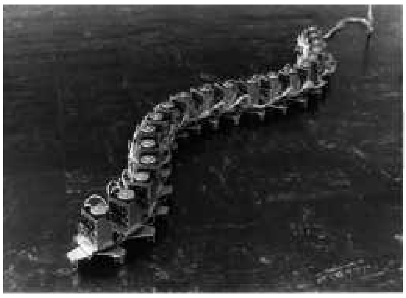
Walking machines:

0-legged-robots

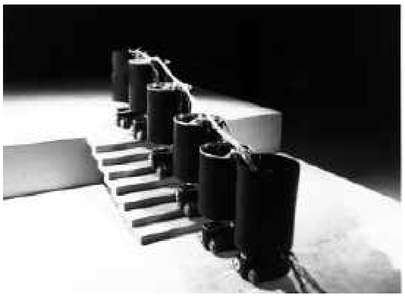
(only snake-like robots, so far)

A compilation by Christian Düntgen

Pictorial Overview on Crawling Robots



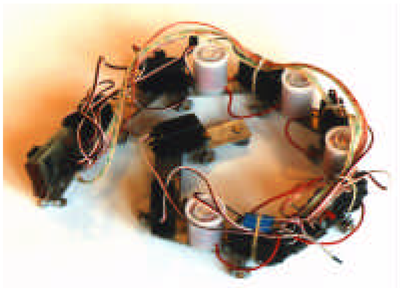
ACM III



KORYU I

KORYU II

OBLIX

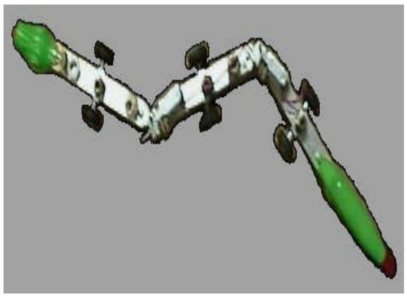


Chabin's snake

GMD-Snake

GMD-Snake2

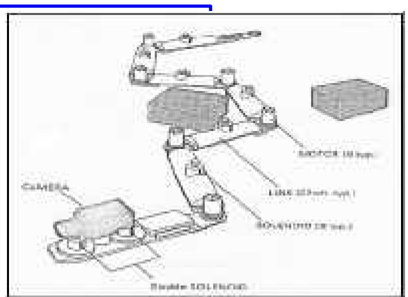
JPL-Snake



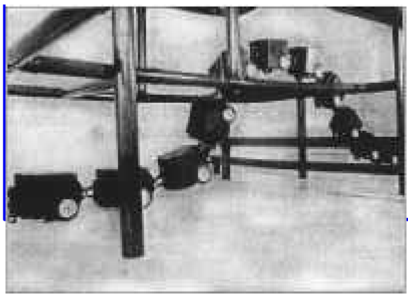
Mita-Lab Snake

NEC-'Quake'-Snake

Snakey

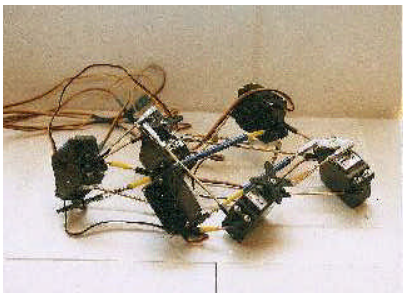


Shan's Snake

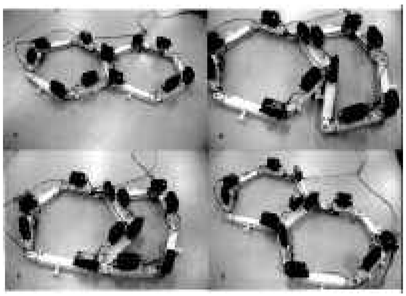


ATMS

KAA Snake



'Henrietta'



JHU Metamorphical Robot

Model

I. **Motivation**

Snakes populate wide regions of our planet. They use different methods to move within varying environments (sand, water, solid surface, within trees, ...). They can even climb obstacles and pass rough, smooth and slippery surfaces. Robotic snake might be used to inspect pipes and underground locations or to explore rough territories. As snakes have a lot of degrees of freedoms, their construction pattern is interesting for manipulators e.g. to work with dangerous materials.
Snake-like architectures' high degree of freedoms and allow three-dimensional locomotion and a lot of other tasks as gripping, moving or transporting objects with the body.

Advantages of snake like motion

1. Terrainability
   Snake like robots can traverse rough terrain: they can climb steps whose heights approach its longest linear dimension, pass soft or viscous materials, span gasps, etc.
2. Traction
   Snakes can use almost their full bodylenght to apply forces to the ground.
3. Efficiency
   Low costs of body support, no cost of limb motion. But: high friction losses, lateral accelerations of the body.
4. Size
   Small frontal area allows penetration of smaller cross-sectional areas than man-equivalent legged or wheeled vehicles.
5. Redundancy
   Serpentine vehicles consist of many similar segments. The loss of function of some of these may be compensated, though some efficiency will be lost.
6. Sealing
   The surface of a serpentine vehicle is small and does not need to be exposed to the environment in the same way as limbs. This provides advantage to applications in hostile environments.

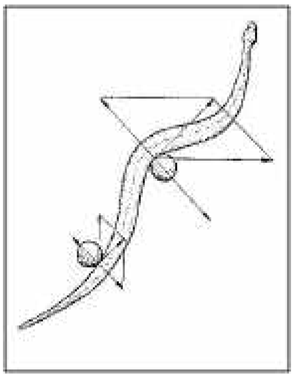
Disadvantages of snakelike motion

1. Payload
   Transport of materials is difficult until an integral conduit is used.
2. Degrees of Freedom
   A large number of actuators is necessary. This provides problems to motion planning and control.
3. Thermal Control
   The long stretched form of snakes makes thermal control somehow difficult.
4. Speed
   Robot snakes are far slower than their natural counterparts (reaching speeds up to 3.0 m/s) and far slower than wheeled vehicles.

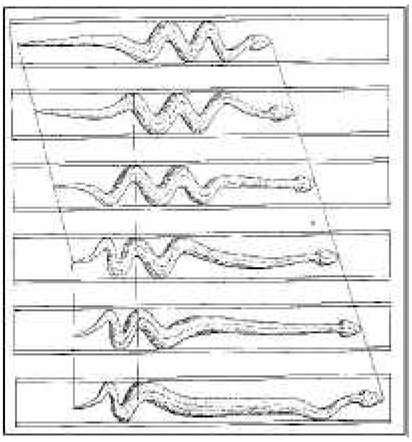
II. Biological/mathematical model

Snakes use different mechanic principles to move. The most frequent are:

A. **lateral undulation**
   "Waves of muscular contraction and relaxion propagate from front to rear. Each point of the body slides along a single track on the ground, without any static contact." (Worst '98).
   - efficient way to progress
   - needs wide space
   - does not work on smooth surface
   - movement hindered by great body mass

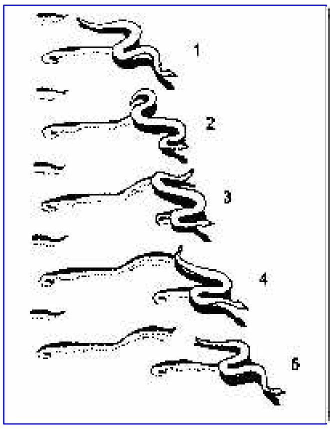


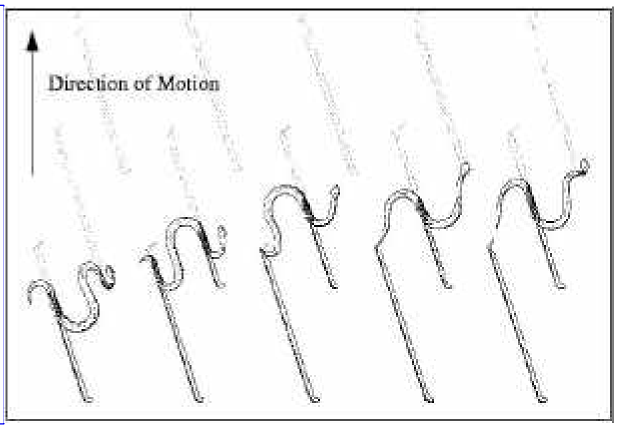
B. **concertina progression**
   Sequential folding and unfolding of the body used differences in static and dynamic friction along different parts of the body.
   - works even in narrow spaces
   - inefficient



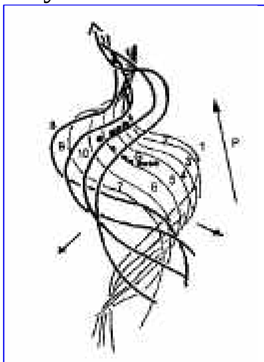
C. **sidewinding**
   Continuos alternating waves of lateral bending while maintaining only two contact points to the ground. Thus, the body is shifted to the side.

- relatively efficient
- useful on soft grounds
- not in narrow locations

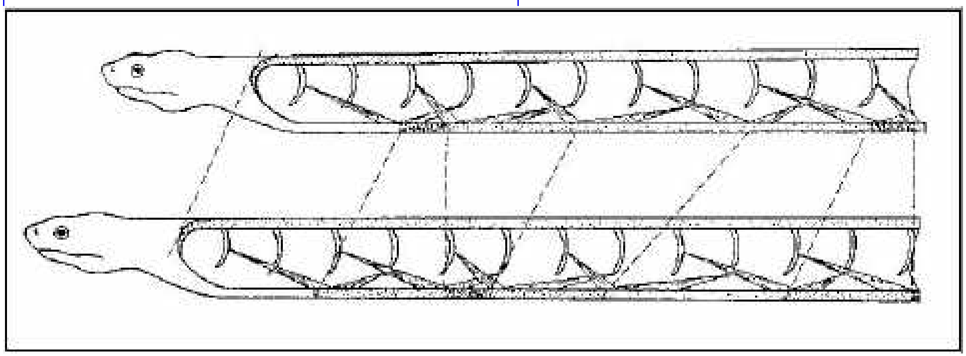




D. **slide-pushing**
Quick waves from head to tail propulse the body as a reaction to slip friction. The belly scales provide the outcome of a forward movement.
- works on low friction surfaces
- very ineffective



E. **rectilinear motion**
Muscles shift the skeleton with respect to the skin. Waves of muscular contraction along the body propulse the whole body. Traction to the ground is enabled by belly scales.
- works with heavy bodies
- effective



F. Other gaits
There are nummerous other types of locomotion, e.g.
1. jumping,
2. rolling around the spinal axis,
3. usage of obstacles to push off from,
4. worm-like motion.

By now, robotic snakes implemented all these methods:
1. lateral undulation (A: ACM III),

2. concertina progression (B: Shan's Snake),
3. sidewinding (C: GMD-Snake),
4. slide-pushing (D: Sniky),
5. rectilinear motion (E: Snakey).

III. Implementation

A. Simulation

In most cases, simulators have been used to develop or learn and test programs for the snake's movement. The results of learning on a simulator can be used as a foundation for further learning on the real robot system. Simulators have been used with GMS-Snake, with L. Dowling's snake.

B. Hardware

A lot of different serpentine robots have been implemented by now. A pictorial overview can be found on the top of this page.

Technology

I. Controller

Special solutions have to be found to move in a serpentine way. Special problems in controlling serpentine robots are:

1. Uncomplete knowledge
   Under working conditions, a robot has only uncomplete knowledge of its environment. Motion planning must contribute to this aspect.
2. Large number of DOF
   The biggest problem is to cope with the grieving problem of the large number of degrees of freedom (respectively actuators and sensors). Possible solutions are the use of symmetries in motion sequences, distributed control systems, and machine learning techniques.
3. Motion planning
   As serpentine robots do wide lateral motions, a special kind of motion planning is necessary to avoid obstacles and to reach certain destination points. If the vehicle is capable of different gaits, the controller should select the most feasible for its momentary situation. Work on this research area has been done by Choset & Burdick who introduced the Generalized Voronoi Graph (GVG) as a roadmap..

A. Motivation

To gain a serpentine movement, the snake robot has to generate sinoid body-motions. Structures used to generate actuator-commands to generate such a kind of movement are:

1. Besselfunctions (Hirose)
   Hirose used a combination of trigonometric functions to calculate what he calls a 'serpenoid curve'. This curve is very similar to real snakes' movement and is used to calculate the positions for each joint. The formula used to compute this "backbone curve" follows:

$$x(s) = sJ_o(\alpha) + \frac{4l}{\pi}\sum_{m=1} \frac{(-1)^m}{2m} J_{2m}(\alpha)\sin\left(m\pi\frac{s}{l}\right)$$

$$y(s) = \frac{4l}{\pi}\sum_{m=1}^{\infty} (-1)^{m-1} \frac{J_{2m-1}(\alpha)}{2m-1}\sin\left(\frac{2m-1}{2}\pi\frac{s}{l}\right)$$

2. Fourier
   Fourier functions are a primitive way to calculate the joint positions to obtain some

certain backbone curve.

3. Parametric curves (Chirikjian)
   Polynomial with more than 20 parameters are used to calculate the backbone curve.
4. Tables and Masks
   For each time step the joint positions are saved in a table. By using masks, a continuos movement can be generated.
   To generate more complicated motion patterns, time/joint matrices are used.

B. **Architecture**
   The easiest way is to adapt the Tables and Masks solution.
   In most cases, one main controller is used to determine the robot's general intention and to send commands to to belly sections. Each section is provided with its own controller, which is connect to other segments and to the main controller via a serial bus.

II. Energy supply

Autonomous power supply is only implemented in few robot snakes (e.g. KAA, PIRAIA, NEC-Quake-Snake). In most cases the energy is provided by a wire connection, thus limiting the snake's range.
Some exemplary data on the GMD-Snake:

- capacity of the battery pack: 47 Wh
- power consumption of built in electronics 20 W, plain motion 25 W, lift of head and 2 sections 40 W

III. Mechanics

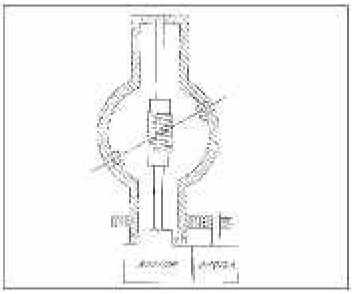
A. **Architecture**
   Robotic snakes are composed from at least 2 or more similar "belly" modules chained together in some way. In most cases, there are additional "head" or "tail" modules providing special sensors, actuators or power-supplying components. The inter-module connection points may be joints or simply stiff connectors.
   Some snakes (ACM) use passive wheels to lessen friction. Others (NEC-Snake) use additional plates that can be used to improve stability in working or spanning situations.

B. **Frame**
   There are three types of frame prevailing:
   1. stiff tubes (OBLIX, NEC Snake, JPL Serpentine Robot, PIRAIA)
      This implements some kind of exoskeleton. It is an easy way to protect the robot's mechanics from external hazards.
   2. unframed functional modules (ACM III, KORYU KR-I & KR-II, Snakey)
      This is somehow working like an endoskeleton and the simplest solution. Protection to the mechanics has to be provided by capsulation of single parts.
   3. ribbed structure - eventually bearing some kind of skin - (GMD-Snake)
      This solution is - for my part - the most convenient. It can provide necessary protection to the inner mechanical parts, bear a skin (necessary for some kinds of snakelike motion) and can be build light weighted.

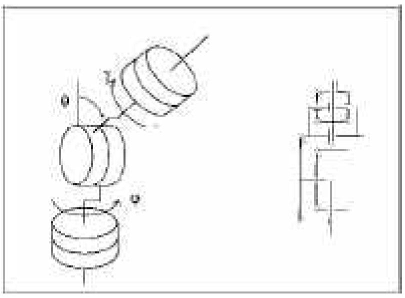
C. **Joints**
   1. simple joints (1 DOF)
      Simple joints are used to allow a robot for bend into horizontal or vertical direction. They are easy to control and very cheap.
   2. ball-and-socket (2 DOF)
      Mostly used in architectures that use stiff tubes as a frame for the robot.
      Ball-and-socket joints are somehow difficult to be controlled with actuators. There are some approaches to construct special-purpose joints for use within robot snakes. They are somewhat expensive but allow the connected modules to act mostly independent from each other.
   3. flexible connection (2 DOF)

Flexible connection can be implemented by using rubber or other elastic material that can be bend easy in any direction. This is used in GMD-Snake. It is easy to use in a combination with string-and-winch actuators.

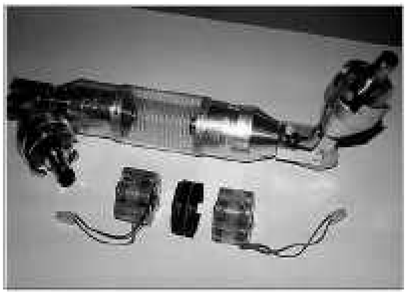
4. special joints
   big efforts are made to develop special purpose joints for robotic snakes, that provide up to 3 DOF.



rotating joint [Ikeda/Takanashi]



NEC-Snake's joint



PIRAIA-joint

IV. Sensors

A. **Tactile sensors**
   Bumpers are used to sense contact to the ground and solid obstacles.
B. **Light sensors**
   Light sensors are used to measure distances to obstacles or to calculate some direction to creep to. In most cases, they are placed within the snake's "head"-module.
C. **Joint-position sensors**
   Special sensors are used to inform the robot of the positions and bending of it's joints. This sensors may consist of potentiometers, tension-sensors, reed contacts, revolution-counters, ... Joint-position sensors are needed for each degree of freedom.

V. Actuators

Snake like robots should not use driving wheels for moving, but bending and stretching or other forms of changing their form (as described before). To achieve these motions, different types of actuators are used, almost all are powered by Electro-magnetic motors (e.g. servos):

A. **motor-lever actuators**
   A motor is shifting a lever transmitting its force, e.g. to bend a joint.
B. **motor-direct actuators**
   A motor is directly connected to a part to be rotated around the motor's axis.
C. **string-and-winch actuators**
   A motor drives a winch to control the length of a string. Thus the string can be used to bend a joint. This mechanism drives the GMD-Snake.

However, some snake robots (GMD Snake2) use driving wheels to move. This allows for higher velocities and allows the snake to locomote much faster.

VI. Skin

Serpentine robots make essential use of their bodies' friction. Additionally, for some gaits specially structured surfaces are required, that emulate the functions of a real snake's scales (this

is providing a higher friction to backward movements of the body, but a low friction to forward motions). The skin has to be elastic to accommodate the body's movements.
So, development of adequate skins for robot snakes seems to be useful.

Applications

- **bridge inspection, inspection of pipe systems (e.g. Kaa snake, GMD Snake2)**
- **minimally invasive surgery**
- **search & rescue, e.g. in collapsed buildings (e.g. NEC-Quake snake)**
- **elephant-trunk-like manipulators**

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II. Links to collections of electronically available papers

- A good collection on different robotic-related papers can be found at http://robby.caltech.edu/papers.html.
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4. Chirikjian G.S.,Pamecha A.,
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JHU Technical Report, RMS-9-95-1.
5. Richard Mason and Joel W. Burdick,
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6. Pamecha A.,Chirikjian G.S.,
A Useful Metric for Modular Robot Motion Planning,
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7. Chirikjian G.S.,

***Kinematics of a Metamorphic Robotic System*,**
IEEE International Conference on Robotics and Automation, pp449-455, May 1994.
8. Peter Dittrich, Andre Skusa, Wolfgang Kantschik, and Wolfgang Banzhaf,
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GECCO'99, Orlando, 1999.
9. Peter Dittrich, Andreas Buergel and Wolfgang Banzhaf,
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Robotics and Autonomous Systems (submited), 1999.
10. Peter Dittrich, Andreas Buergel and Wolfgang Banzhaf,
Learning to Move a Robot with Random Morphology
In: Evolutionary Robotics, First European Workshop, EvoRob98, Paris, France, April 1998, Proceedings, Phil Husbands and Jean-Arcady Meyer (eds.), LNCS 1468, pp. 165-178 Springer, Berlin, 1998.
11. Andreas Buergel,
Zwei mechanische Systeme lernen ``Laufen''
Diploma thesis at the CS-department at University of Dortmund, Dortmund, 1997.

Links

I. To the project

http://www.cybercomm.net/~alindsey/rw97/snake.htmlhttp://mozu.mes.titech.ac.jp/research/snake/

Information on different snakelike robots and manipulators at Hirose & Yoneda Labs

http://mozu.mes.titech.ac.jp/research/snake/acm3/acm3.html
Active Code Mechanism No.3 (ACM III) (1972-1975)
First artificial serpentine movement.

http://mozu.mes.titech.ac.jp/research/snake/kr2/kr2.html
Articulated Body Mobile Robot KORYU II (KR-II) (1989)

http://mozu.mes.titech.ac.jp/research/snake/kr1/kr1.html
Articulated Body Mobile Robot KORYU I (KR-I) (1985-1992)

http://borneo.gmd.de/RS/snake/
GMD Snake - Robot (1996)

http://ais.gmd.de/BAR/snake2.html
GMD Snake2 - Robot (1998-)

http://borneo.gmd.de/~worst/snake-collection.html
Link-Collection

http://www.sics.se/piraia/
PIRAIA-Project at the Swedish Institute of Computer Science, including a snake robot

http://www.ctrl.titech.ac.jp/ctrl-labs/mita-lab/snake/
First approaches to a new robot snake...

http://kamine.dse.ibaraki.ac.jp/~shugen/snakeE.html
Analysis of Snake Movement and Development of Snake-like Robot
Only few informations, by now...

http://www.gmd.de/FIT/KI/CogRob/Projects/Makro/makro.html
Snakelike multi-segmented wheel driven robot

http://robby.caltech.edu/~chen/res-medical.html
Snakelike robot-micro-endoscope

http://agip.sciences.univ-metz.fr/~mihalach/Copernicus_projet_engl.html
Snake-like Flexible Micro-robot (1995-)

http://ourworld.compuserve.com/homepages/laurent_chabin/snake.htm
Sniky - A Mechanical Snake (1994-1995)

http://mozu.mes.titech.ac.jp/research/snake/snake.html
Overview on different snakelike robots

http://mozu.mes.titech.ac.jp/research/snake/snake.html
Biomechanics of the snakes

http://ourworld.compuserve.com/homepages/laurent_chabin/slither.htm
How Snakes Walk

http://ourworld.compuserve.com/homepages/laurent_chabin/insects.htm
Insectlike, snakelike, ... robots

http://robby.caltech.edu/papers.html
Some papers on Sensor Based Planning, Robot Locomation, etc.

http://robotics.jpl.nasa.gov/tasks/rsi/accomplishments/snake/snake.html
JPL-Serpentine Robot for visual inspection

http://httpsrv.ocs.drexel.edu/~st93yjls/SDP/HTML/fphtml/fpaper.html
Semi-Autonomous Snake-Like Robot

http://www.cybercomm.net/~alindsey/rw97/snake.html
Snake - a combatant at Robot Wars 97

II. To related websites

A. Hyper-redundant manipulators

1. http://mozu.mes.titech.ac.jp/research/snake/oblique/oblique.html
   OBLIX and MOGURA - snakelike hyper-redundant arms (1978-79, 1982-84)
2. http://mozu.mes.titeh.ac.jp/research/snake/endscope/endscope.html
   ELASTOR - Shape Memory Alloy Robot (1980-1986)
3. http://mozu.mes.titech.ac.jp/research/snake/sg/sg.html
   Soft Gripper I, II, III (SG I, II, III) (1976-1984)
4. http://robby.caltech.edu/~chen/res-medical.html
   snakelike robot-endoscope

5. http://uirvli.ai.uiuc.edu/tlewis/pics/snake.html
   R7 - a snakelike manipulator (late 1980's)

B. **Morphologic robots**

1. http://caesar.me.jhu.edu/metamorphic.html
   metamorphic robot
2. http://www.sics.se/~ojala/protozoa.shtml
   Protozoa inspired robot control (1995)
3. http://ls11-www.cs.uni-dortmund.de/alife/rmrobot
   Random Morphology Robot "Henrietta" (1997-)

C. **Other forms of non-legged locomotion**

1. http://mdesign.os.u-tokai.ac.jp/katolab/katolabe.html
   underwater robots
2. http://robotics.eecs.berkeley.edu/~koo/bear.html
   BEAR-Berkeley Aerobot (Autonomous Helicopter) (1996-)

Notes

ftp://publications.ai.mit.edu/ai-publications/1000-1499/AIM-1126.ps
Twilight Zones and Cornerstones: A Gnat Robot Double Feature