

# Softworm: A Soft, Biologically Inspired Worm-Like Robot

Alexander Boxerbaum<sup>1</sup>, Hillel Chiel<sup>2</sup>, and Roger Quinn<sup>1</sup>

<sup>1</sup>) Dept. of Mechanical & Aerospace Engineering, <sup>2</sup>) Dept. of Biology, Case Western Reserve Univ., Cleveland, OH 44106, USA

## Abstract

We have developed several innovative designs for a new kind of robot that uses peristalsis, the same method of locomotion earthworms use, and have recently completed building the first working prototype. This method of locomotion is particularly effective in constrained spaces, and although the motion has been studied for some time, it has not been effectively or accurately implemented in a robotic platform. A new kinematic model and 2D simulation shed light on the limitations of discrete actuators acting on large segments to create this motion. We present a technique of using a continuous braided mesh exterior to produce waves of motion along the body of the robot. The concept is highly scalable, and we present methods of construction at two different scales. We also present a concept for a robot specifically designed for pipe crawling, where it can take advantage of flowing fluid to locomote very efficiently, even upstream.

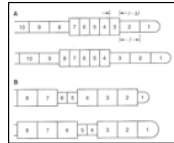
## Previous Work in Peristaltic Motion

A soft-bodied worm-like robot could find many uses in domestic and military applications, where it could be used for inspecting pipelines, patrolling or maintaining tortuous plumbing, for exploring complex underwater structures, or for search and rescue missions in piles of rubble. Miniaturized versions of worm-like robots could find multiple applications in medicine, such as endoscopy or angioplasty.

A previous worm robot was developed using long braided pneumatic actuators (artificial muscles) in series [4]. The robot moved much slower than expected. The power requirements were substantial and required an off-board pressurized air supply. Its unusually slow speed made us re-evaluate our understanding of peristaltic motion. We found that not only our robot, but **all robots known to attempt peristaltic motion use an inappropriately crude approximation by using very long actuators with gaps between actuators.** This is probably a direct result of the way peristaltic motion is explained in the literature, with large blocks illustrating differentially small muscle segments for the purpose of clarity.



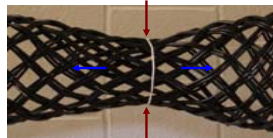
Previous worm robot with 10 cm long McKibben style actuators



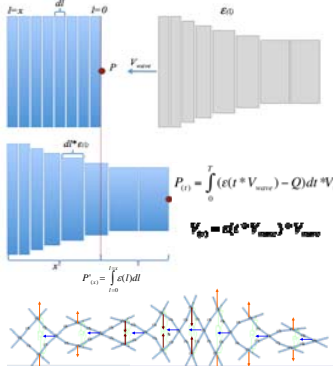
Common misleading diagram

## A New Twist on an Old Material

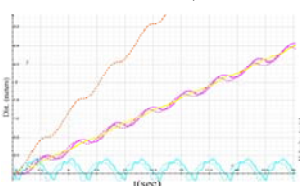
The braided pneumatic actuators in the previous robot used a braided mesh to create a material that has anisotropic strain properties. When it is compressed in one axis, it causes expansion in another. In this case, a bladder inflated a cylinder that caused axial contraction. In this new concept, we use a similar material, but we only squeeze one part of the cylinder at a time. This causes a gradient of deformation that can move down the length of the robot. The result is a fluid motion identical to peristaltic motion.



## A New Differential Model of Peristaltic Motion



We have developed a new differential mathematical model for peristaltic motion. If one knows the waveform that describes the state of the hoop actuators, then the position and velocity of any point can be described as a function of time. This model can also describe robots that have discrete or too few actuators, and explains why they move much slower. We have also developed a 2D simulation of a robot with ten discrete actuators for comparison.



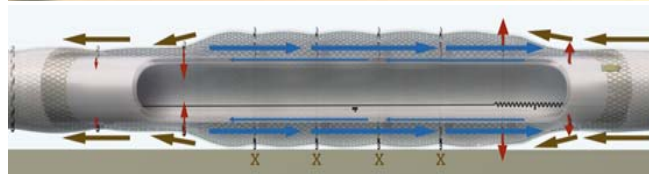
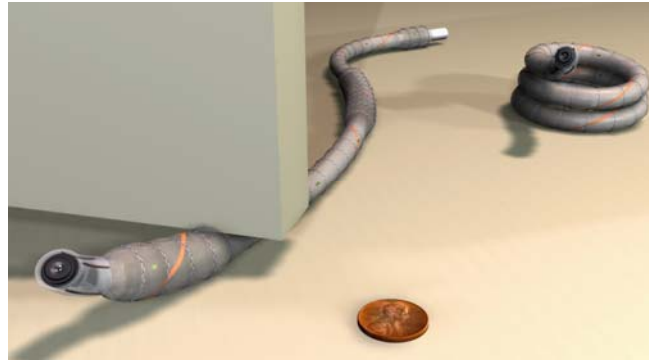
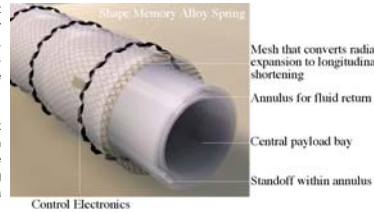
The position and velocity of a single point on the robot. Solid lines are the simulation, while the dashed lines are the analytical model. Tail is velocity, magenta is position. The red dashed line is the theoretical maximum position.

## Applications In Very Small Spaces

### Shape Memory Alloy Concept

This robotic concept is highly scalable. A robot with a diameter on the order of one centimeter would have several applications in medicine, including examination of the entire GI tract, as well as applications in search and rescue environments and military reconnaissance.

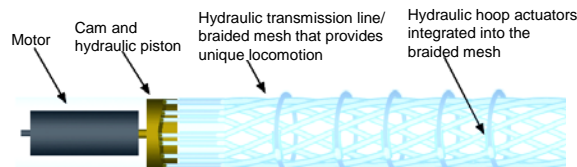
Shape Memory Alloys (SMAs) are a good candidate for actuation at this scale. Micro helix SMAs have length change of up to 200% and can be actuated in under a second. The SMA can be wrapped around the robot, and actuated by wiring that also constitutes the braided mesh. Such a robot could run on as little as 1 watt of power and travel at speeds of 25 centimeters per minute.



At this small scale, it may be advantageous to use a hydrostatic fluid to expand already contracted actuators. In this implementation, a bolus of fluid (**large blue arrows**) moves between the outer skin and the inner payload of the robot by the sequential constriction of hoop SMA actuators (**red inward pointing arrows**). As the fluid is squeezed at the trailing edge of the wave, it causes radial expansion at the leading edge of the wave (**red outward pointing arrows**). The result is the generation of continuous peristaltic waves along the robot, causing it to move in the opposite direction of the wave (**brown arrows**).

### Micro-Hydraulic implementation

An alternative method of actuation is being explored as well. The braided mesh of the robot could be made of hollow tubing and serve as hydraulic lines for micro-hydraulic actuators at each hoop. Hydraulic actuators are generally only effective as pushing actuators, so the natural state of the robot must be elongated and narrow. Expansion at one of the hoop actuators can be achieved by applying pressure at the end of the hydraulic line. This would also allow for mechanical coupling of the hoop actuators, and they could be driven by a single motor at the end. This setup could achieve faster waves, and therefore faster robot speeds than the SMA implementation, but requires an effective micro-hydraulic piston to be developed.



## Applications In Larger Spaces

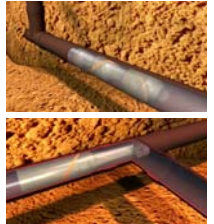
### Current Prototype

A prototype has been built at a larger scale to demonstrate the principles of motion. At a maximum diameter of ten inches, it is scaled appropriately to function in water mains. The hoop actuators are made of steel cable wrapped around the robot, which is fed through the braided mesh made of brake cable sheathing. At one end of the robot, a cam mechanism pulls on the actuator cables in sequence, generating two traveling waveforms. In this way, all ten actuators are controlled with the a single degree of freedom. The robot has successfully moved forward during initial trials.



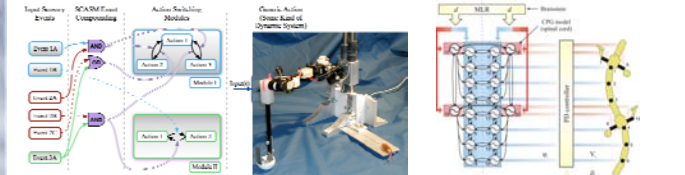
### Water Main Inspection and Maintenance

There are no robotic technologies that can currently examine or maintain fresh water lines without draining them first. Turning off the water grid is a big enough problem that early diagnosis of water leaks is nonexistent. Instead, the leaks are ignored until they have become catastrophic, at a huge cost to infrastructure. The current prototype is completely hollow, and other techniques may be used to make the robot even more effective in a pipe with running water. For instance, the robot could travel down stream by simply detaching itself from the pipe wall when it constricts its whole body. The robot can travel up stream using peristaltic motion. The alternating flow of water around and through the robot may enhance the desired peristaltic waves in the downstream direction, which cause motion in the upstream direction. This suggests that upstream locomotion could be even more efficient than standard peristaltic motion.



### Future Control Work and Neurobiological Modeling

A robot is currently being designed that is similar to the current prototype, but with independent hoop actuators. With this change, the system can be used as a neuromechanical simulation of biological organisms, such as earthworms. Postulated neural control mechanisms such as CPGs and SCASM can be tested, and adaptive behaviors will be explored.



SCASM (Sensory Coupled, Action Switching Modules, POSTER 287.3) [7]

CPG Network[9]

More videos and images of SoftWorm are available at: <http://www.peristalticmayhem.com>

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