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WormBot: Mimicking Earthworm Locomotion

Research Article

Ari Firester[1]*

1 Hunter College High School, New York, NY, USA

Abstract: This research designed, constructed and tested an earthworm-inspired robot that can maneuver through narrow spaces in order to search for survivors in rubble or inspect dangerous sites without risking lives. An earthworm can crawl through dirt or passages little wider than its own diameter. Like an earthworm, the "WormBot" alternately elongates and contracts its body and uses retractable claws to grip its surroundings to prevent it from slipping. This research made use of biomimicry, emulating animals or biological processes, as well as soft-robotics, using pliable parts and actuators to interact with moving environments and flex instead of breaking.

The WormBot is modular, and is built from inexpensive, commonly available parts. It is powered by compressed air, and the control and power components are remote, connected to the robot through a "leash" of thin, plastic air tubes. Thus, a crushed or lost WormBot could be abandoned and inexpensively replaced. The working prototype has an extension section, which can lengthen, bend, or contract using inflatable actuators based on surgical tubing, and two claw sections, each with eight plastic claws that extend and retract. It is controlled by an Arduino microcontroller, which switches electric valves in precise sequences to move the robot.

Additional research will test potential claw improvements, adding more modules, more accurate and repeatable extension, and air pressure sensing to provide feedback to the control programs. With additional research and improvements, earthworm-based robots could save lives in disasters, improve the safety of machinery maintenance, or even assist in minimally-invasive surgery.

Keywords: robotics • earthworm • biomimicry • soft robotics • peristalsis

1. Introduction

The objective of this research was to design, construct, and test the capabilities of a robot that moves like an earthworm. A robot that can crawl into narrow passages or burrow through debris could assist in many situations that routinely endanger human lives. These include searching rubble for survivors after a disaster, pulling wires through pipes or construction, and inspecting toxic or dangerous sites or machines. Many recent advances in robotics have come through biomimicry, or emulating animals or biological processes. Soft robotics,

* *E-mail: arijf1@gmail.com*

which uses pliable, elastic, or soft parts and actuators like the WormBot, can also help robots interact with moving or unpredictable environments and flex instead of breaking.

Earthworms move using a process called peristalsis, whereby the worm alternately elongates and contracts its body using sets of longitudinal and circular muscles. The outside of the worm is covered with tiny hair-like claws called setae, which grip the earth to prevent it from slipping. Unlike most legged animals, a worm can crawl through a passage no wider than the worm's own diameter and can force itself through dirt or other debris.

This research created a modular robot with movement based on the earthworm, built from commonly available parts. The "WormBot" uses pressurized air from an air compressor to lengthen and contract, and to extend and contract plastic claws. It is controlled by an Arduino microcontroller, which switches electric valves in precise sequences to pressurize actuators made of segments of vacuum cleaner hose. The controller mechanisms are attached to the robot through a long "leash" of thin, plastic air tubes.

The current WormBot prototype has front and rear clawed sections for gripping and an extension section that can elongate, contract, and bend. It can crawl on various surfaces. Additional research underway will test potential claw improvements, more accurate and repeatable extension, and air pressure sensing to provide feedback to the control programs.

The WormBot itself is a simple mechanism, which could be inexpensive to produce commercially, and even considered "disposable" if it were cut off from its controller. Since the power and control electronics are remote, a crushed or lost WormBot could be abandoned and inexpensively replaced. With additional research and improvements, worm-based robots could save lives in disasters, improve the safety of machinery maintenance, or even assist in imaging the body, drug delivery or minimally-invasive surgery.

1.1. Background / Rationale

The goal of this research was to design, build, and experiment with a robot that moves like an earthworm. Earthworms move by elongating their bodies in the direction of motion. (See more on earthworm biology below.) They can crawl through dirt and other environments where debris surrounds their entire body. This enables them to move through passages no wider than their diameter and even to clear soft material from ahead of them, to make their own path.

1.1.1. Animal-based Robots

As robotics evolves, many current robot designs use biomimicry - they have copied forms of locomotion from the animal world. Boston Dynamics' famous Cheetah and WildCat robots run based on motions similar to those of cats [1]. HiBot's ACM-R5H snake robot slithers (and rolls and swims) much as a snake [2]. There is even a robot that hops like a kangaroo, built by Festo [3]. See Figures 2, and 3 for pictures of these robots. In fact, DARPA, which has promoted many advances in technology through its famous Challenges, recently announced a Subterranean Challenge, which will require robots - many snakelike - to maneuver through caves, urban "bunkers" and confined tunnels [4].

In addition, the emerging field of soft robotics studies the application of robots with flexible actuators and body components [5, 6]. Soft robotics enables robots to move through and interact with complex or shifting environments, and to bend or accommodate instead of breaking when subjected to unexpected forces, mimicking the properties of biological creatures [7].

1.1.2. Earthworms

Earthworms move by elongating and contracting their bodies. Circular muscles around the worm's body contract its diameter causing it to elongate lengthwise. Longitudinal muscles contract along its length, causing a portion of the worm to grow fatter but shorter [8]. Earthworms extend setae or bristles into the earth around them to hold parts of their body in place [9]. By gripping behind the section of their body that is elongating, a worm can extend itself forward. By gripping ahead of that section, they can then pull the rest of their body forward. (See Figure 1 for a diagram showing how earthworms move.)

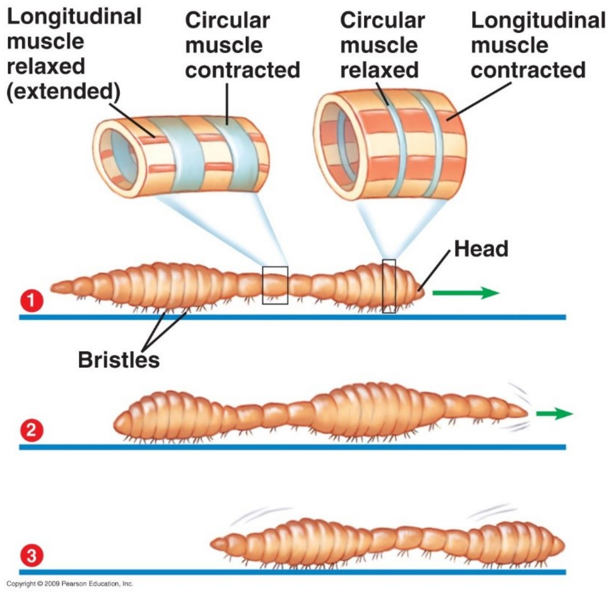
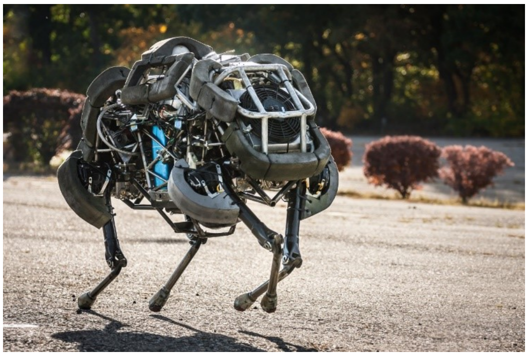


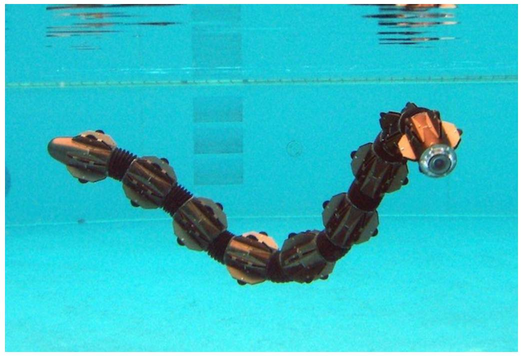
Figure 1. **How earthworms move [10].**

1.1.3. Worm Robots

Various researchers have created robots based on worms, having various types of locomotion. Research at Ben-Gurion University has produced a SAW robot that moves like an inchworm, by "wriggling" its body in a sinusoidal wave [11]. The Compliant Modular Mesh Worm designed at Case Western uses a flexible mesh made of a 3-dimensional web of jointed segments to move via peristaltic action, by shifting waveforms down its body [12]. Scientists at the Swiss Federal Institute of Technology (EFPL) have created a worm-shaped robot that uses vacuum power to bend and stick to surfaces [13]. The Robo Worm designed by EmamiDesign uses magnetization of metal rings embedded into a flexible tube to bend, although it is not clear whether this robot has been constructed or just conceptualized [14]. Stanford scientists have developed an innovative soft robot that grows like a vine, basically by inflating a long, collapsed, plastic bag [15] (see Figures 3, 4, and 5 for pictures of these worm-based robots.) However, the author's research did not find any published examples of robots that use simple mechanisms to move as earthworms do, by elongating and contracting their bodies. Constructing most of the above-described robots would be beyond the resources of this research in terms of cost and complexity.

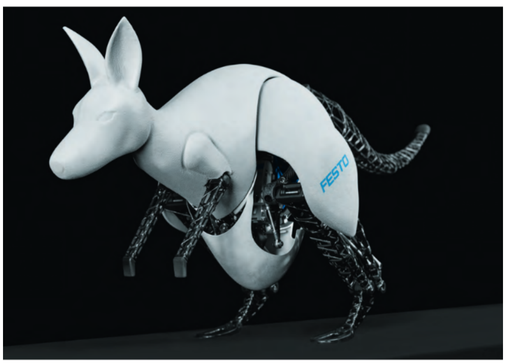


Boston Dynamics WildCat Robot [16].



HiBot Snake Robot [17].

Figure 2. **Examples of robots based on a wildcat (left) and a snake (right).**



Festo Bionic Kangaroo [3].

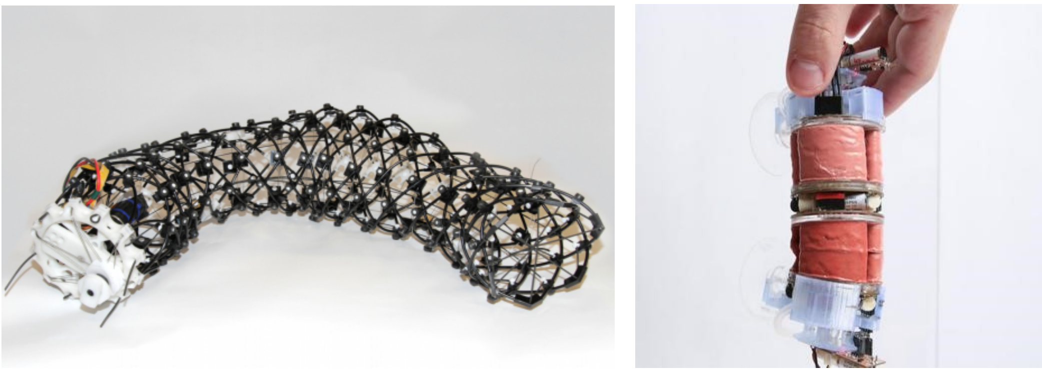
Ben Gurion SAW robot [11].

Figure 3. **Examples of robots based on a kangaroo (left) and an inchworm (right).**

1.1.4. Applications

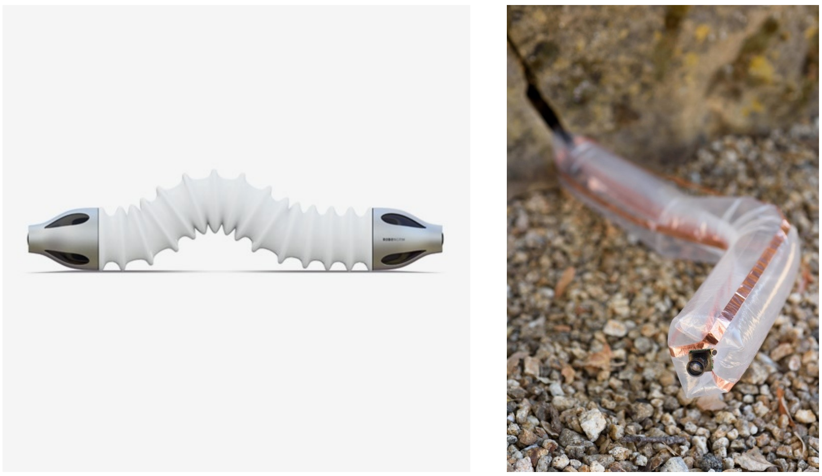
There are many potential applications for a worm-based robot. A robot could be used to crawl through debris, underground passages, or snow to search for survivors in a disaster such as a building collapse, an earthquake, or an avalanche. In addition to finding survivors, a WormBot robot could deliver a communications wire, an air or drinking-water supply line, or a towline attached to heavy rescue equipment. In fact, robotic snakes were used to search for survivors of the 2017 Mexico earthquake [18].

Worm-shaped robots could crawl into otherwise inaccessible holes, narrow passageways, or other constricted and/or dangerous environments, to film, take air samples, or actuate simple controls. Applications might include



Compliant Modular Mesh Worm [12]. EFPL Vacuum-powered robot [19].

Figure 4. **The Compliant Modular Mesh Worm (left) moves by "rippling" waves down its segmented body. The Vacuum-powered Robot (right) contracts flexible cylinders to bend its body.**



EmamiDesign Robo Worm [14]. Stanford Vinebot worm robot [15].

Figure 5. **The Robo Worm (left)uses magnetization of metal rings in a flexible tube to bend. The Vinebot (right) robot grows like a vine, basically by inflating a long, collapsed, plastic bag.**

remediation or damage control in mines, nuclear reactors, tunnels, or large pipes. Robots are also used to inspect machinery in situations where a human entering or inserting his arm might be too dangerous [20]. Example applications might include inspections or damage assessment of, say, a turbine, metal-shaping machinery, or threshing apparatus.

Sufficiently small worm robots might be able to enter the human body to provide pictures, deliver drugs, or even assist with certain types of minimally invasive surgery. The Ben-Gurion University plastic worm robot, which moves by wriggling its body, is envisioned for colonoscopy or endoscopy someday [11]. Scientists at the Max Planck Institute for Intelligent Systems have prototyped a worm-shaped robot made of elastomer rubber and magnetic particles, meant to deliver drugs to targets within the body [21].

Most of these applications involve a worm robot that may get lost, damaged or abandoned. This points to a need for an inexpensive worm robot, made of durable parts, and having remotely located expensive control components. The WormBot's design is simpler than others. It moves simply by extending and contracting its body, just as an earthworm does. The robot is made of inexpensive materials, and the power and control components are separate from the main body, making the worm part "disposable".

1.2. Engineering Goals

The goals of this research were to design, build, and test a worm-based robot that moves like an earthworm, by longitudinally elongating and contracting sections of its body, and using setae-like claws to hold parts of its body in place. Such a worm-based robot could be expected to maneuver through narrow spaces not much wider than its own diameter, and to "burrow" through debris, creating its own path.

Design goals included using inexpensive, readily available parts and construction tools, making it possible for this author to build the prototype at home, and easier for others to expand on this research. Another goal was to separate the power, controls, and electronics from the worm robot itself, so as to make the robot somewhat disposable in case of loss or damage. For example, a worm robot exploring a disaster site could be crushed or lost, but the expensive computing and other machinery would be preserved.

To keep the design and construction simple, it was decided that the WormBot would be built out of plastic, primarily PVC, which is commonly used in water pipes and fittings, and can be easily cut and glued. The WormBot is powered by compressed air from a compressor typically used for powering tools or inflating tires. The robot is attached to the control panel and mechanisms by a long "leash" made up of thin air tubes. Figures 6 and 7 below show the initial design for the WormBot and a prototype, respectively.

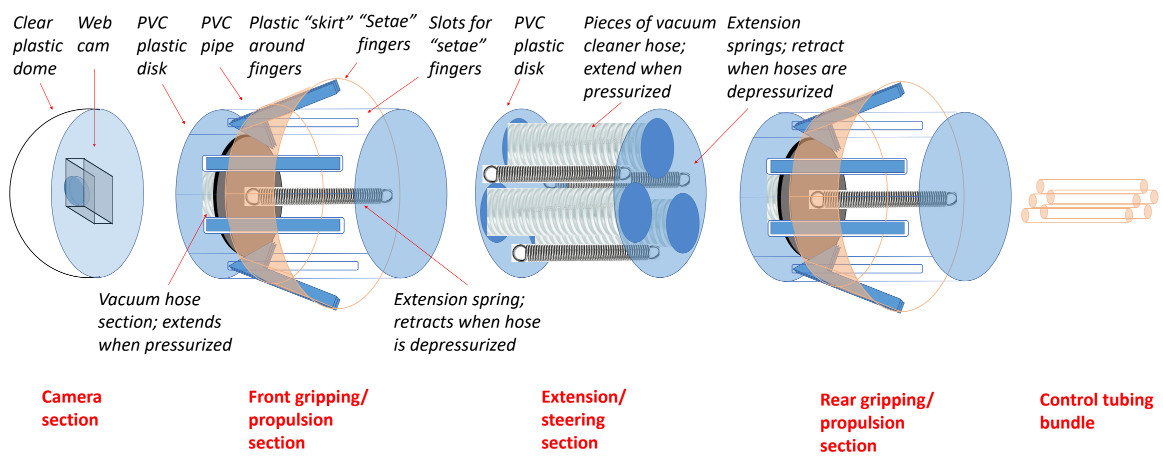


Figure 6. **The WormBot was first designed using PowerPoint schematics. Certain originally planned aspects - such as claw-retracting springs and plastic "skirts" were later modified or improved.**

2. Materials and Methodology

The WormBot was constructed from everyday items and inexpensive parts, some purchased online. It was constructed in sections, gripper sections that extend setae-like claws, extension sections that elongate or bend, and a camera section in the front. The WormBot is powered with compressed air from a compressor used to power hand tools or inflate tires. An Arduino micro-controller controls an array of electric valves to actuate the worm sections. The worm is connected to the control panel through a "leash", which is a bundle of thin air tubes. This means that the worm itself contains no power source, no mechanical parts (e.g., valves or motors), and no electronics, all of which is on the control panel, making the WormBot itself potentially lightweight, inexpensive, and rugged.

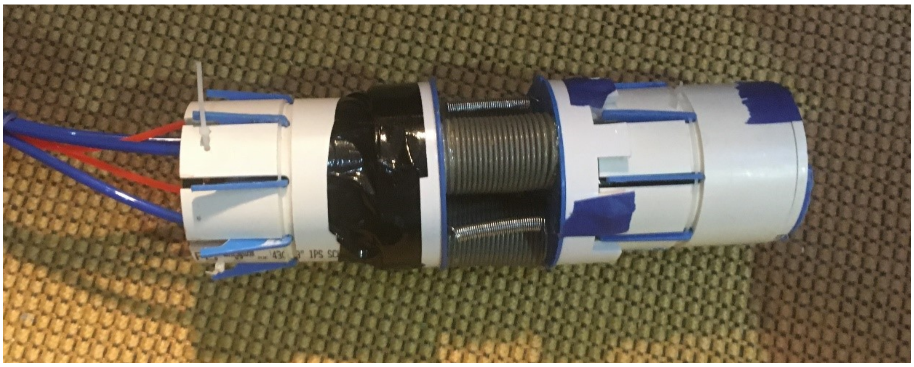


Figure 7. **One of the earlier WormBot prototypes used smooth claws, which hinged from the front. These had trouble gripping certain surfaces, and sometimes pushed the robot backwards when they extended.**

2.1. Extension Section

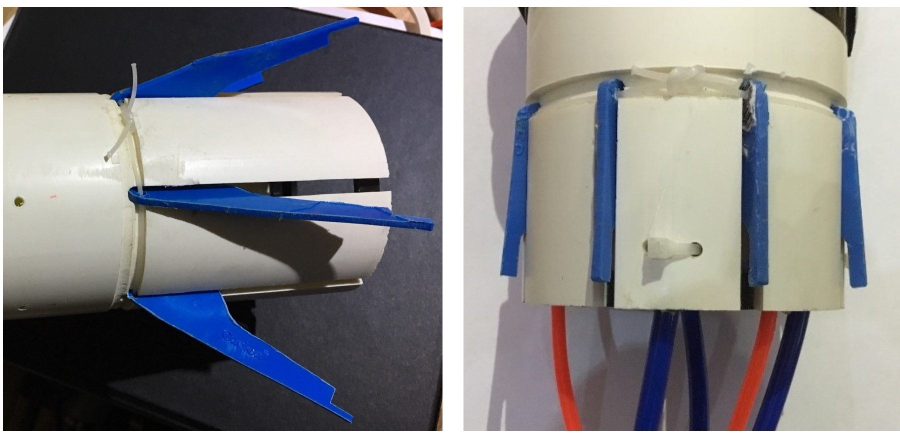
The WormBot sections were constructed out of strong, lightweight PVC (plumbing) pipes, which can be cut with woodworking tools, and welded with PVC cement. The WormBot uses actuators made of pieces of collapsible vacuum cleaner hose, sealed to plastic disks (sold as electrical box covers) with epoxy, with a quick-connect air-hose fitting at one end. When inflated, the hose sections extend, and when the air pressure is removed, tension springs are used to collapse them. The extension section of the WormBot uses three hose actuators. If all three are inflated evenly, the section extends, and if only one or two hose actuators are inflated, the section will bend. (See Figure 10 showing the WormBot extension section.)

2.2. Gripper Section

Various gripper sections were built and tested. The first few used thin plastic claws (cut from outlet box cover plates), which hinged outward from the front. Either 6 or 8 claws were cut on a bandsaw and inserted into slots routed into the PVC pipe. (See Figure 8.) Later claw sections used rubberized "treaded" claws to grip better. The claws hinge on a thick fishline, (from a weed-whacker), and are spring-loaded with rubber bands.

Inside the PVC, the claws have triangular "shoulders". When inflated, a vacuum cleaner hose-based actuator presses a spherical plastic cup down against these shoulders to extend the claws, and when the pressure is released, the shoulders guide each claw back into its slot. (See Figure 9 of gripper sections with six 4-inch claws and eight 2-inch claws, respectively.)

Figure 8. **Routing slots in PVC pipe to make gripper section. (Power turned off for photograph.)**

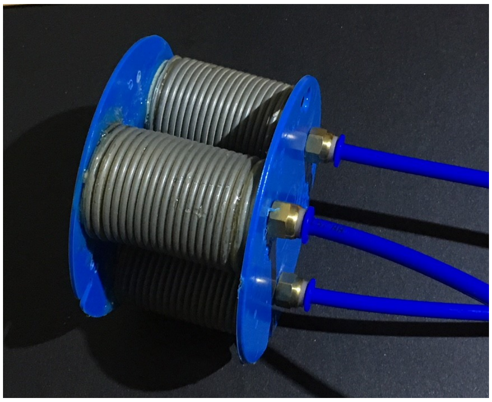


Gripper Section with 6 four-inch claws. Gripper Section with 8 two-inch claws.

Figure 9. **Early Gripper Sections had six, longer claws (left). However, longer claws had trouble retracting, and six claws were not enough to ensure that two claws are in contact with the ground at any time. Later Gripper sections used eight, shorter claws (right). These claws are plain, but later claw designs used "treads" for better gripping.**

2.3. Camera Section

The camera section at the front of the WormBot contains a small camera, sold as a replacement for the rear-view cameras on many cars. The camera has a wide view from a fish-eye lens, and it is surrounded by LED illuminators. A clear acrylic dome protects the camera from debris. (See Figure 10 of the WormBot camera.)



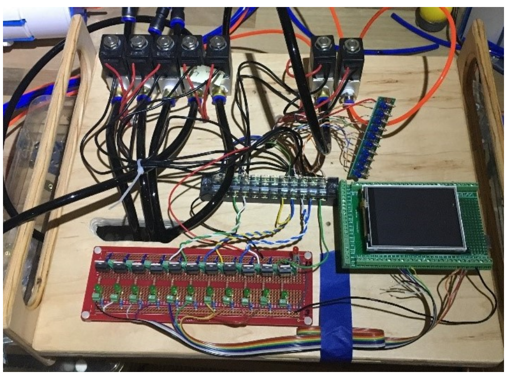
WormBot Extension Section.

WormBot Camera.

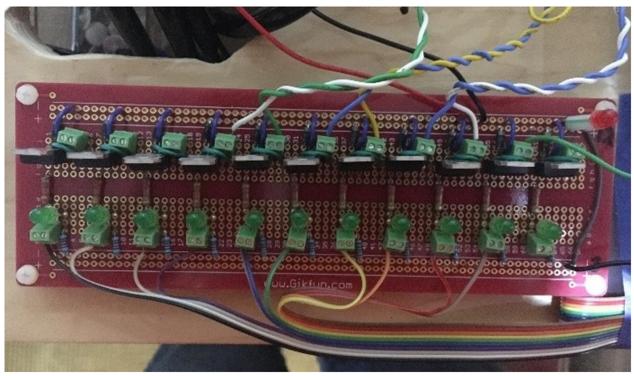
Figure 10. **Early Extension Sections (left) used pieces of vacuum cleaner hose as actuators, which extended when inflated with pressurized air. They tended to leak where the ends were glued and did not lengthen consistently. Sections of surgical tubing were placed inside the hose section to fix these issues. The WormBot's front camera (right) is an inexpensive automotive rear-view camera, which has built-in LED lighting.**

2.4. Control Panel

The control panel holds the Arduino microcontroller, the solenoid valves, a circuit board of power transistors to control the valves, a power supply, and the air supply tubes that provide compressed air to each valve. The control panel and all its circuitry were built for this experiment. A supply tube from the compressor provides compressed air to each of the valve inlets. (See Figure 11 of the control panel.)



WormBot control panel.



Close-up of valve control power transistor circuits.

Figure 11. **The WormBot control panel (left) includes the Arduino microcontroller (bottom right), the power transistor array (bottom left, and closeup on right-hand side)), and the solenoid valves (top). Not shown, underneath, are the power supply and the air compressor supply line. The power transistor array (right) contains 11 Darlington transistor circuits to drive the solenoid valves.**

2.5. Solenoid Valves

The WormBot uses inexpensive 12-volt electric solenoid valves. These valves are normally closed. When energized, a solenoid opens the valve allowing air to flow from the inlet port to the outlet port. When the power is turned off, an internal spring closes the valve. The valves can actuate quickly; the WormBot control program opens and closes them for intervals as short as 1/10 of a second.

The valves use approximately 500 milliamperes, too much current for the Arduino to produce. In addition, when the valve closes, the magnetic field in the solenoid collapses, sending current back through the circuit, which could damage the Arduino microcontroller. For these reasons, a simple power transistor circuit was used to enable the Arduino to control the valves [22]. (See Figure 12 showing the circuit diagram.) The Arduino output drives a Darlington power transistor, and a "clamping" diode across the valve prevents any "back-current" from flowing into and damaging the Arduino. An LED light to show that the valve has been actuated, and resistors limit the current to protect the Arduino digital circuitry. Eleven such circuits were soldered on a small circuit board. (See Figure 11.)

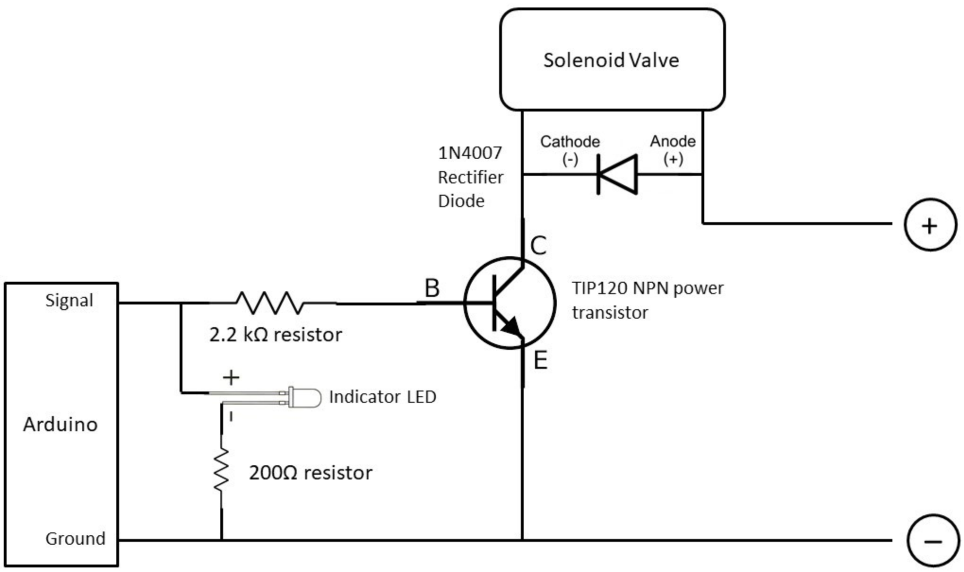


Figure 12. **The solenoid valves use over 500 milliamperes of current and cannot be driven directly by the Arduino microcontroller. The Arduino signals are amplified through Darlington power transistors using this circuit. Rectifier diodes protect the Arduino from "back-currents" that can be caused when the solenoid field collapses.**

2.6. Valve Configurations

Controlling the WormBot requires being able to pressurize certain actuators while simultaneously exhausting others. A single on-off valve for each actuator would not be sufficient, and leaving open any valve that exhausted compressed air would quickly overcome the compressor's ability to produce compressed air. Thus, controlling the WormBot with inexpensive valves e.g., on-off valves as opposed to 3-position valves required designing airflow configurations to control the actuators.

Two configurations were researched (so far), a manifold-based design and a double-valve design. (See Figure 13 for schematics of both airflow designs.) The double-valve design requires two valves for each actuator, one to admit compressed air from the compressor, and one to exhaust air from the valve supply hose. Opening the former and closing the latter pressurizes the actuator, and reversing both exhausts it.

The manifold-design more efficient, using one valve per actuator with only two additional valves. One of these valves admits pressurized air into a manifold, a length of tubing with branching supply tubes going to each of the actuator valves. A second valve exhausts air from the manifold. In this design, the manifold is pressurized, and valves for actuators to be pressurized are opened. These valves are then closed, the manifold is exhausted, and valves for actuators to be exhausted are then opened.

The manifold-design uses fewer valves, but requires more complex programming. With one extension section and two gripper sections, the WormBot has five actuators. Using the double-valve design would require 10 valves, while the manifold-design requires only seven. With two extension sections, the difference in valves would be more significant.

2.7. Arduino and Programming

The WormBot is controlled by an Arduino Mega 2560 R3, an inexpensive microcontroller that can be programmed in C++. A 3-inch touchscreen was connected to the Arduino to display various status indicators and to create virtual "buttons" that are used to control the WormBot. The Arduino has numerous output "pins" that can be configured as digital outputs. Each valve was controlled by such a pin, using the power transistor circuits. C++ classes were created to (1) initialize and control the display and touchscreen, (2) create graphical shapes and text (dot by dot) on the display, (3) create and display buttons and detect when one is pressed, (4) control the solenoid valves and track their status (e.g., open or closed), (5) adjust (using the touchscreen) various timing and delay constants, and (6) actuate sequences of valves to effect specific motions of the WormBot.

Programming challenges were mostly related to timing: Changes in air pressure occur slowly from a programming perspective, albeit in fractions of a second. The WormBot programming had to account for delays such as for valves to fully open (e.g., 10-40 milliseconds), for actuators to pressurize (e.g., 100-200 milliseconds), for manifolds or air lines to depressurize (e.g., 300-600 milliseconds), and for depressurized actuators to be collapsed by spring or rubber bands (e.g., 400-800 milliseconds). Delays such as these were determined experimentally, testing various valve sequences and adjusting delay constants.

In addition, most of the actuators and air supply tubes have small leaks, perhaps due to imperfect gluing of the vacuum cleaner hose sections to the plastic end plates, or to small leaks in the quick-connect fittings. This meant that valve actuation sequences had to occur quickly, much faster than could be done manually, without computerization. For example, a single "step" forward by the WormBot could use the following sequence of valve actuations, all happening in about a second, but precisely timed:

- Extend rear claws: (1) close manifold outlet, (2) open manifold inlet, (3) delay for pressurization, (4) open

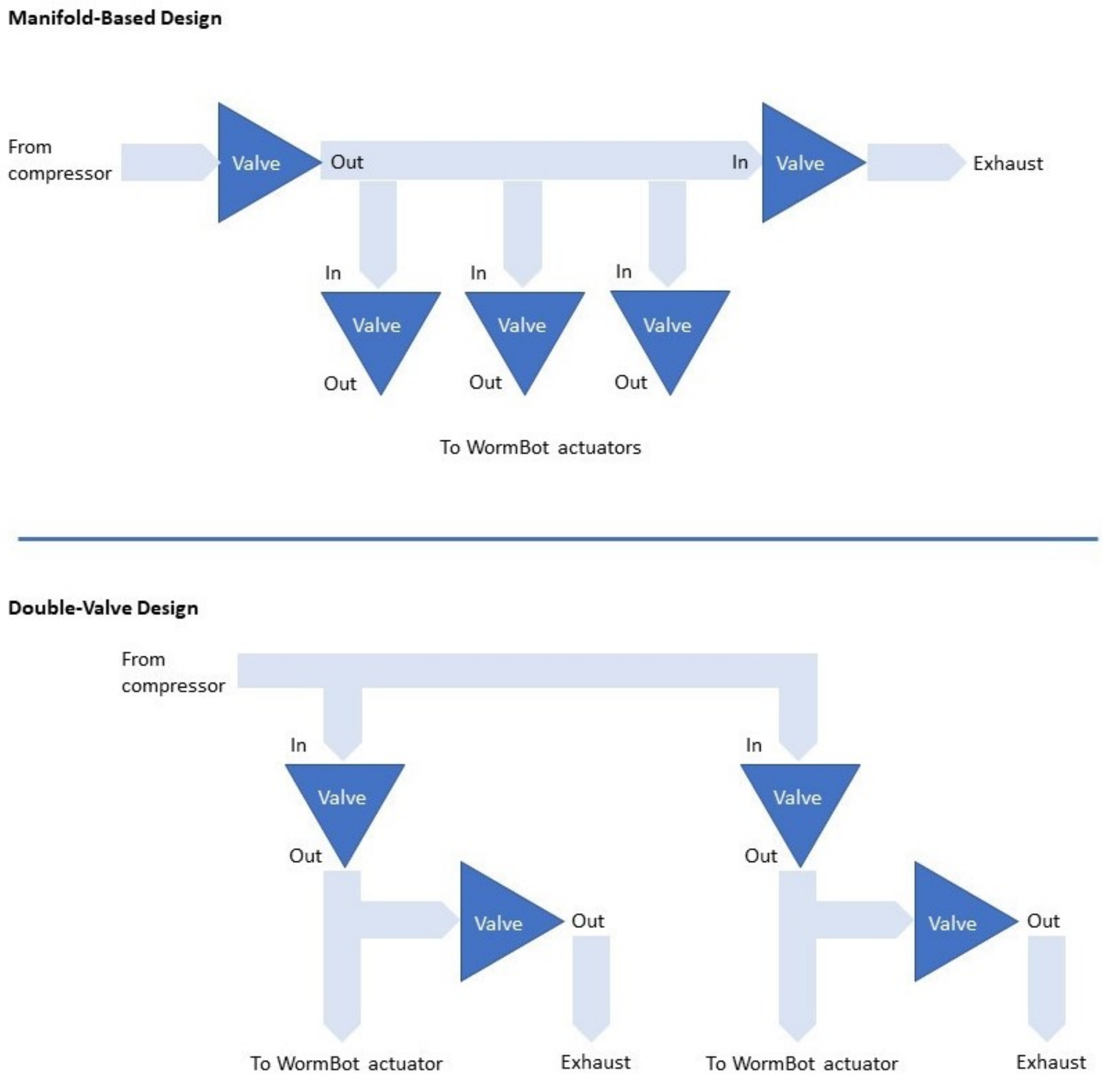


Figure 13. **Various valve "topologies" were explored in order to manage pressurizing and exhausting the solenoid valves. The "Manifold-Based" based design, which was chosen, use fewer valves but more sophisticated software.**

rear claw valve, (5) delay for actuator motion

- Elongate: (6) open three extension-section valves, (7) delay for actuator motion
- Extend front claws: (8) open front claw actuator, (9) delay for actuator motion
- Release rear claws and contract: (10) close front claw valve, (11) close manifold inlet, (12) open manifold outlet, (13) delay for depressurization and collapse of rear claw and extension actuators, (14) open front claw valve

The current version of the WormBot does not incorporate feedback; the Arduino microcontroller cannot measure the current air pressure in an air tube or actuator. This is a planned improvement, however there are miniature air pressure sensors that can be read by an Arduino. Without feedback, the ”open loop” control of the WormBot requires experimentally finding the right delays to program into the valve timing, and assuming that actions (like an actuator depressurization) always take the same time. Feedback will allow more precise control of the WormBot and accommodate more variability in the behavior of its parts and changing external forces on the WormBot.

2.8. List of Materials

The WormBot sections were built out of plastic parts, cut and shaped with woodworking tools:

- PVC (plumbing) pipes and coupler fittings of various sizes
- Flat plastic (PVC) outlet boxes covers (sold in square and round shapes)
- Collapsible vacuum cleaner hose (with embedded spiral, steel wire)
- Surgical tubing (for inflators)
- Round, plastic measuring cups
- Extension springs (of various sizes)
- Thick (weed-whacker) plastic fish-line
- Rubber bands, drinking straws, cable ties

The pneumatics used electric solenoid valves, standard polyurethane air tubing, and quick-connect fittings:

- Yosoo 1/4-inch 12-volt electric valves (single pole, two-way)
- 6mm and 4mm polyurethane plastic tubing
- 6mm and 4mm 1/4-inch NPT quick-connect fittings
- 6mm quick-connect plastic manifold and union fittings

The electronics were built around the Arduino Mega 2560 R3:

- Arduino Mega 2560 R3
- ITead Arduino 3.2-inch TFT Touch Mega touchscreen display
- TIP120 NPN Darlington power transistors
- 1N4007 1-amp rectifier diodes, miniature colored LEDs, and 220 and 2000-ohm resistors
- 12-volt power supply (meant to run LED cabinet lighting)

3. Data & Results

The WormBot is able to crawl forward on various surfaces under computer control, by elongating and contracting its body. Various types of claws and inflatable actuators have been tested. See below for comparison of various types. Depending on the surface, certain claw types grip better than other. Gripping is important because claws must grip sufficiently to capture the forward motion created by the extension section. Certain claw types and surface resulted in some ”back-sliding” when the worm body contracted. This is due to variations in the timing for claws to retract and the extension section to contract, perhaps due to frictions against the (floor) surface and maybe small air leaks.

3.1. Claws

Four different types of claws were tested. The first gripper section had six 4-inch plastic claws that hinged from the front. These four-inch claws were deemed too long. (See Figure 9.) This gripper section lifted the worm too high off the floor, expending most of its force in lifting the worm. Also, only two claws remained in contact with most surfaces when extended. A subsequent claw section used eight 2-inch plastic claws. However, these hinged claws contributed to pulling the worm backwards slightly as they extend, because of the way they rotate forward. The extension is powered and thus more forceful than the retraction, which is from the tension springs. The setae on real earthworms appear to extend perpendicularly from the worm's body. A claw section was built with eight, short claws that slid outward perpendicularly. However, these claws did not always retract smoothly and tended to stick. To improve the WormBot's grip, the latest gripper sections use “treaded” claws with rubberized tire treads on the ends (see Figure 14.) These claws hinge at the rear, so that the powered extension pulls the worm forward if at all.

3.2. Extension and Bending

The three vacuum cleaner hose sections, which inflate and extend to actuate the extension section, sometimes leaked and did not always inflate evenly. Repairing leaky actuators required regluing with epoxy. Their unreliability caused the worm to bend sometimes instead of just extending. Later prototypes of the WormBot used inflatable actuators made of sections of surgical tubing, inside of the vacuum cleaner hose sections. The surgical tubing, sealed at one end with a glued pencil eraser, inflates without leaking, like a balloon but with much more force. When inside the vacuum cleaner hoses, with their embedded steel coils, the force of the inflating surgical tubing is limited to one direction. These ”compound” actuators using surgical tubing inside vacuum cleaner hose sections turned out to be far more consistent and reliable.

When extending, all three hose sections are inflated simultaneously for the same amount of time. In subsequent tests, a more sophisticated control program will allow for adjustable delays for each hose section, to account for differences in how quickly they can inflate. Also, the extension section is meant to both extend and/or bend, depending on how many of the three hose sections are inflated simultaneously. Bending the WormBot is achieved by pressurizing one or two of the three vacuum cleaner hose actuators in the extension section while simultaneously exhausting the others. In the current prototype, bending is inconsistent in terms of the specific direction and degree of the bend. This is likely due to unequal pressurization and motion of the hose actuators.

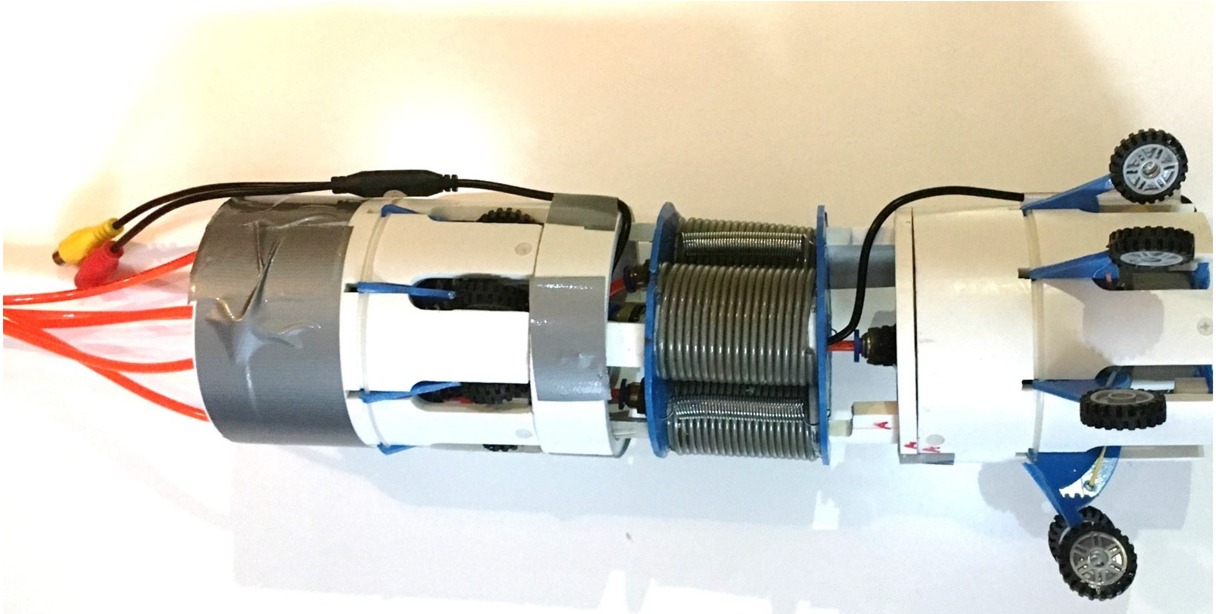


Figure 14. **The latest WormBot prototype has two Gripper Sections, each with eight "treaded" claws that hinge from the rear, as well as an Extension/bending section.**

4. Discussion

As of this writing, the current WormBot prototype is able to crawl slowly over different surfaces. (See Figure 14 of current WormBot prototype.) It demonstrates that it is possible to build and control a worm-based robot that moves like an earthworm, by using setae-like claws and elongating and contracting its body. Subsequent experiments will improve the prototype and further test its capabilities. The WormBot body is built from a few dollars of plastic parts. Using more industrial techniques, such as injection molding or 3D-printing, the WormBot could be built very cheaply. This could allow for "disposable" worm robots, ideal for sending into rubble piles or active machinery. The WormBot body could also be miniaturized. There is nothing electronic or mechanical inside the body unit, so it seems possible that tiny WormBots could be created for medical and other applications.

An important planned improvement is to add pressure sensors and feedback. The Arduino can read digital and analog inputs, and reading the pressure of each of the supply lines will enable the WormBot programs to precisely control the air pressure and monitor the degree of extension (via pressure) of each actuator. While more complex, such programming should enable more precise control of the WormBot. Subsequent research will also investigate potential new airflow designs. Precise control of the WormBot depends on quickly and precisely switching on and off the air pressure to numerous actuators. In theory, each actuator can be (1) pressurizing, (2) exhausting, or (3) "sealed" to maintain its current pressure and position. In reality, the pressurized air is usually moving, leaking, or otherwise changing. Different arrangements of valves may make it easier to quickly pressurize and exhaust specific actuators.

As of this writing, the WormBot has only been tested crawling on flat surfaces, (smooth and carpeted.) Subsequent research will test additional terrain, as well as sloped and jagged environments, and ”burrowing” through debris to simulate dirt or rubble. The current WormBot prototype has an uneven exterior, including sections of slightly different diameters and sharp corners where the robot sections meet. Subsequent WormBot designs will minimize such corners and edges to make the robot more maneuverable.

Conflict of Interest

Author of this article declares that he has no conflict of interest.

Human Studies/Informed Consent

No human studies were carried out by the author for this article.

Animal Studies

No animal studies were carried out by the author for this article.

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