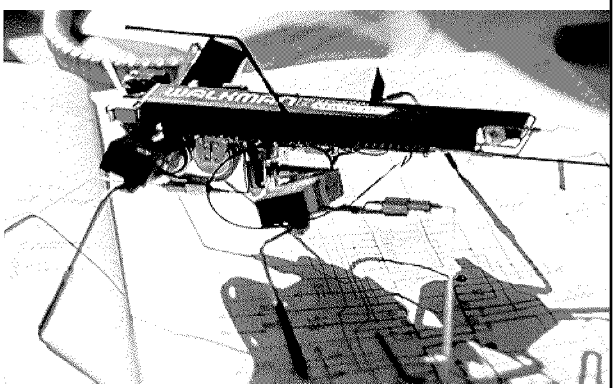
The Design of "Living" Biomech Machines: How low can one go?



VBUG 1.5 "WALKMAN"
Single battery. 0.7Kg. metal/plastic construction. Unibody frame.
5 tactile, 2 visual sensors.
Control Core: 8 transistor Nv.
4 tran. Nu, 22 tran. motor.
Total: 32 transistors.
Behaviors:
- High speed walking convergence.
- powerful enviro. adaptive abilities
- strong, accurate phototaxis.
- 3 gaits; stop, walk, dig.
- backup/explore ability.

Mark W. Tilden
Physics Division,
Los Alamos National Laboratory
<mwtilden@lanl.gov>
505/667-2902

July, 1997

"So... what you guys have done is find a way to get useful work out of non-linear dynamics?" - Dr. Bob Shelton, NASA.

Abstract

Following three years of study into experimental Nervous Net (Nv) control devices, various successes and several amusing failures have implied some general principles on the nature of capable control systems for autonomous machines and perhaps, we conjecture, even biological organisms. These systems are minimal, elegant, and, depending upon their implementation in a "creature" structure, astonishingly robust. Their only problem seems to be that as they are collections of non-linear asynchronous elements, only a very complex analysis can adequately extract and explain the emergent competency of their operation. On the other hand, this could imply a cheap, self-programing engineering technology for autonomous machines capable of performing unattended work for years at a time, on earth and in space. Discussion, background and examples are given.

Introduction to Biomorphic Design

A Biomorphic robot (from the Greek for "of a living form") is a self-contained mechanical device fashioned on the assumption that chaotic reaction, not predictive forward modeling, is appropriate and sufficient for sustained "survival" in unspecified and unstructured environments. On the further assumption that minimal, elegant survival devices can be "evolved" from lesser to greater capabilities using silicon instead of carbon (using the roboticist as the evolutionary force of change), over two hundred different "biomech" robots have been built and studied using solar power, motors, and minimal Nervous-Net control technology. A range of such creatures is shown in Figure 1.

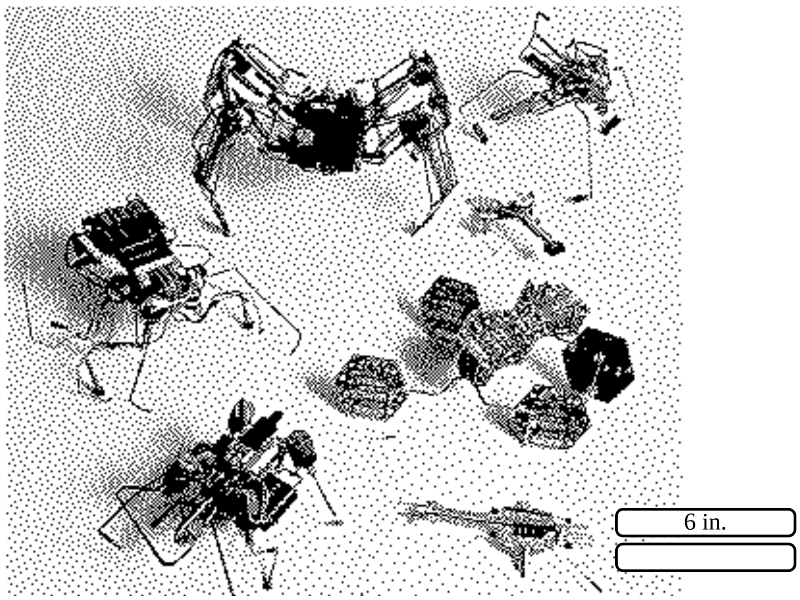


Figure 1: Some Biomech walkers, hoppers and solar rovers. Over two hundred Nv machines of thirty-five "species" have been built so far. Some have been in continuous operation for over seven years.

Nervous Networks (Nv) are a non-linear analog control technology that has been "evolved" to automatically solve real time control problems normally difficult to handle with conventional digital methods. Using Nv nets many sinuous robot mechanisms have been demonstrated that can negotiate terrains of inordinate difficulty for wheeled or tracked machines, as well as exhibiting very competent strategies for resolving immediate survival conundrums. The scale of devices developed so far has ranged from single "neuron" rovers to sixty neuron distributed controllers with broad terrain abilities, and from machines under one-inch long to several meters in length. They have recognizable behaviors that, if not efficient, are at least sufficient to resolve otherwise intractable sensory integration problems. They remember, and more, use that knowledge to apply new strategies to acquire goals ("Living Machines", 1995).

This work has concentrated on the development of Nv based robot mechanisms by electronic approximations of biologic autonomic and somatic systems. It has been demonstrated that these systems, when fed back onto themselves rather than through computer-based control generators, can realistically mimic many of the abilities normally attributed to lower survival-biased biological organisms. That minimal non-linear systems can provide this degree of control is not so surprising as the part counts for successful Nv designs. A fully adept insect-walker, for example, can be fully controlled and operated with as little as twelve standard transistor elements.

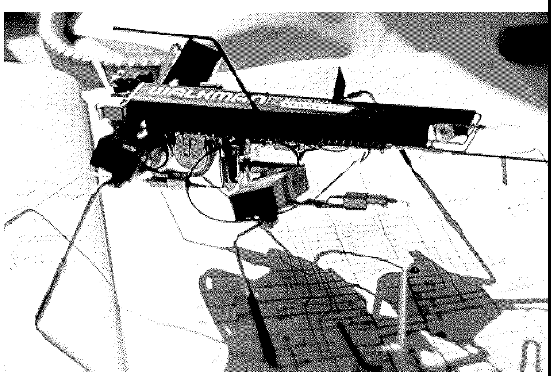
The initial focus of Nv technology was to derive the simplest control systems possible for robotic "cradle" devices. The reason for this is threefold. First, such systems would feature robustness characteristics allowing inexpensive machines reliable enough to be trusted with performing unsupervised work in unstructured environments. Second, using Nv technology we hoped to resolve one of the most enviable things about biological designs, namely how nature can stick large numbers of lightweight, efficient actuators and sensors almost anywhere and still have them operate effectively. Third, and most important, exploration of minimal control systems may explain the biological paradox of why biological mechanisms can get by on so few active control elements. A common garden ant has roughly twenty-thousand control amplifiers distributed throughout its entire body, whereas a digital watch may have as many as half a million amplifiers and still be unable to even walk. How does nature do so much with so little? The question is, what are the fundamental properties of living control systems, and what relationship do they have to the implicit abilities of Nv control topologies? Does Nv technology use some approximation of natural living things, is it the other way around, or is it neither?

Applications are now focusing on the use of this technology for adaptive survivor-based space hardware, and for use in unexploded ordinance, mines, and munitions detection and destruction. Interest and funding sources are JPL, DARPA, NASA, DOE, DOD, NIS and the Yuma Flats proving grounds.

Acedemic research is now concentrating on analysis of the non-linear characteristics of these systems, the development of an engineering lexicon, and several books on 'chaotic engineering', the science behind biomorphic robot construction.

MWT
July 2, 1998

Theoretical Foundations for Nervous Nets and the Design of Living Machines:



VBUG 1.5 "WALKMAN"
Single battery. 0.7Kg. metal/plastic construction. Unibody frame.
5 tactile, 2 visual sensors.
Control Core: 8 transistor Nv.
4 tran. Nu, 22 tran. motor.
Total: 32 transistors.
Behaviors:
- High speed walking convergence.
- powerful enviro. adaptive abilities
- strong, accurate phototaxis.
- 3 gaits; stop, walk, dig.
- backup/explore ability.

Brosl Hasslacher
Theoretical Division
Los Alamos National Laboratory
Los Alamos, NM 87545, USA
<bhass@lanl.gov>

Mark W. Tilden
Biophysics Division
Los Alamos National Laboratory
Los Alamos, NM 87545, USA
<mwtilden@lanl.gov>

[Nov. 1995]

"So... what you guys have done is find a way to get useful work out of non-linear dynamics?" - Dr. Bob Shelton, NASA.

Nervous Net (Nv) technology is a non-linear analog control system that solves real time control problems normally difficult to handle with conventional digital methods.

- Nervous nets (Nv) are to electrical Neural nets (Nu) the same way peripheral spinal systems are to the brain.

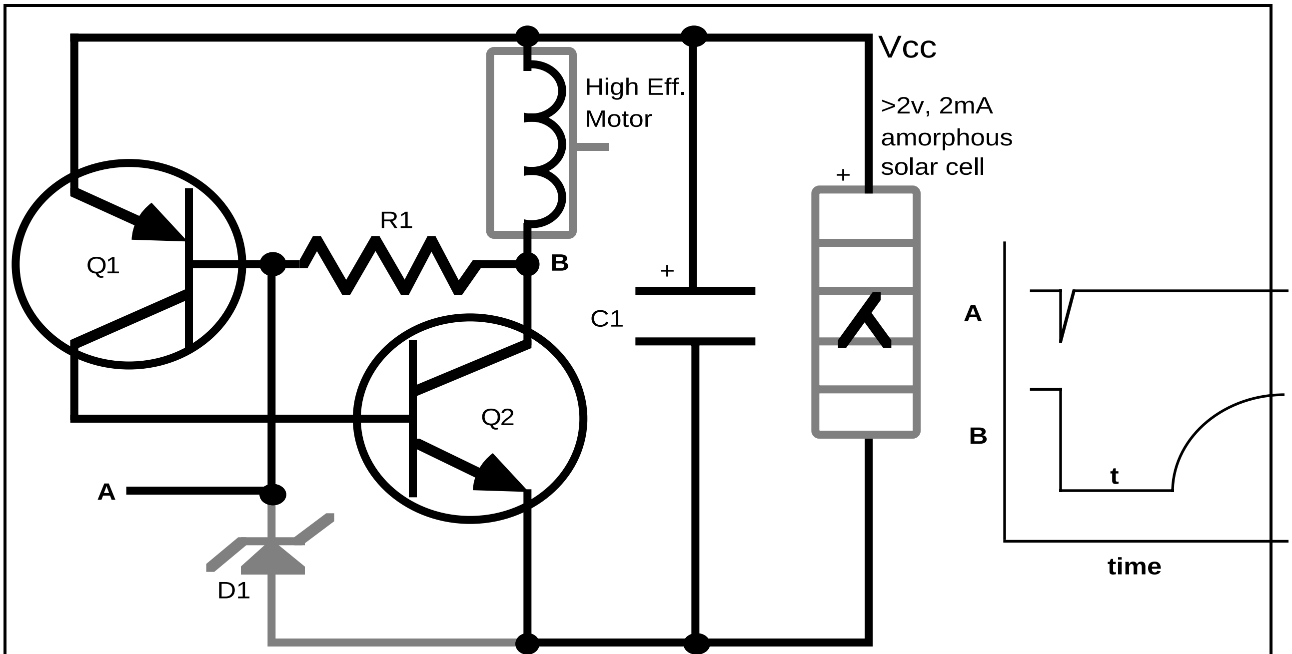
- Using Nv nets, highly successful legged robot mechanisms have been demonstrated which can negotiate terrains of inordinate difficulty for wheeled or tracked machines. That non-linear systems can provide this degree of control is not so surprising as the part counts for successful Nv designs. A fully adept insect-walker, for example, can be fully controlled and operated with as little as <u>12 standard transistor elements</u>.

- This work has concentrated on the development of Nv based robot mechanisms with electronic approximations of biologic autonomic and somatic systems. It has been demonstrated that these systems, when fed back onto themselves rather than through a computer-based pattern generator, **can successfully mimic many of the abilities normally attributed to lower biological organisms.**

- Nv technology is analog and currently a "Black Art". However, some clues as to the nature of its operation can be gleaned from Non Linear Dynamical Theory.

SAMPLE (non-exclusive) CIRCUITRY:

The basic circuit used in minimalist "Biomechs" is the quasi-periodic "Motor Neuron" (Nv) shown below:

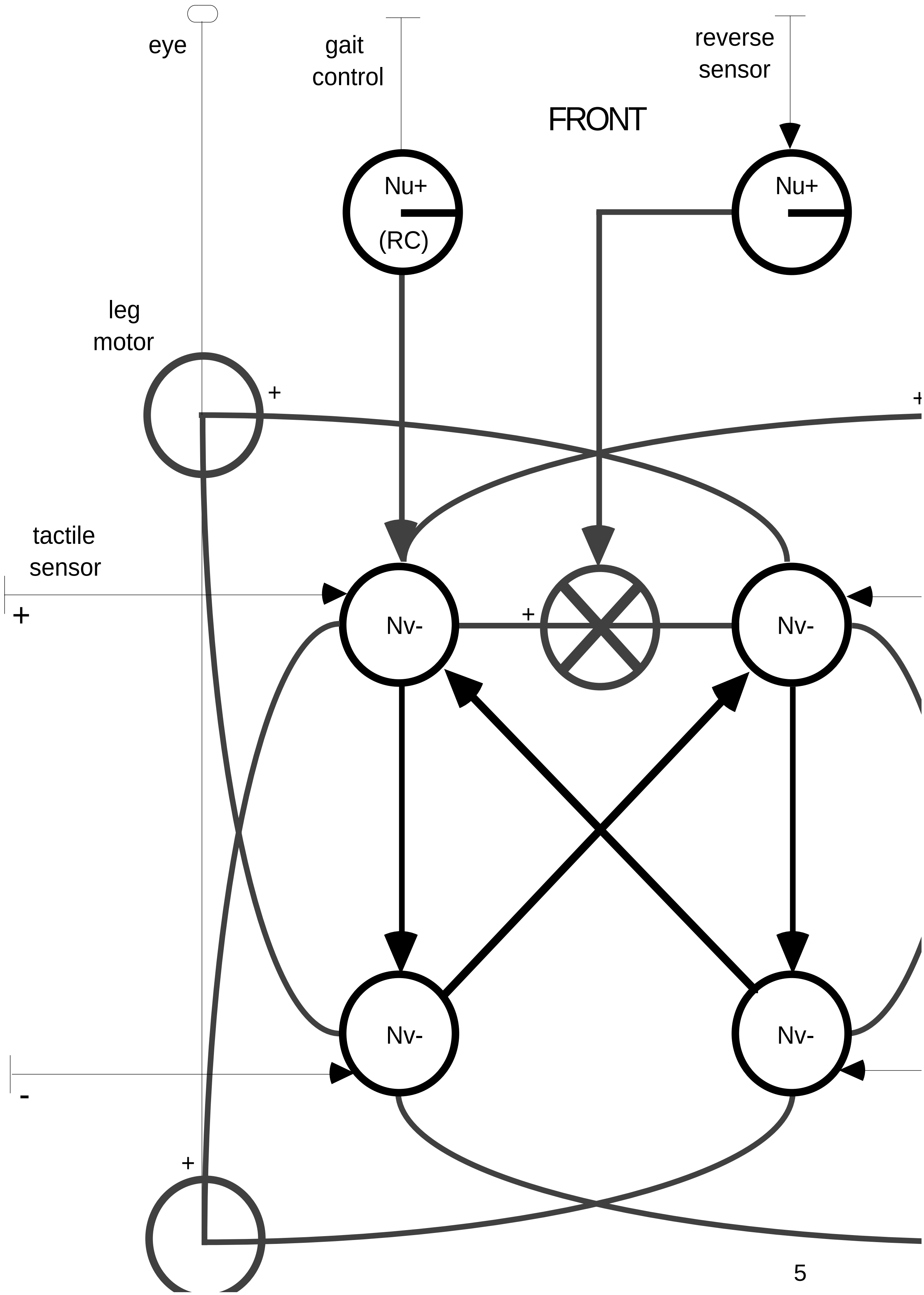


The patented Nv "Solarengine", with Zener self trigger.

The **Nv Solarengine** can be considered an effective quasi-chaotic oscillator, more so when considering variables in motor load, inertia, and the variability of environmental light sources. The advantages of this design are small component count and adjustability, but mostly its very low current drain until tripped. This means that <u>Biomorphic designs can be very small, robust, and self-contained.</u>

- Coupled clusters of these oscillators provide the dynamical richness of Biomech systems.

For example:


eye
gait
control
reverse
sensor
FRONT
Nu+
(RC)
Nu+
leg
motor
+
+
tactile
sensor
+
Nv-
+
Nv-
Nv-
Nv-
-
+

Vbug 1.5 "Walkman", Complete Microcore Structure.

- This figure shows the smallest possible nervous network (defined as the "Microcore") for a capable quadruped with 1.25 DOF per leg. It features 12 transistors in a single hex-inverter chip.

Background Theory Behind Scalable, Adaptive, Autonomous Walking Machines:

Properties:

- Motion implies walking.

- Scale Invariance implies adequacy for nanotech applications.

- Limited internal world representation.

- Minimal solutions for high reliability.

- Survival Oriented, Self Contained Machines. Such robots are not technically "workers" as the word robot implies, but artificial life forms *in situ.* As such, the term "**Biomorph**" (**BIO**logical **MORPH**ology) is more appropriate to describe devices that "live" a progressive existence until failure in strategy or structure forces immobility.

- Dynamically adaptive.

- Machines "Flow through the world", not against it.

- Digital Solutions are known, but require large computing power without scale ability features.

Solutions used here:

Simple electronics and mechanics makes the whole machine an analog computer, but where is the complexity for walking?

Answer: In a phase space of quasi-periodic, mode locking analog oscillators, capable of chaos and spun out dynamically.

ADVANTAGES: Even for very elementary electronics, adaptability, survivability, minimality of structure, and immense effective computation has been shown to be automatic.

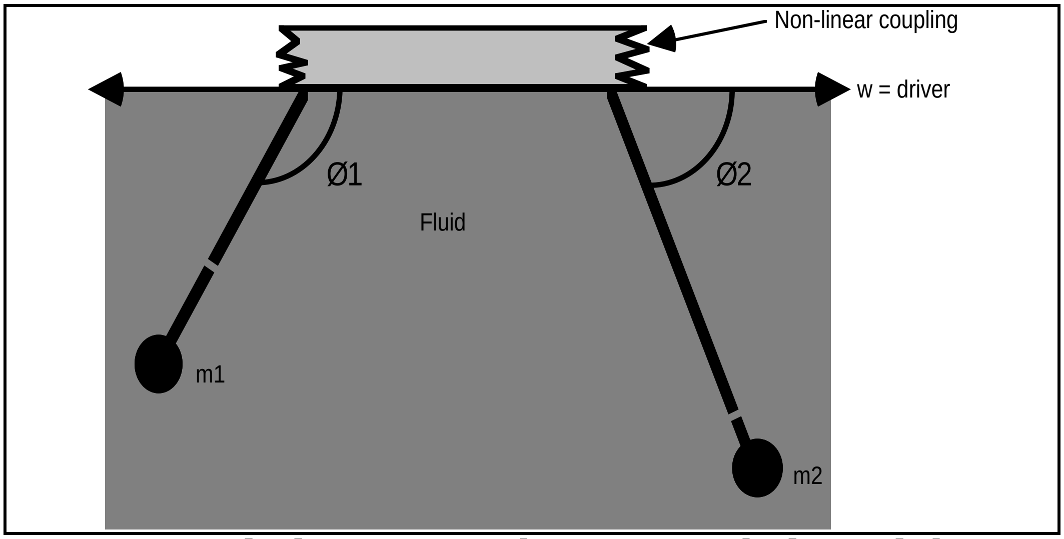
Why this complex?:

1. Structural Robustness of Behavior.

2. Universality.

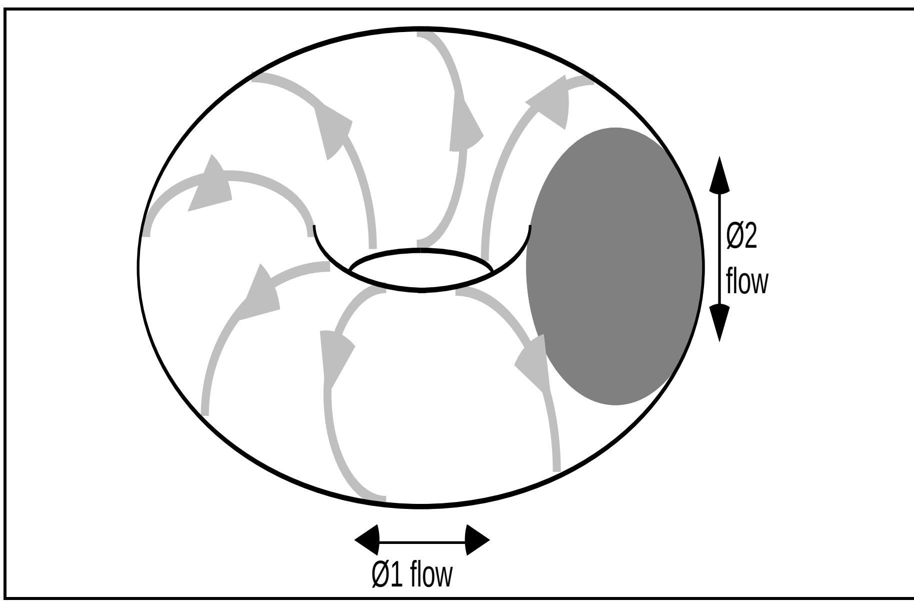
Universality: Difficult (if not impossible) to write out equations of motion for the systems because of the variable chaotic dimensions involved (both in the robot and from the environment), but fortunately we can bound them because the dynamic parameters are **Globally Organized** (so we study Domains in Parameter Space for various maps and characterize typical behaviors (**Principle of Genericity**).

The control systems discussed have a **dynamic** μ **space** that couples to the world [fractality] and uses it to compute its dynamics. A generic model can be visualized as follows:



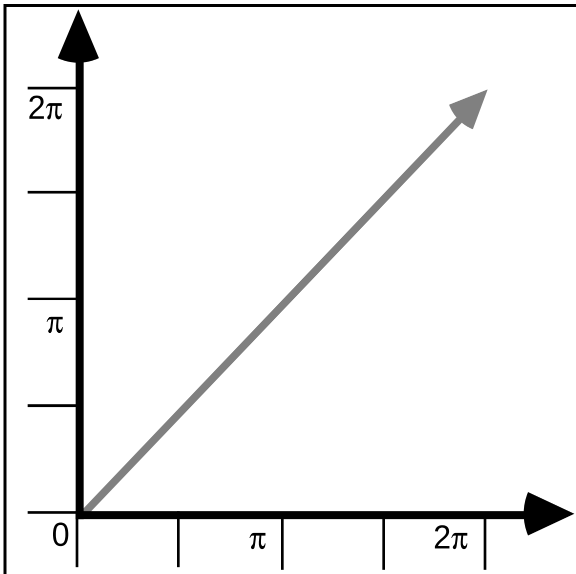
Damped, driven, non-linear coupled pendula.

Dynamicists Torus (2 Torus)

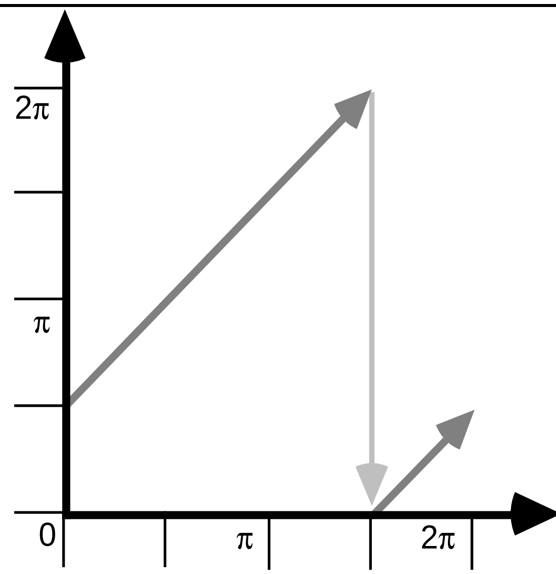


Example of two oscillator two-torus with directed theta flows which can map onto unfolded linear space as follows:

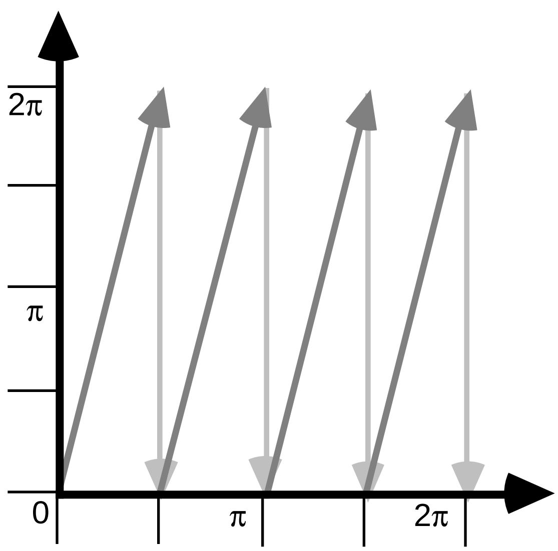
(Example Ø1 vs. Ø2 plots)



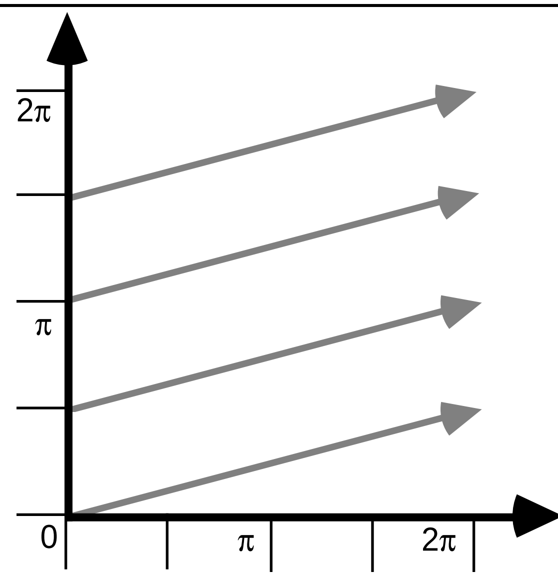
Ex: "Unfolded" 2-torus, phase matched.



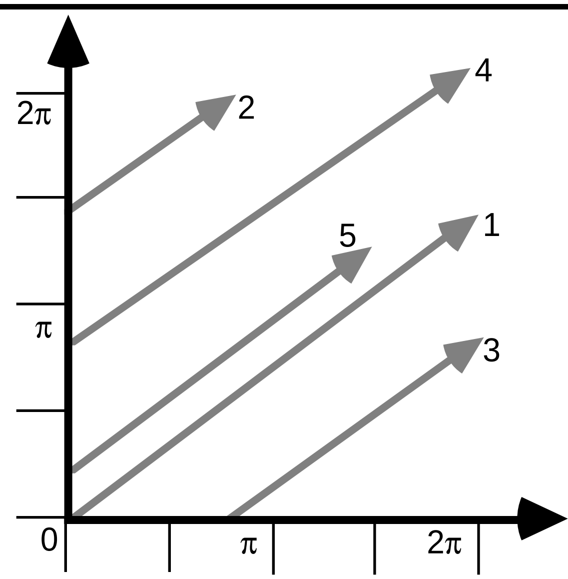
Ex: π/4 phase delay.



Ex: Classic Harmonics



Ex: Classic Sub harmonics.



Quasi-Periodic Irrational Winding of 2 Torus. In real-world systems with uncontrolled perturbations, this is the general case; the windings eventually cover the entire surface area.

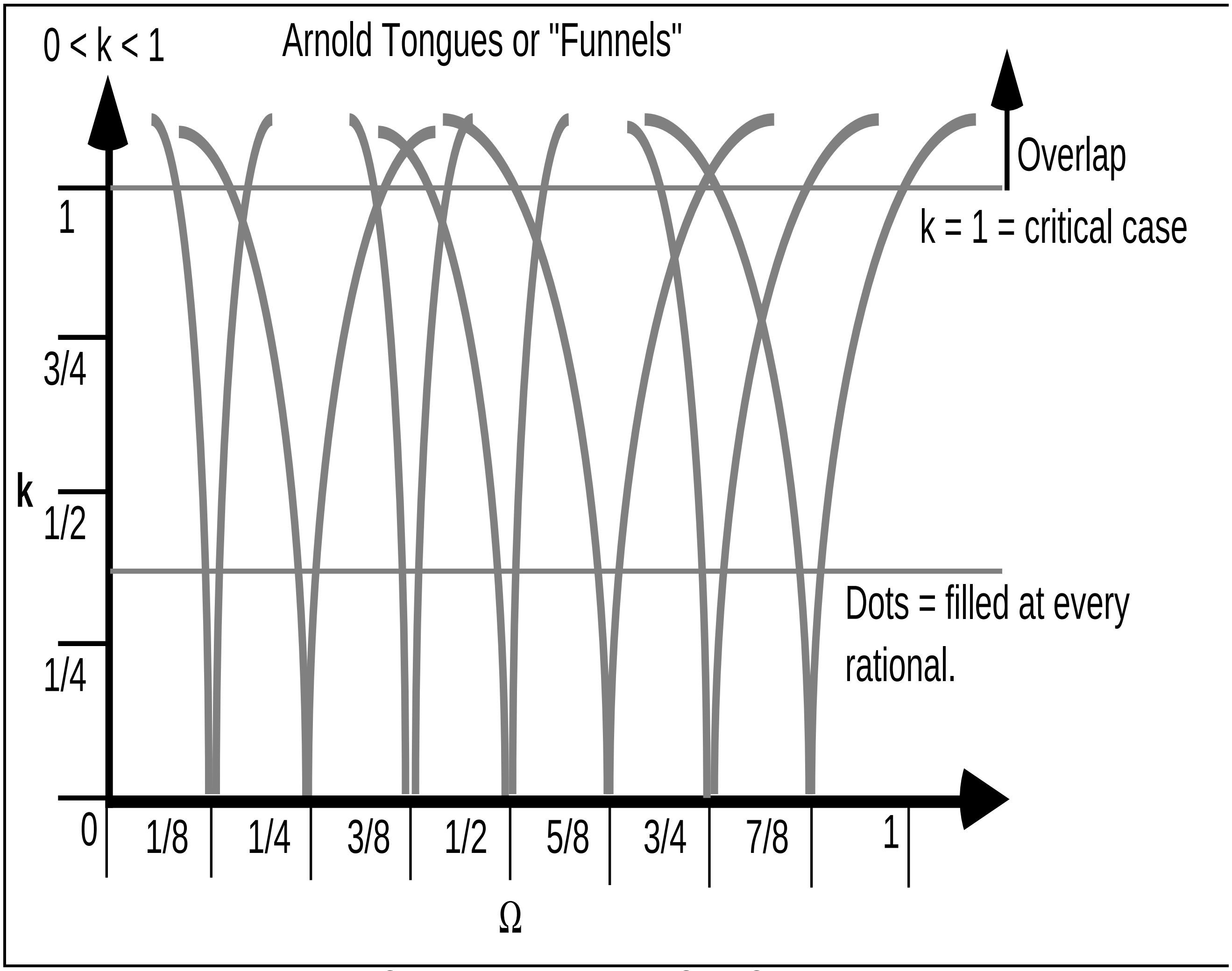
Response to Driving Terms of 2 Non-linear Oscillators: Arnold Tongues and Critical Regions:

If Ω = A winding number; the number of times the combined orbits wind or cover the torus, then **Ω = f1/f2**, where fx represents the unperturbed frequency of the individual oscillator systems.

k = As the degree of driving of a non-linearity, k represents a scalar. For example, as in **Arnold's Circle Map**:

$$\mathbf{Ø \rightarrow Ø' = Ø + \Omega - (k/2\pi)\sin(2\pi Ø)}$$

(Where the sine function is a convenience, any reasonable periodic function will do.)

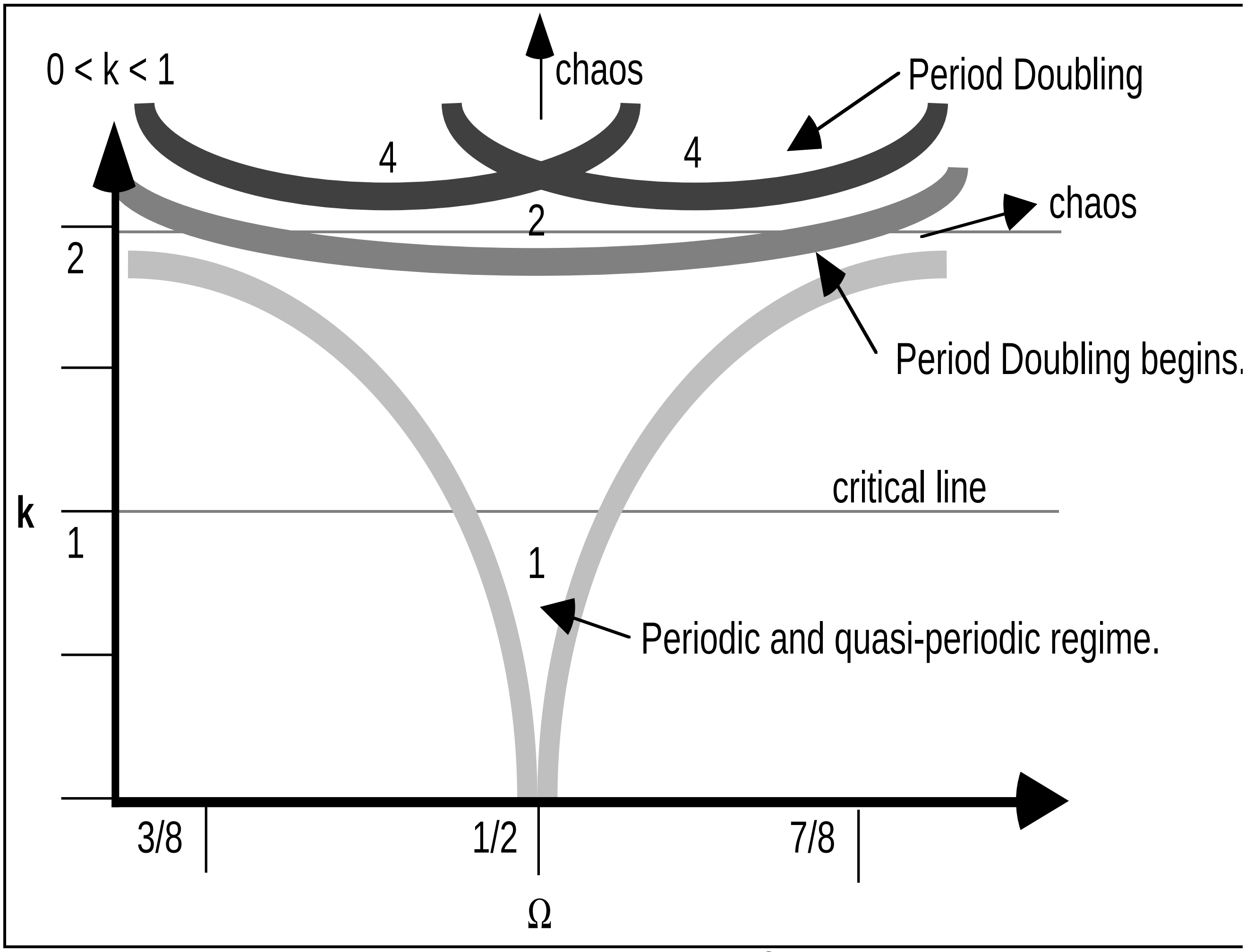


Range of non-linearity of k from 0 to 1:

In this range of non-linearity of k up to 1, there are almost no irrationals locked. Mode locking is multiple and rational and at all rationals under external driving we get periodic and quasi-periodic orbits, supporting the **Peixoto Theorem**.

Above k = 1, the critical line, the situation is very complex (tongues overlap, hysterisis [which could account for the evidence of "short-term learning" in these systems], multi-stability regions and soon chaos).

Global Portrait of Sub harmonic Structure of a simple Arnold Funnel: Supported by both theory and experiment.

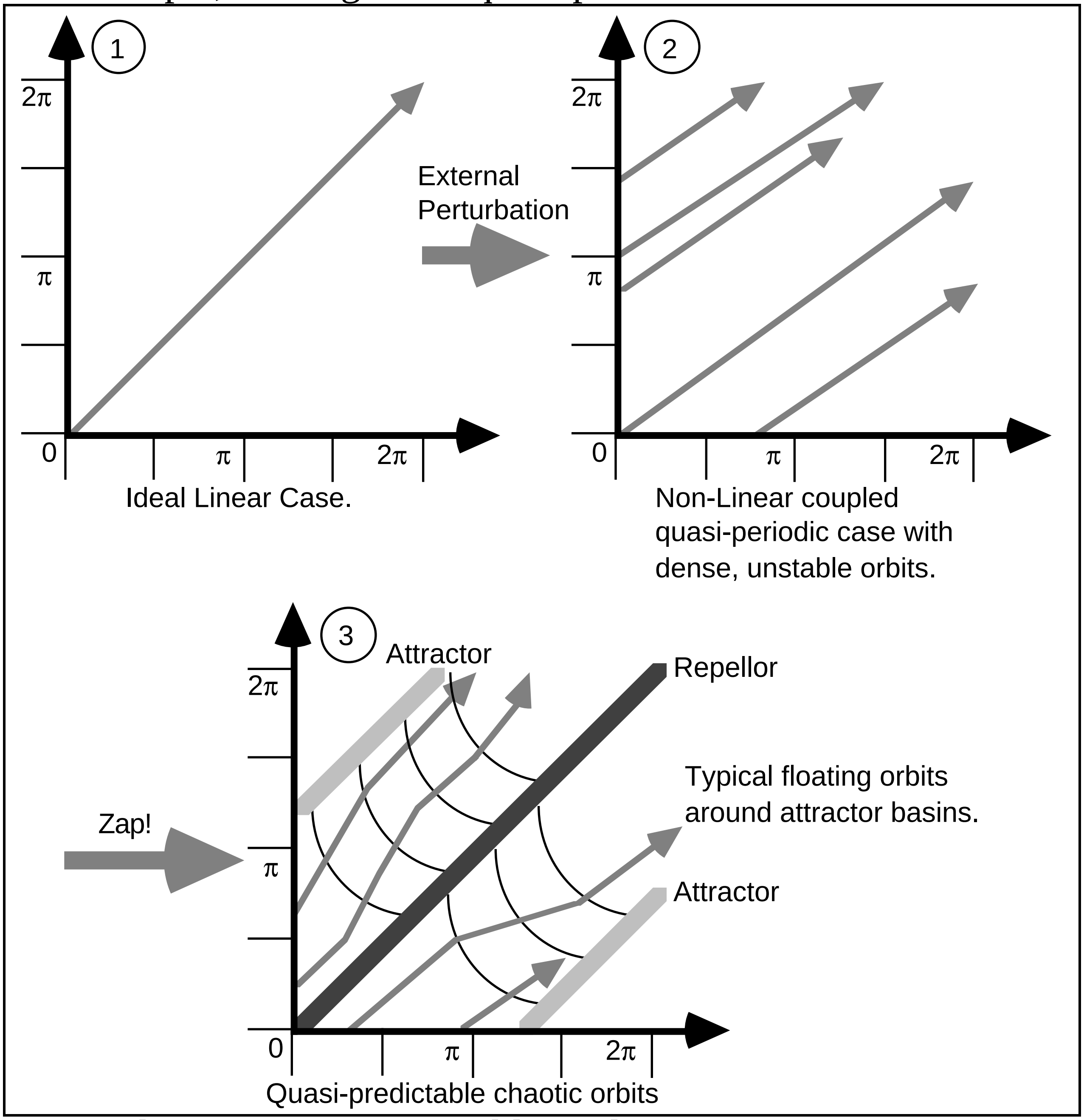


So the machine **"adapts"** by hopping from tongue to tongue depending on the coupling strength k; the feedback of the world onto the non-linear system. This way the machine can alter its global behavior into **"basins"**, the Biomech classic example being the emergent **walking gaits** or **search modes** that combine to form the capable **general problem solving ability** seen in all such systems.

Peixoto's Amazing Theorem:

This theorem on structural stability for **general** motion of coupled oscillators on a 2-torus (circa 1960) is the **complete** theoretical foundation for the adaptive behavior of biomorphic machines.

For example, in the generic quasi-periodic case:



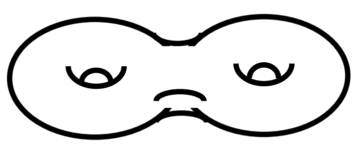
Where "Zap!" is a variable settling/convergence time.

Peixoto's Theorem states that <u>a finite, even number of closed trajectories will always phase lock between alternating attractors and repellors.</u> That is, the attractors are bisected by a giant repellor orbit basin. This leads to unpredictable but bounded braid structures on the torus surface (still structurally unstable under external perturbations), but **any random walk in this extended phase space is immediately converted to motion on an attractor basin.**

The bottom line is that it's both robust and flexible in all the right places.

Such dependence on bounded structure rather than predictive certainty (rendered plausible by **Peixoto)** is what constrains the behaviors into function rather than chaos. This implies that to scale the systems into higher degrees of function, the coupling between tori cannot be higher than the criticality threshold, but also not lower than the purely chaotic threshold. **Biasing considerations are thus crucial for effective designs.**

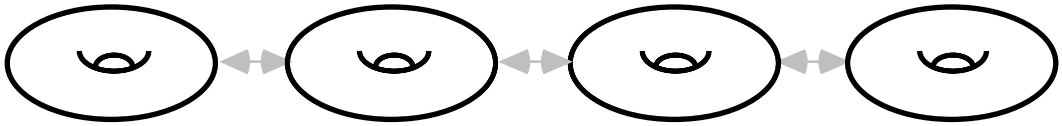
For example, such a conclusion immediately rejects the following configuration from having stable, useful states:



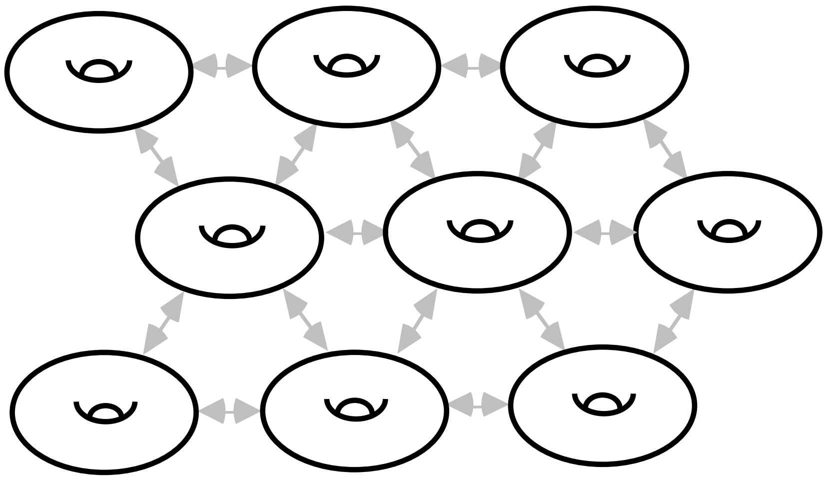
Double Punctured 2-torus; a Hyperbolic space which can only be chaotic.

And experiment has certainly proven this so.

Whereas the following tori configurations can and do have stable operating regimes:



A beaded chain of sub-critically coupled tori (as could be used in an adaptive "robo-centipede" design for example.



An example of a "Wave Processor" configuration, A cluster of sub-critically coupled tori.

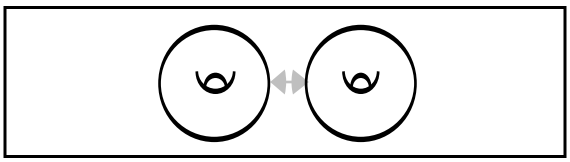
The last example being the design of a two dimensional, hexagonally beaded Nervous system. Many others are possible provided the coupling stays below the "puncture" threshold of the tori. In this case, the results of interaction mimic many fluid-turbulence characteristics and is thus called a **"Wave-Processor"**, useful in everything from retinas to cooperative robot "hive" organisms.

Chaotic Engineering:

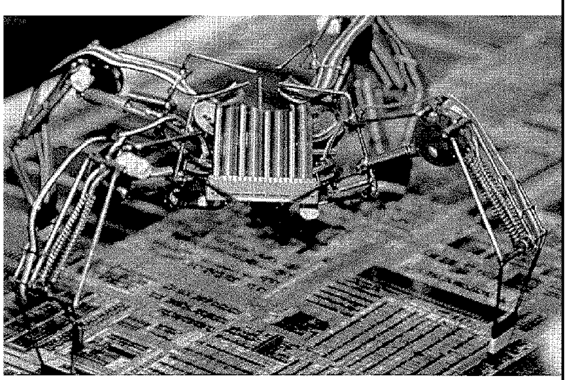
A real advantage of coupled non-linear tori design is that it directly maps into the real world circuits necessary to build a Biomech creature.

For example, in a standard, semi-symmetric four legged Biomorph Design Structure, the following map is one-to-one. The most complex biomorph so far designed has a 12 Nv core and 8 motors on a single, suspensive platform, all designed from a simple double 2-torus design.

That is, this...

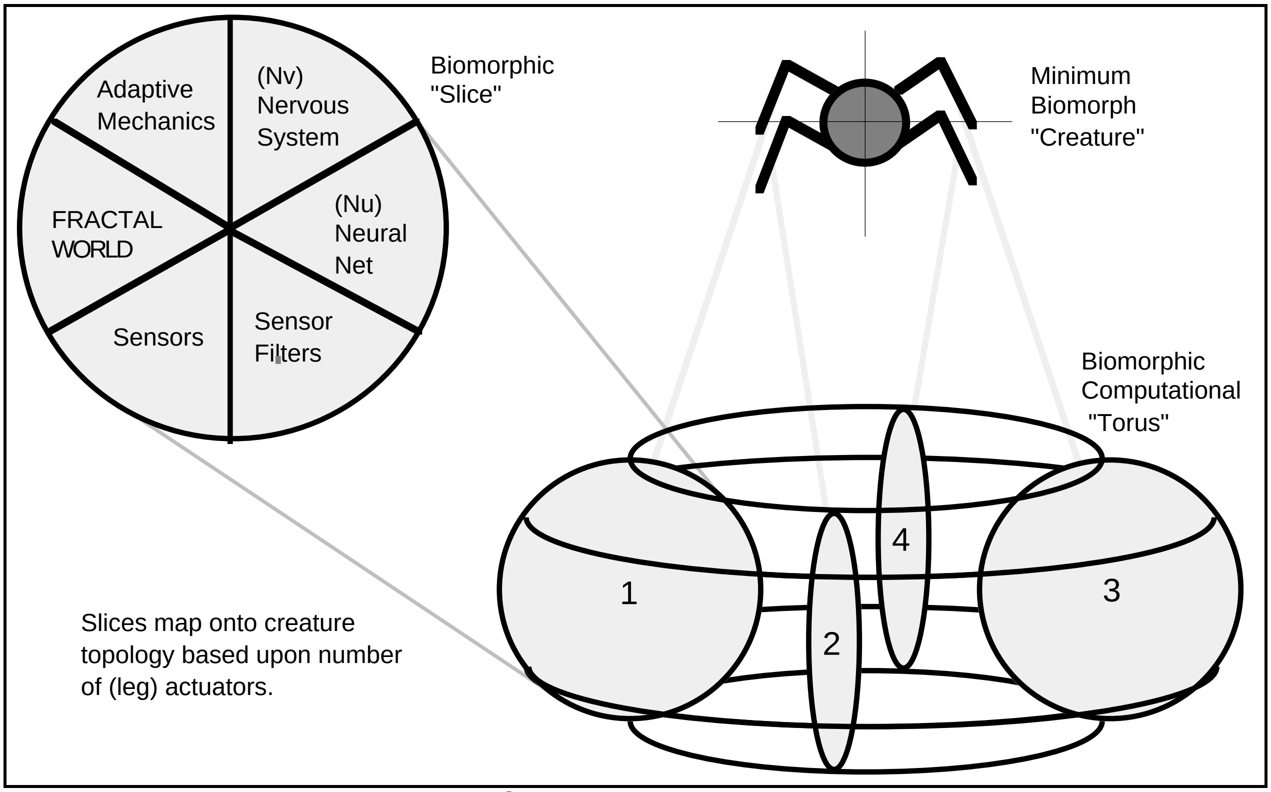


...becomes this...



VBUG 1.1 "SPYDER":
SIngle battery, 1.4Kg., Metal constr. exoskeletal framework, 2.5 DOF per leg.
Control Core (Experimental):
2 linked "microcore" Nv structures with adaptive linkages, 4 trans Nu "head".
Total: 28 transistors.
Emergent Behaviors:
2 quasi-independant control structures converge on a cooperative quadralaterally symetric walking gait after only 4 steps.
Leg independence allows for directed action/response despite chaotic control.

...through this.



A Design map of necessary Biomech elements.

Conclusions:

- There are minimal, elegant solutions to real world complexity.

- Nervous nets would be an excellent "buffer" to allow neural nets (and other controllers) to handle fractal worlds, but Nervous Nets seem sufficient by themselves.

- Chaos Science is a valid engineering discipline, but it needs further work to formulate analytical tools.

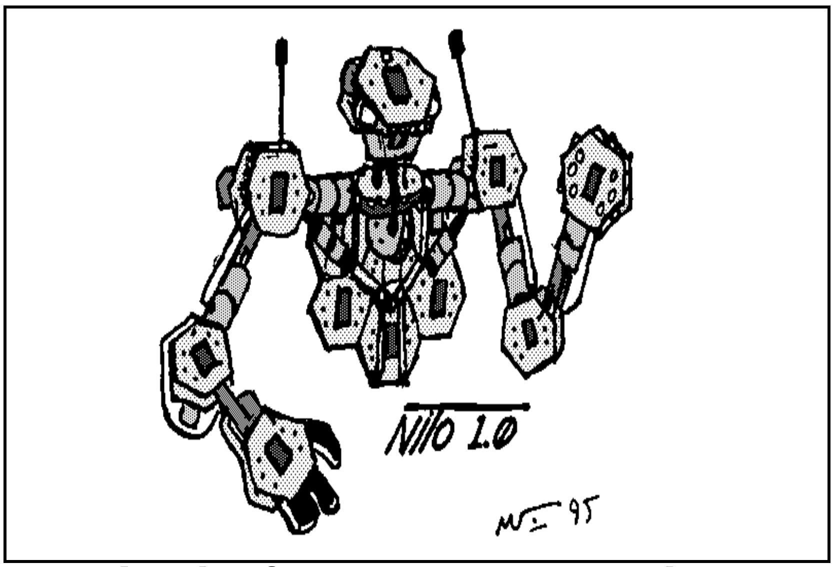
- Differentiating Nv neuron structures seem capable of short-term learning behavior, that is, they anneal into temporary solution abilities.

- We ain't seen nothin' yet. The field is just barely cracked.

Prospects:

Since the start of research in the spring of 1994, development of this technology has advanced to solving currently difficult sensory and cognitive problems. The goal is the reduction of currently complex systems down to an inexpensive but robust minimum. Further efforts are also being made to apply this control strategy to the expanding **nanotechnology** field. At the nanometer scale Nv's may prove more feasible than nano-computers for control of self-assembling micro structures.

Big Question: Is the Nv survivalism paradigm sufficient to emerge forms of complex AI learning? Work into a device for the testing of complexity structure optimization is under way.



A preliminary sketch of "Nito 1.0", a complete 212 transistor compliant anthropoid.

Nito 1.0 (**N**ervous **I**ntegration of a **T**orso **O**rganism) combines features from all current research areas of Biomorphic Technologies into one machine with a goal to exploring the internal dynamic space between bounded value Nervous Network tori.

Biomech Tech:
Pointers to Electronic Info Sources:

For copies of papers or just discussion, the following are accessible:

WWW sites:

Homepage - http://sst.lanl.gov/robot/

Photos, plans, kits - http://solarbotics.com

Pointers to 371 active BEAM Robotics links.

http://www.ee.calpoly.edu/~jcline/beam-links.html

E-Mail:
Theory - <bhass@raptor.lanl.gov>
Applications - <mwtilden@lanl.gov>

Real-Mail:
Mark W. Tilden,
MSD454, LANL,
Los Alamos, NM 87545,
USA.

Phone: Brosl - 505/455-2657
Mark - 505/667-2902

Further Reading:

1. Tilden, M. W., "BEAM 4: The International BEAM Robot Olympic Games Rulebook", Los Alamos National Laboratory (LANL) Press, Los Alamos, New Mexico, USA,. Jan. 1995, (LALP-95-29)

2. Hasslacher, B., Tilden, M. W., "Living Machines", ROBOTICS AND AUTONOMOUS SYSTEMS: The Biology and Technology of Intelligent Autonomous Agents. Editor: L. Steels. Elsivier Publishers, Spring 1995. (LAUR - 94 - 2636)

3. Tilden, M. W., "Biomorphic Robots as a Persistent Means for Removing Explosive Mines", Symposium on Autonomous Vehicles in Mine Countermeasures Proceedings, U.S. Naval Postgraduate School, Editor: H. Bayless, LCDR, USN. Spring 1995. (LAUR - 95-841)

4. "Genesis Redux: Experiments Creating Artificial Life", Author Ed Rietman (ear@clockwise.att.com). Windcrest/McGraw Hill, 1994, ISBN 0-8306-4503-9. Pgs 295-301.