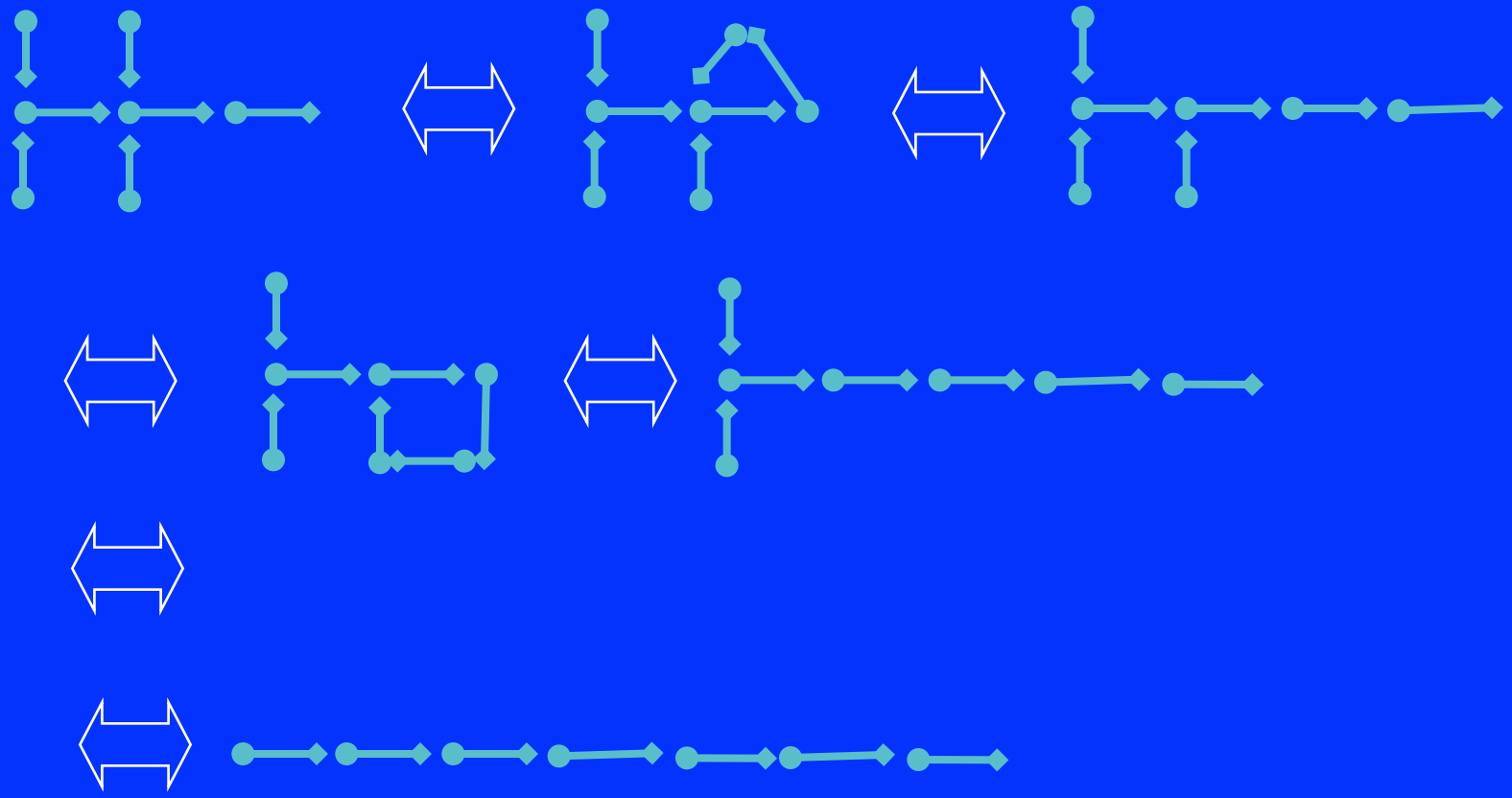
Hormones for Caterpillar Move

- A simple one-pass hormone from head to tail
- Controls and synchronizes all motor actions
- Independent from the length of the snake

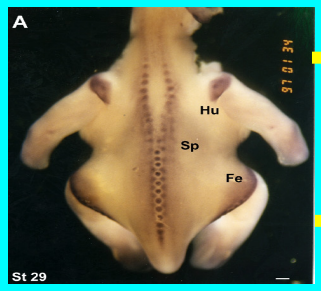


Hormones for Reconfiguration

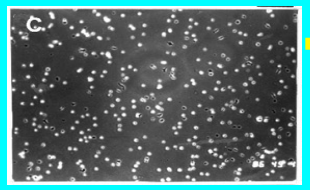
Insect ←→ Snake

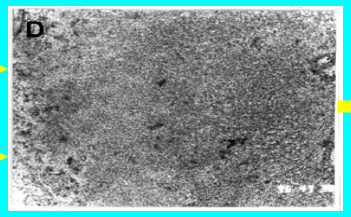


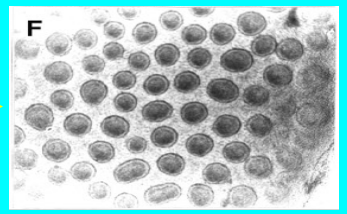
Hormones in “Feather Formation”

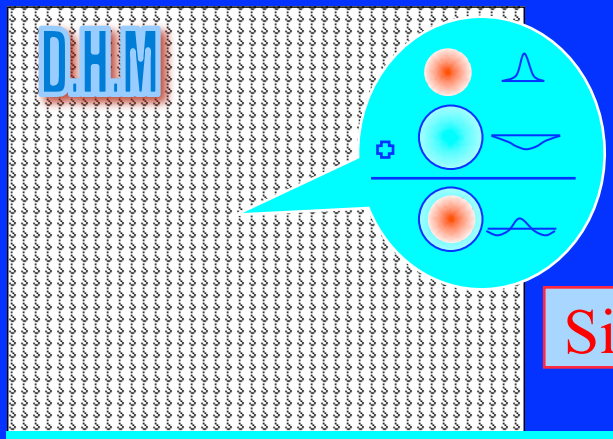




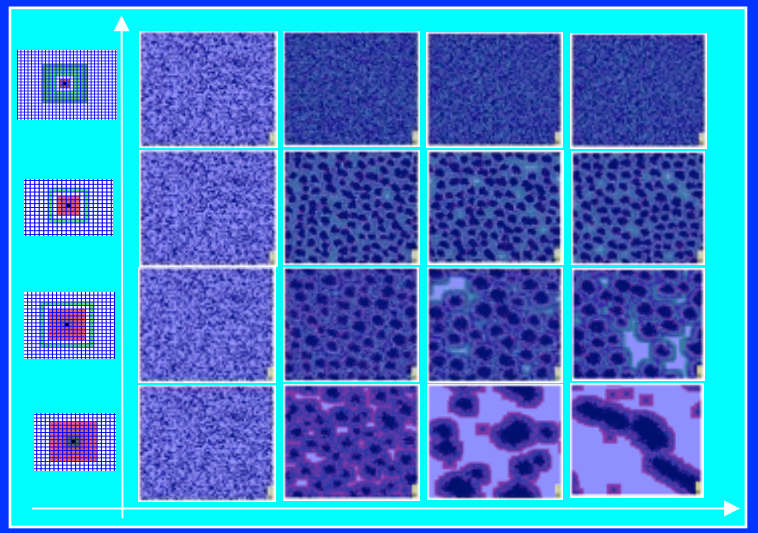








Simulation



1. Reconfigurable networks
2. Reaction-Diffusion model
3. Stochastic action selection

Scalable Self-Healing





Self-healing



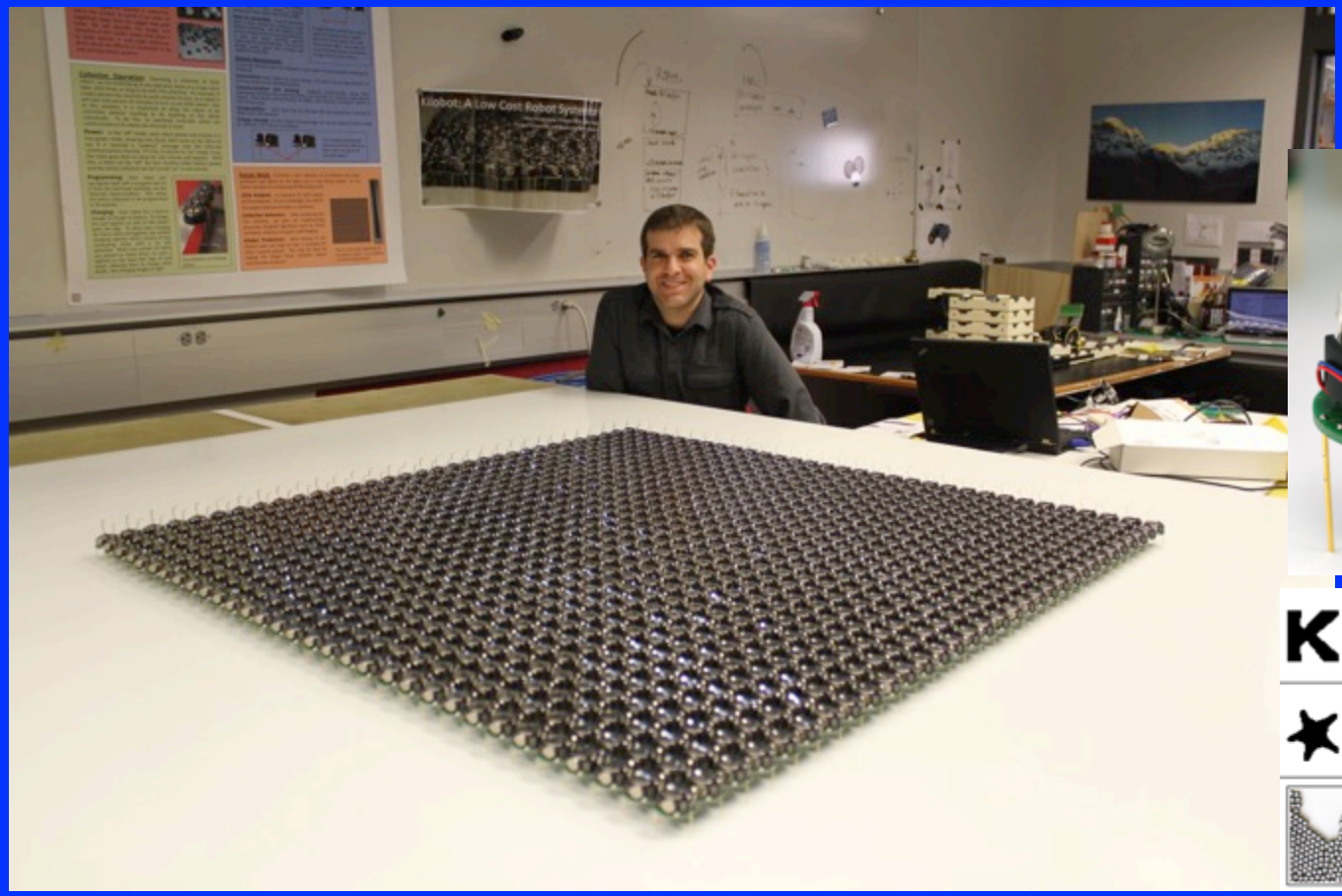


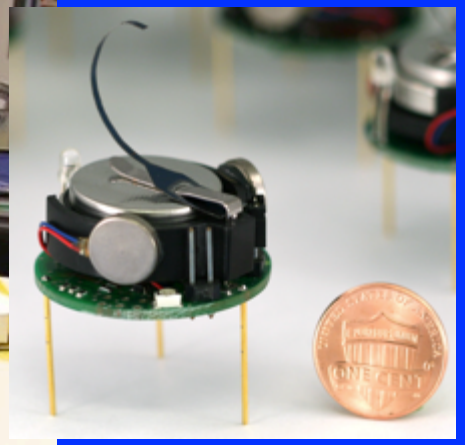
Self-healing

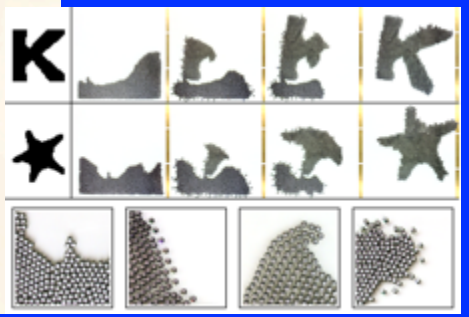




Robotic Swarms







UAV Swarms



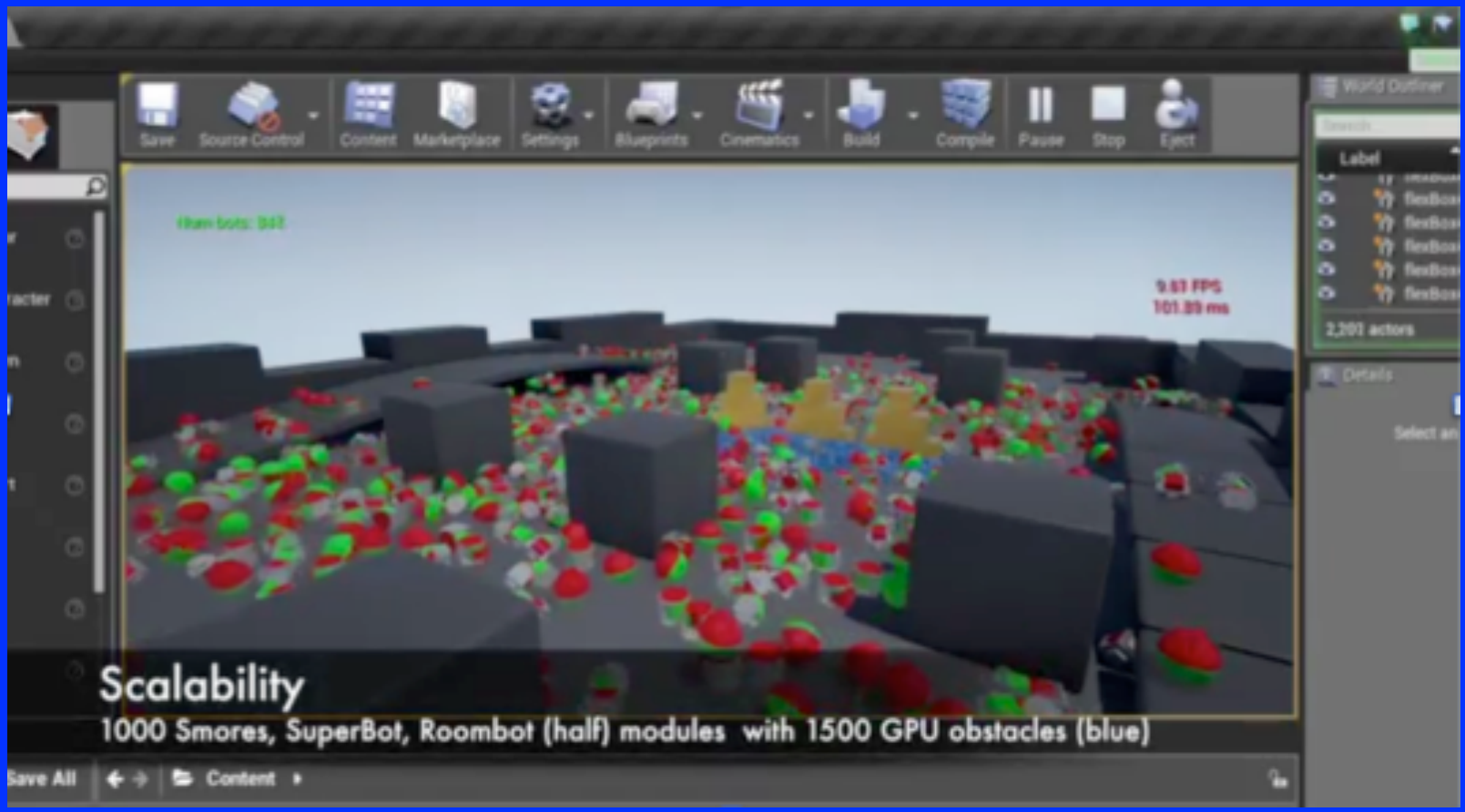




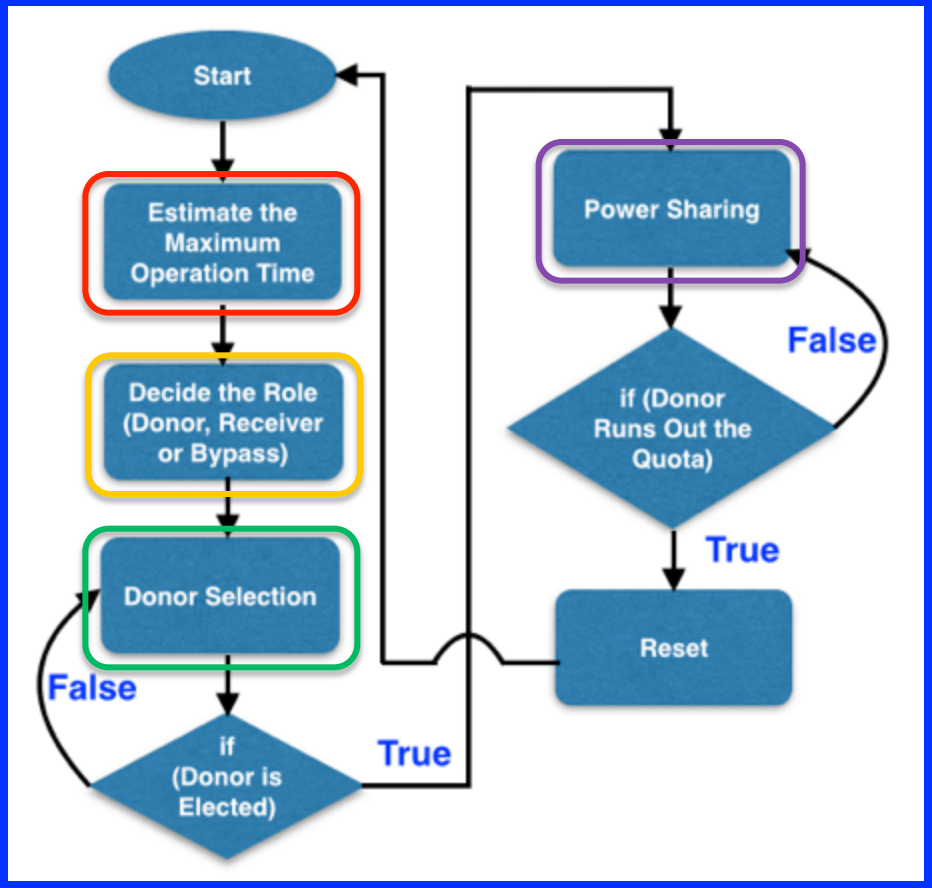
Self-Assembly



Very Large Scale Simulation



Near-Optimal Dynamic Power Sharing for Self-Reconfigurable Modular Systems



$$\widetilde{O}(n) = \frac{\widetilde{R}(n)}{\widetilde{C}(n)},$$

$$\widetilde{R}(n) = \sum_{i=0}^{k} \tilde{r}_i(n), \text{ and } \widetilde{C}(n) = \sum_{i=0}^{k} \tilde{\bar{c}}_i(n)$$

$$\widetilde{R.C.A.}_{\cdot i} = \widetilde{O}(n) \times \tilde{\bar{c}}_i(n) - \tilde{r}_{i,n}$$

$$\widetilde{D.C.A.}_{\cdot i} = \tilde{r}_{i,n} - \widetilde{O}(n) \times \tilde{\bar{c}}_i(n)$$

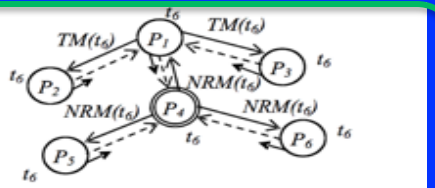


Fig. 3: Distributed Task Negotiation [6].

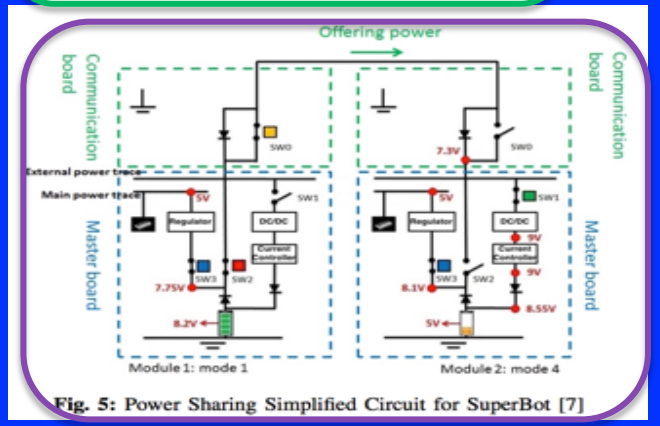
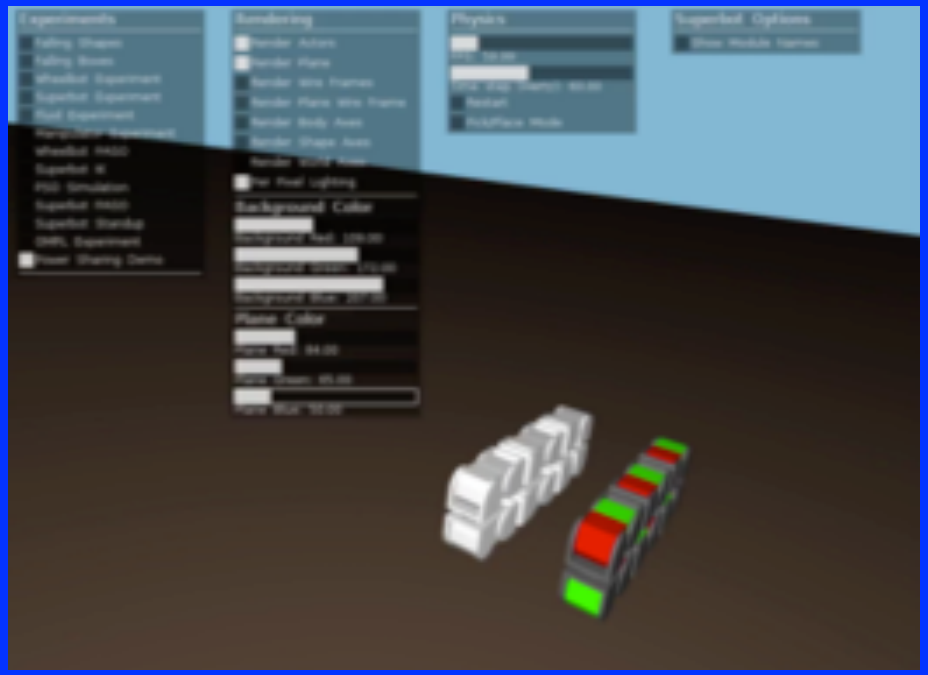


Fig. 5: Power Sharing Simplified Circuit for SuperBot [7]



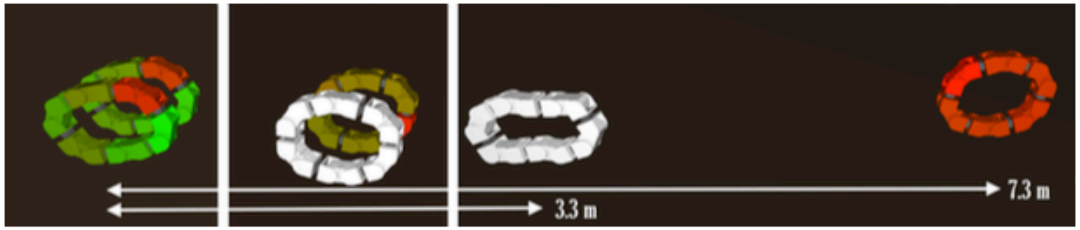


Fig. 10: Rolling track simulation in ReMod3D. On the left, we see the initial state of the simulation. The battery levels of each module are different, as illustrated by the colors (green means high battery, red low battery). The middle image shows the point at which the robot system that does not use power sharing (front) fails. The image on the right shows the near-optimal power sharing rolling track locomoting far past the one that does not use power sharing.

Surprise-Based Learning

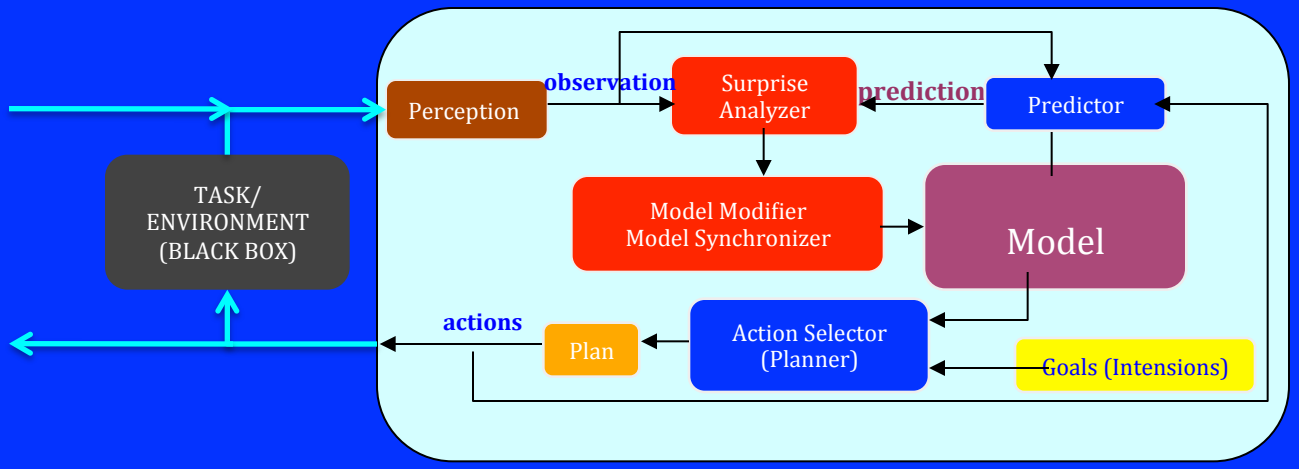
- New Environment/Task → Learning → Knowledge/Skill
- Key Idea: To detect and learn from "surprises"
  - Adaptive to new environments
  - Learn to accomplish new tasks
  - Self-heal from unexpected failures or dynamics (e.g., inverted visions)
    - Know-how → Surprises → Learn → Recovery

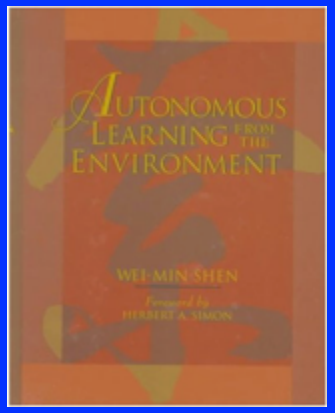






Surprise-Based Learning





- The Learner continuously makes predictions, detects surprise, analyzes surprises, extracts critical information from surprises, and improves and use its action models

Surprise ==> Model ==> Prediction



Related Research Topics

- Biological morphgenesis
- Self-organizing swarm robots
- Self-healing (scalable) systems
- Underwater robot swarm
- Self-assembly in space
- Smart and deployable structures
- Oil and energy robotics
- Self-configureble network
- Evolution of brains

Conclusions

- Self-Reconfigurable Robots Are Coming!
  - Fundamental research challenges
    - Physics, chemical, biology, structures, robots, networks, agents, ...
  - Offer critical capabilities for many applications
    - Search/rescue, homeland security, self-assembly, smart structures, space, ocean, deep-water, oil production, infrastructure inspection, …
  - Has many future potentials
    - Autonomous, Resilient, Adaptive, and Learn
    - Intelligently selection of configurations (very challenging)