Multiple Modes of Locomotion with a Modular Reconfigurable Robot

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Abstract:

When operating autonomous robots in an unstructured and unknown environment it is important to have the versatility to adapt to different environmental conditions. One such condition is the topography of the terrain. Use of a modular reconfigurable robot employing multiple modes of statically stable locomotion can be used to deal with changing terrain types.

We will present a robot system built in 1994 called Polypod that is capable of using many alternate modes of locomotion, some of which mimic the movements of biological systems such as an earthworm or a caterpillar. Polypod is made up of many repeated modules, up to several hundred modules. One of the main issues in implementing this type of robot is the control of this highly redundant system. We will present a simple control method called a “gait control table” for controlling locomotion.

A taxonomy of statically stable locomotion generalizes the modes of locomotion employed by Polypod. In addition to this taxonomy, we will present the evaluation of the Polypod modes in terms of efficiency, payload and stability..

One of the advantages of using a modular reconfigurable robot for exploring unknown environments is its ability to reconfigure itself to adapt to the environment being explored. There are many issues that need to be examined to implement a reconfiguring system. These include determining which configuration to assume (based on optimizing task parameters), when to assume a new configuration (by sensing and understanding the environment), and how to execute the reconfiguration process (planning in the “reconfiguration space”).

Spider configuration (simulation)

3 legged caterpillar configuration

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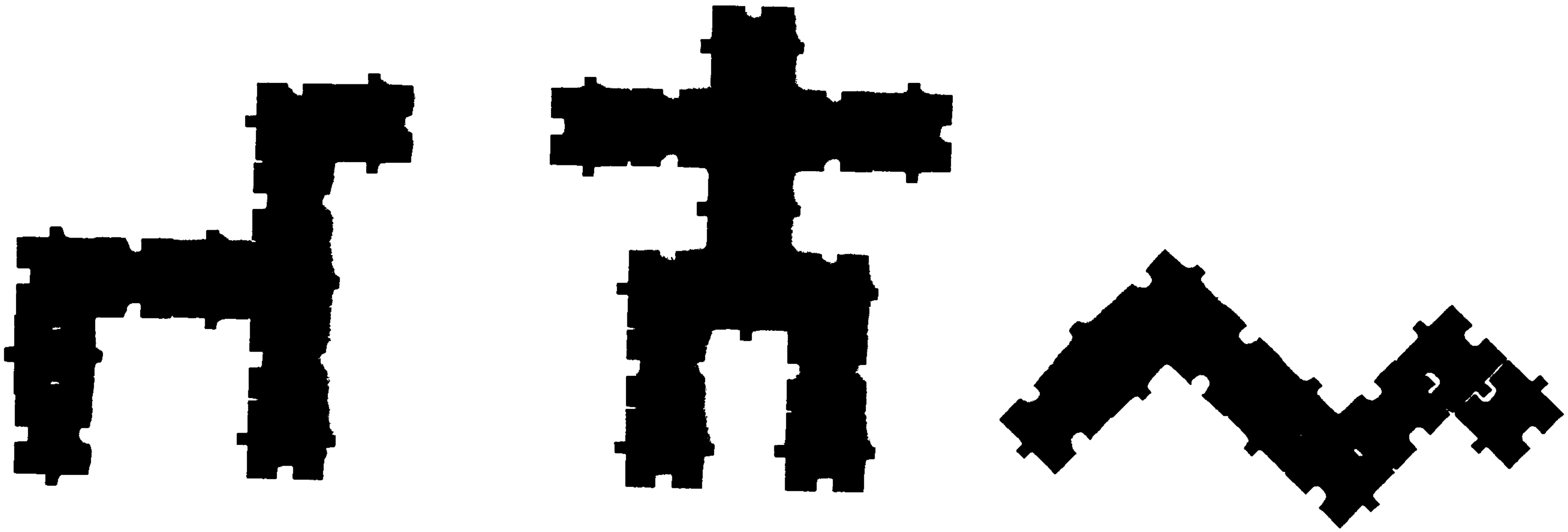
Motivation



Versatility

We will examine the locomotion class of tasks.
Statically stable locomotion in particular.

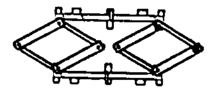
Polypod Background

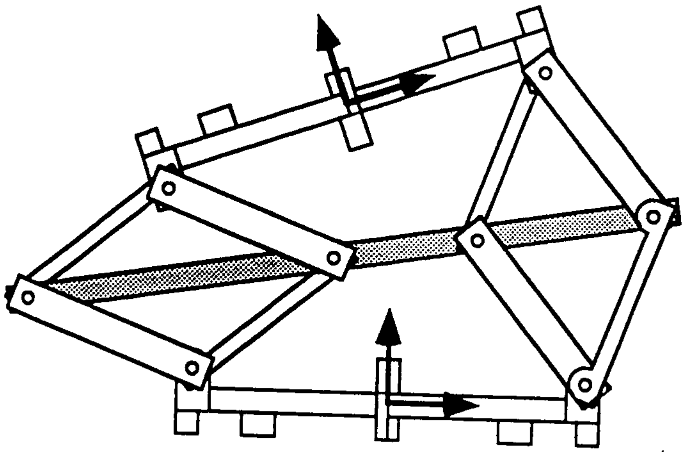
- Thesis work at Stanford University
- Studying statically stable locomotion
- Motivation: modular reconfigurable robots can be
  - Versatile (adapting shape to task)
  - Self repairing (from having high redundancy)
  - Inexpensive (from batch fabrication)

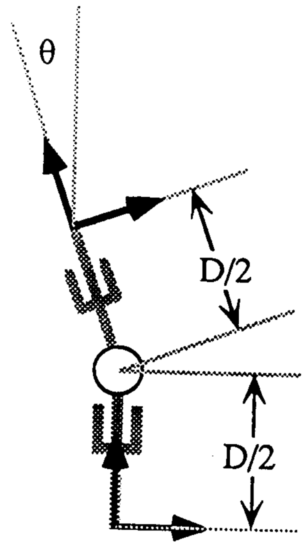
Past Modular Reconfigurable Work

- Polypod, Mark Yim (1994)
- CEBOT (Mark I, II, III, IV) Toshio Fukuda (1988 - 1998)
- Metamorphosing robot, Chirikjian (1994, 1997)
- Fracta I, 3D Fracta, Satoshi Murata (1994, 1998)
- Molecular Robotics, Daniela Rus (1997)
- Planar self assembling robot, Hajime Asama (1998)

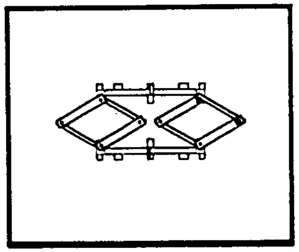
Segment Kinematics



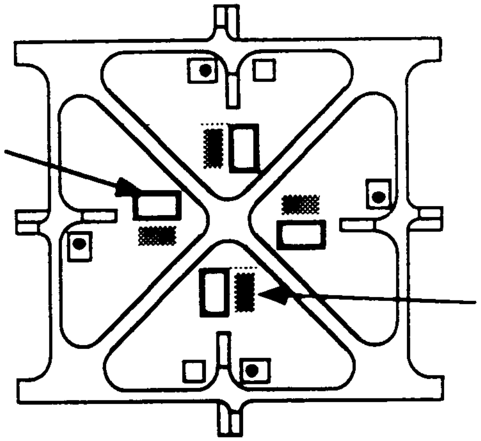


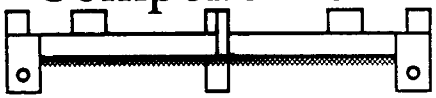


Connection Plate



Female electrical connector (4x's)

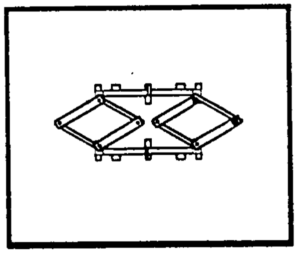


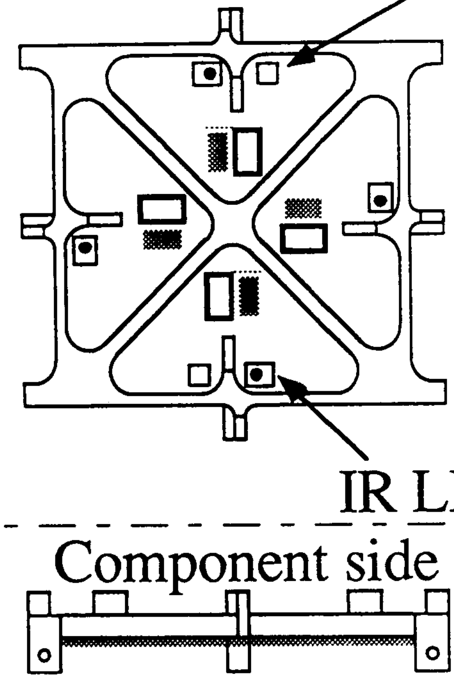


Printed Circuit board

- 4 x's Rotational Symmetry
- Latching Mechanism
- Connector redudancy

Segment Sensing





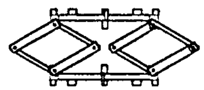
- Actuator Position

- Three Function IR
  - Proximity
  - Force
  - Local Comm bus

Computing

- MC68HC11E2
  - 2Mhz 8-bit micro computer
  - 2K EEPROM
  - 25 Digital I/O
  - 8 channel 8-bit A/D
- 1MHz RS-485 single master serial communications bus

Node

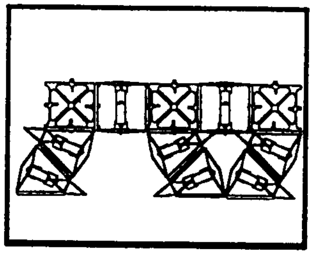


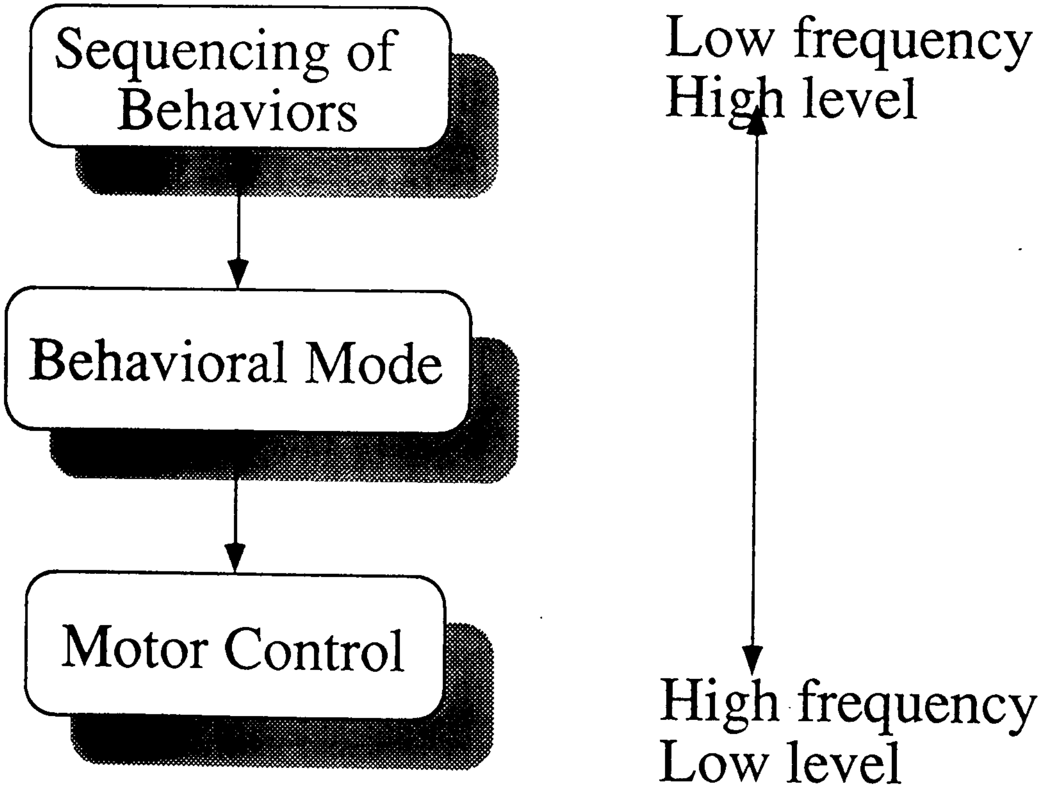
- Made up of six connection plates in a cube. Cubes are the only space filling regular solid.

- Allows non-serial chains

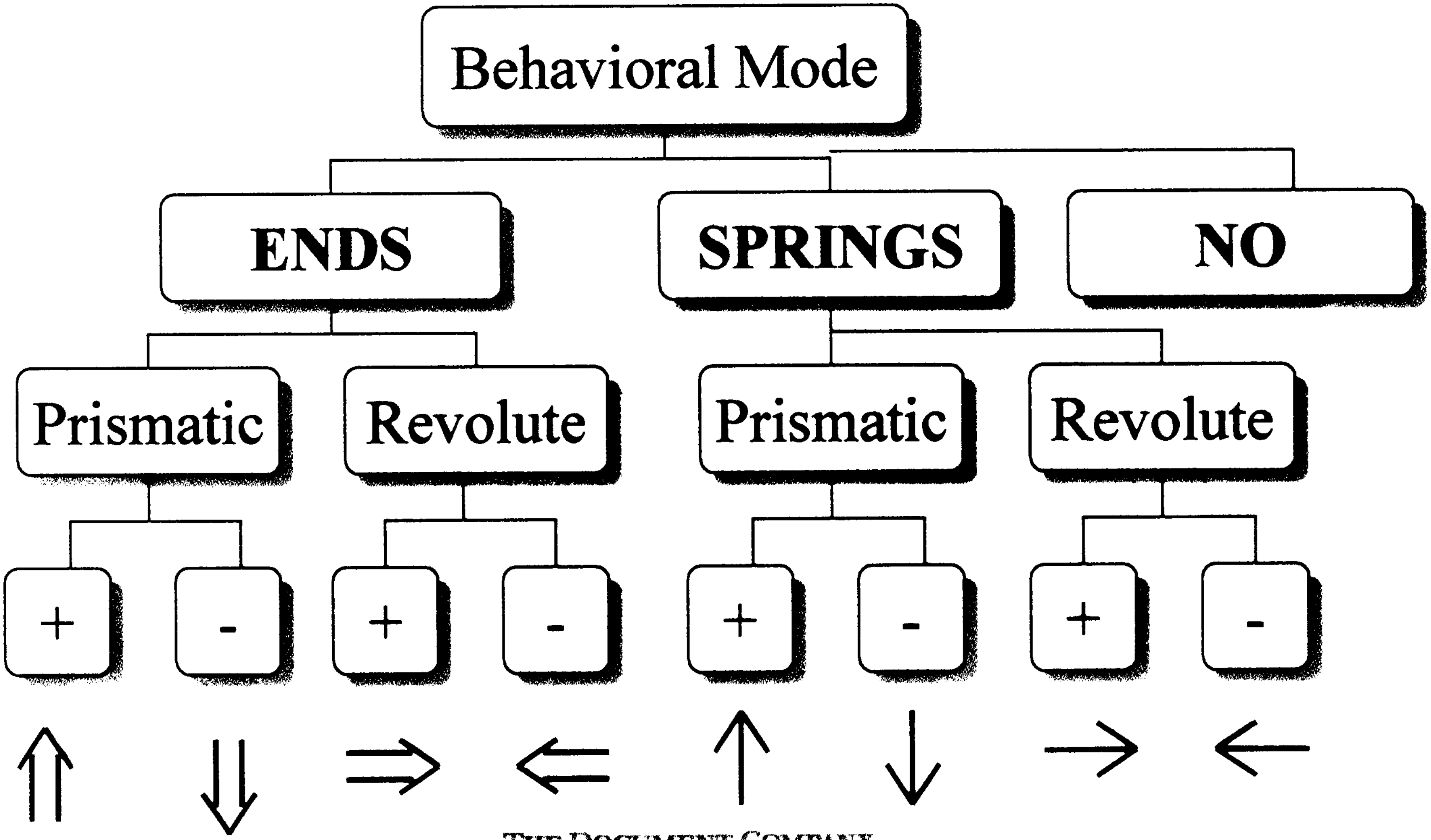
- Holds gel-cell batteries

Hierarchical Control Architecture





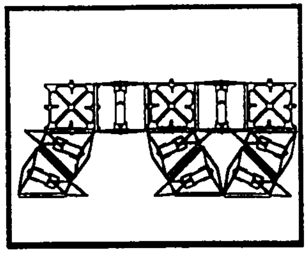
Behavior Modes



Gait Control Table

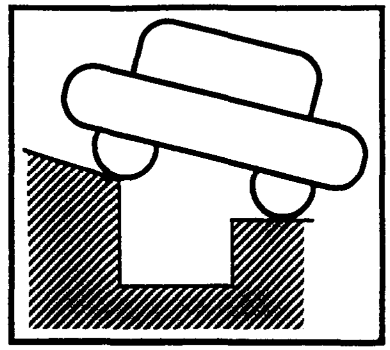
step	Segment number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	→	→	→	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐	⇐	⇐
1	←	→	→	→	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐	⇐
2	←	⇐	→	→	→	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐
3	←	⇐	⇐	→	→	→	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐
4	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐	⇐	⇐	→	→	→	→
5	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐	⇐	⇐	→	→	→
6	→	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐	⇐	⇐	→	→
7	→	→	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐	⇐	⇐	→
8	→	→	→	→	⇐	⇐	⇐	⇐	→	→	→	→	⇐	⇐	⇐	⇐

Masterless Control



Caterpillar Segments		Rolling Track Segments
odd feet	even feet	
⇐ ⇒	⇓ ⇓	⇑⇑⇑⇑⇑⇑⇒⇒⇒⇒⇑⇑⇑⇑⇑⇑⇒⇒⇒⇒
	⇒ ⇐	
⇓ ⇓	⇐ ⇒	
⇒ ⇐		
⇐ ⇒	⇓ ⇓	
	⇒ ⇐	⇒⇑⇑⇑⇑⇑⇑⇒⇒⇒⇒⇑⇑⇑⇑⇑⇑⇒⇒⇒
⇓ ⇓	⇐ ⇒	
⇒ ⇐		
⇐ ⇒	⇓ ⇓	
	⇒ ⇐	
⇓ ⇓	⇐ ⇒	⇒⇒⇑⇑⇑⇑⇑⇑⇒⇒⇒⇒⇑⇑⇑⇑⇑⇑⇒⇒
⇒ ⇐		
⇐ ⇒	⇓ ⇓	
	⇒ ⇐	
⇓ ⇓	⇐ ⇒	
⇒ ⇐		⇒⇒⇒⇑⇑⇑⇑⇑⇑⇒⇒⇒⇒⇑⇑⇑⇑⇑⇑⇒
⇐ ⇒	⇓ ⇓	etc.

Polypod Vehicle Parameters

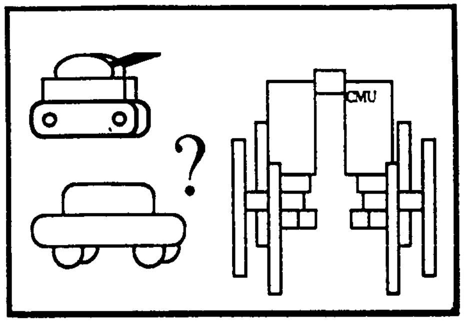


Polypod Static Feature Vehicle Parameters

Gait	V_d	V_{hu}	V_b	V_h	V_w	V_c
Earthworm *	$1.1(s+n)$"	0.0"	$1.1(s+n)$"	4.0"	2.3"	3.8"
Rolling track *	$0.55(s+n)$"	0.0"	$0.55(s+n)$"	6.4"	2.3"	3.8"
Spider	$0.10(s+n)$"	0.0"	$0.10(s+n)$"	$(0.14s+2.3)$"	8.3"	8.3"
Turning-cater	$0.26(s+n)$"	0.0"	1.1"	4.3"	2.3"	8.3"
Caterpillar	$0.26(s+n)$"	0.0"	$0.26(s+n)$"	4.3"	2.3"	∞
Exotic	$0.13(s+n)$"	0.0"	$0.13(s+n)$"	6.3"	2.3"	∞
Moonwalk	$0.13(s+n)$"	0.0"	$0.13(s+n)$"	6.3"	2.3"	∞
Cater-cater	$0.55\sqrt{s+n}$"	2.3"	1.1"	4.3"	$0.92\sqrt{s+n}$"	$1.3\sqrt{s+n}$"
Slinkyslinky	5.2"	3.2"	$0.22(s-1)$"	$(0.35s+2n)$"	2.3"	∞
Slinky	5.2"	3.2"	$0.22(s-1)$"	$(0.35s+2n)$"	2.3"	∞
Cartwheel	4.0"	2.0"	$0.13(s-1)$"	$(0.18s+2)$"	2.3"	∞
3-seg slinky	4.0"	0.0"	0.1"	4.6"	2.3"	∞

n = number of nodes
s = number of segments

Polypod Efficiency

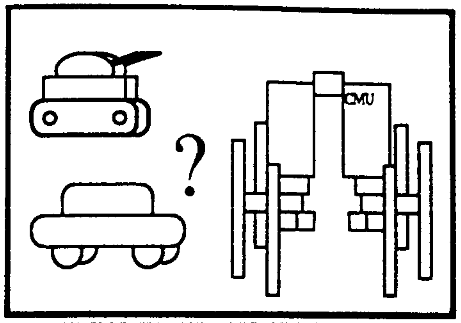


Polypod Efficiency

Gait	d	$\Updownarrow$	$\leftarrow$	$N(s)$	$N(n)$	$n = 16, s = 56$
3-seg slinky	4.0"	3	0	3	0	0.31
tloop	3.6"	4	0	s/2 + 8	n/2 + 4	0.010
rolling track	2.4"	4	0	s/2 + 4	n/2 + 4	0.0073
cartwheel	4.0"	4	4	s	n	0.0064
slinkyslinky	5.2"	6	4	s	n	0.0060
slinky	4.0"	6	4	s	n	0.0048
cater-cater	2.4"	3s/5	0	7	2	0.0046
spider *	2"	12	0	2s/5	n/2	0.00036 *
exotic	6"	4+4s/8	0	s/4+10	n/2+4	0.0031
Turning-cater	2.4"	2s	0	5	2	0.0025
caterpillar	2.4"	2s	0	5	2	0.0016
earthworm	2.4"	8s	0	4	4n/s	0.00060
moonwalk	(-)2"	4+3s/4	0	s/4+10	n/2+4	0.00041

* The spider efficiency rating uses estimated equivalent parameters

Polypod Stability



Energy Stability Margin (ESM) [Messuri et al 1985]

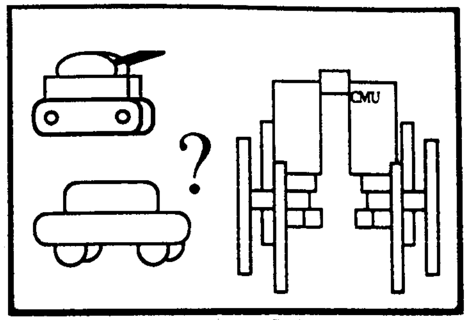
Polypod Stability

Gait	R_X	R_Y	S	$n = 16, s = 56$
spider *	4.4”	4.1”	1.91	1.91
cater-cater **	$6.2(\sqrt{n} - 3)$”	3.4”	$\approx 2\sqrt{(n)}$	1.78
earthworm	1.1”	2.1”	0.27	0.27
3-seg slinky	1.1”	2.6”	0.22	na
tloop	1.1”	3.2”	0.18	0.18
rolling track	1.1”	3.2”	0.18	0.18
Turning-cater	1.1”	3.4”	0.17	0.17
caterpillar	1.1”	3.4”	0.17	0.17
exotic	1.1”	6.2”	0.097	0.097
moonwalk	1.1”	6.2”	0.097	0.097
cartwheel	1.1”	$0.26s$”	0.14	0.04
slinkyslinky *	1.1”	$3.3n + .4 * s$	$<< 0.01$	0.008
slinky *	1.1”	$3.3n + .6 * s$	$<< 0.01$	0.007

* assumed nodes distributed evenly among segments

** assumed n >> 16

Polypod Payload



Polypod Payload

Gait	min. ground legs	load surface	payload	$n = 16, s = 56$
cater-cater	n	$16n$ in^2	$3n$ lbs	48 lbs
Turning-cater	n	$8n$ in^2	$3n$ lbs	48 lbs
caterpillar	n	$8n$ in^2	$3n$ lbs	48 lbs
exotic	$\frac{1}{2}(n-8)$	$2(n-8)$in^2	$\frac{3}{2}(n-8)$lbs	12 lbs
spider	4	4 in^2	12 lbs	12 lbs

Current Work

- Distributed Robotics program DARPA (ETO/DSO)
- Designing reconfigurable modules
- Making multiple mode simulation **real**
- Examining computational and design issues in scaling up numbers through simulation and a reduced functionality module