Creepy Climber and Leaping Robots -Biologically Inspired Design

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Abstract

This paper presents the design evolved for two types of biologically inspired robots. They have the ability to creep, climb and leap. One of the robots was modeled after observing the motion of an earthworm and the other utilizes a design that combines the motion of an earth worm and a leech. A number of actuators located at different sections of the robot control the motion of various linkages and mechanisms incorporated in the design. The robots use onboard sensors to monitor critical positions of various members of the robot for control purposes. Both the robots are totally controlled by micro-controllers that were programmed using an external personal computer. A working model of the two types of robot has been built and tested and the results are quite promising and show that the complex biological motions of insects and creatures can indeed be recreated with innovative engineering design.

Keywords: biologically inspired machines, robots

1 Introduction

Earthworm and leech use unique types of motion to traverse over surfaces within their habitat. From an engineering perspective, the mechanisms used for movement by these insects are a real engineering marvel. Many of them are quite complex and hard to duplicate. They also utilize sensory organs that can smell and feel the surrounding when they move from one place to another. The work reported in this paper presents an engineering design of two types of robots that mimic the motion of two biological creatures, namely an earthworm and a leech. Earthworms (Figure 1) burrow through the soil by producing successive waves of muscle contraction and relaxation along their body. They move along surfaces by first extending the front side of their body. They then take a hold over the surface by using their front bristles. This is followed by a retraction of the bristles at the rear of the body to release hold on the surface followed by drawing up the trunk towards the front. The repetition of wave like motion in a sequence allows them to move forward. A leech (Figure 1) is composed of a series of segments, thirty four in total. Leeches unlike worms do not possess bristles and use suckers instead. The suckers are present at each end of the body. They move by alternately attaching and detaching these suckers, and leaps. There has been a growing interest in the scientific community to study biological motions and design robots for a wide variety of applications. This new approach is also being made more possible with the increased interest in modeling biological systems, availability of low cost and high speed computing systems, evolution of smart materials, intelligent sensors and miniaturized yet powerful actuators. In the current design, motion along the axis passing through the trunk is incorporated. Twisting and turning on axis perpendicular to the trunk will be considered in the next phase. The two types of robots presented in this paper have certain common design principles even though functionally different. A brief summary of relevant research work conducted by different investigators is presented next.

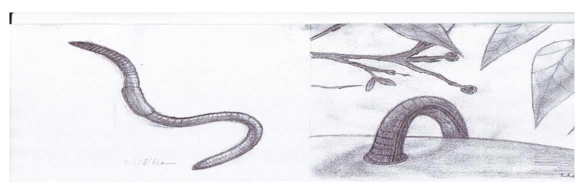


Figure 1*: An earthworm (left) and a leech (right)
*** artwork by author**

2 Relevant research

Traditionally the field of robotics has benefited from application of principles in the field of engineering and computer science. This has resulted in the development of a wide variety of industrial robots. However in recent times a growing interest in mimicking living creatures for evolving newer type of robots can be seen. This has resulted in “new wave” of robots (1). Of particular interest to this study is the work done by a number of investigators on the development of robots with bio-inspired actuators and mechanisms. Multi-legged robots ranging from eight-legged to one-legged with the full body weight supported by the limbs and capable of walking have been developed (2). Most walking creatures are warm blooded and generally have greater speed of movement in comparison to cold-blooded counterparts such as snakes, turtles, crocodiles, fish, etc. The latter species rely on their environments to support their weight. They are also more efficient in using only 10 to 50 times less energy than warm-blooded animals. A class of robots that move like reptiles have been evolved (3-5). Of the many bio-inspired robots, only a few can achieve locomotion by dragging their bodies with limbs. Many of these robots use passive or active wheels. A robot termed "TerminatorBot" drags itself without any wheels (6). Body drag can result in loses in energy due to friction; however it tends to conserve energy during lift and reduces the complexity in maintaining balance. The design is also more amenable to the use of lighter and smaller mechanisms. An inchworm like robot with grippers at each end has been reported (7). It is larger in comparison to the "TerminatorBot" and the design is highly suitable for tasks such as repair and inspection in space station. Insects have often served as inspiration for robot design. In addition to the above developments, designs based on cockroach (8, 9) and cricket (10) to name a few has also been proposed. The design proposed in this paper incorporates unique and novel mechanisms and linkages to mimic very closely the motions exhibited by earthworms and leeches and rely on sensory feedback and microcontrollers for coordinated motion.

3 Requirements of the Design

The basic components considered in the design are: (i) a trunk capable of contracting and expanding with appropriate actuators; (ii) appropriate feet or other mechanisms that provide the robot a stable grasping of surfaces; (iii) capability of mimicking the different types of motions seen in these insects; (iv) appropriate feedback sensors that allows coordination of various motions; (v) ability to control the various motions using programmable controllers and (vi) identify and demonstrate appropriate applications in the real-world.

The first robot developed is modeled as a creeper. A creeping/crawling motion is one wherein the robot is assumed to cling to both sides of the surface negotiated and produces slow and stealthily motion. A creeper is assumed as incapable of rotation about the foot anchored to the surface. A leaping motion is when the robot is capable of producing both creeping motion as well as capable of rotary motion about the foot anchored and thereby has the ability to jump over obstacles. The creeper robot was modeled following the principles used by an earthworm. Hereafter it will be referred to as 'Pole-Climber'. The leaper robot was modeled as a leech and will be referred to as 'Tower Climber'. It has the ability to creep and leap over surfaces. Both have the ability to climb surfaces. The names also reflect the type of applications they are ideally suited for.

3.1 Design aspects of Pole climber

The pole climber robot mimics the motion of an earthworm and has the following components. All descriptions are with reference to Figure 2. The body of the robot is comprised of two separate decks, (A-upper, and B-lower). Three stabilizer rods located on the vertices of an equilateral triangle are firmly attached to the bottom deck. The top deck can freely slide up or down the rods. A bushing firmly attached to the rods (on the top side of the upper deck) will prevent the top deck from sliding out of position. A set of compression springs (three in each rod) inserted between the two decks will position the two decks at a certain distance from each other. The lower deck also carries three separate actuators (DC motors), referred to as muscle actuators. A tension cable analogous to the function performed by a muscle wound over each shaft of the motor has its other end firmly anchored to the top deck. When the motors are rotated one-way, the tension in the table increases and pulls the top deck towards the bottom deck and thereby increasing the compressive forces on the springs. This corresponds to the contraction motion of a worm. When the springs are fully compressed, the distance between the two plates will be at its minimum. Rotation of motors the other-way on the other-hand will loosen the springs and the decks will move away from each other due to the release of compressive forces on the springs. This will represent the extension motion of the worm. Deck 'A' will lead deck 'B' during climbing. The springs are free to slide on the shafts and are always under compression even when they are fully relaxed. The pre-loading of the springs provides the necessary stability for the upper deck with respect to the lower deck. By controlling the amount of rotation of each motor the upper deck can be positioned at various distances and inclinations with respect to the lower deck. This feature mimics the contraction and expansion of the trunk of a worm. The upper and lower decks are also provided with a set of rollers that roll over the surface freely, as the robot climbs up or rolls down the surface (a smooth pipe in this case). The rollers stabilize the position of the decks with respect to the surface. The rollers are provided with compression springs and apply a preset force on the surface. The rollers are passive mechanisms. The rollers do not correspond to any specific part in a worm. The above parts are identified in Figure 3.

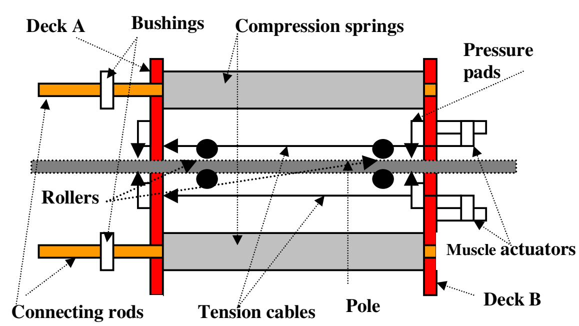
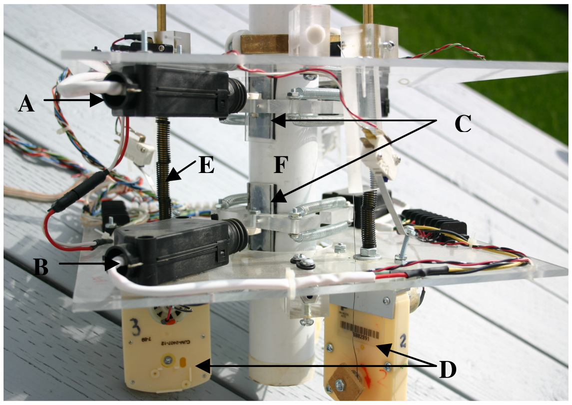


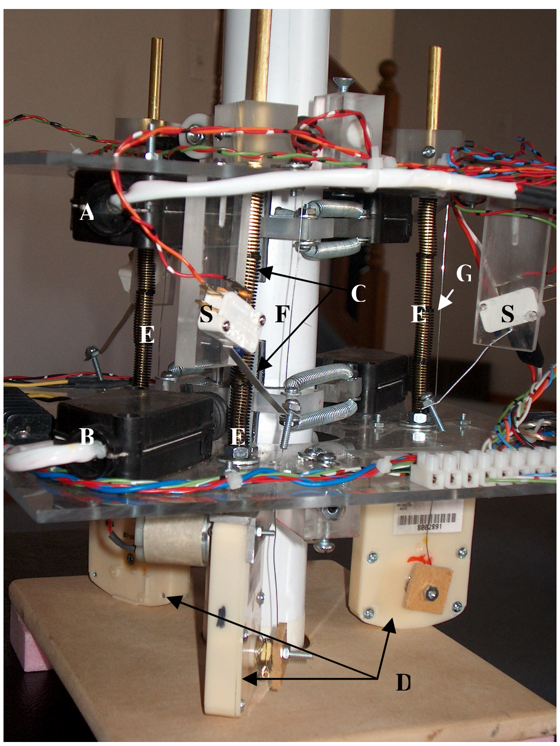
Figure 2: Line diagram of pole climber robot

Two pressure pads located diametrically opposite to each other on the upper and lower decks perform the role of bristles used by worms to grasp the surface when required, as the robot climbs or descends. The pressure pads are actuated by electric solenoids and hence hold/release actions can be controlled. The default position is set as hold and thereby in the event of a power failure the robot remains stable in its current position. Two springs on either side of the pressure pad apply a constant force on the surface. The pressure pads are also coated with compliant material to confirm to uneven surfaces. Six touch sensors monitor the position of the upper and lower plates. A micro-controller capable of being programmed using a personal computer was interfaced to the robot to monitor the status of sensors as well as control all the actuators. Figure 4 shows the robot constructed.



A-Top foot actuator, B-Bottom foot actuator, C-Top and bottom feet, D-Two of the three muscle actuators, E-one of the three compression springs, and F-Pole.

Figure 3: Location of actuators and springs with respect to the two decks



A-Top foot actuator, B-Bottom foot actuator, C-Top and bottom feet, D-The three muscle actuators, E-Compression springs, F-Pole, G-Muscle tension cables, and S-sensor.

Figure 4: Constructed Pole climber robot

The preliminary phase of the design involved evolving a concept for the design. It went through many iterative phases until a workable idea was found. This was the most difficult step. The next step identified various components required for the design as well as performing design calculations such as sizing of motors/actuators, torque and speed requirements, foot design considering material required in the contact surface between the foot and the surface, identification of appropriate tension and compression springs, and finally the overall placement and structural aspectual of various components. The last phase involved building of the robot.

3.1.1 Working Principles

The sequence of steps required for climbing is described assuming the following initial conditions: (i) the robot is at the bottom of the pole with both feet on the upper and lower deck fully released (having a firm grip on the surface); (ii) the upper and lower decks are at their minimal distance from each other with the springs fully compressed; and (iii) the steel wires attached to the dc motors under maximum tension. The sequence of steps for climbing is given below. Figure 5 pictorially represents the sequence.

Step1 The gripper on the upper platform releases its hold and thereby the upper-deck is free to move, but is prevented from moving due to the tension in the cable.
Step 2 The three motors are energized to rotate clockwise releasing the tension on the cables. The compression springs will in unison push the upper deck upwards. The micro controller will simultaneously sample the sensors that monitor the extreme positions of the two decks. The three motors will stop when the upper deck reaches a predetermined height above the lower deck and the feedback is obtained using three sensors located on the lower deck.
Step 3 The gripper on the upper platform will be deactivated and a short time later, the gripper on the lower platform will be activated. This will enable the upper deck to regain its hold with the surface and the lower deck looses hold. The two decks will be farthest apart. At the end of step 3, the upper deck would have moved up by the pre-set distance.
Step 4 The three motors are energized to rotate counterclockwise increasing the tension on the cables. The lower deck will move upwards and the springs will be compressed back to their original position. The micro controller will simultaneously sample the sensors that monitor the extreme positions of the two decks. The three motors will stop when the lower deck reaches a pre-determined height below the upper deck and three sensors located on the upper deck will provide the necessary feedback to the controller.
Step 5 When the motor stops, the grippers on the lower platform will release and thereby the lower-deck will regain its anchor on the pole.

The steps described above are for one cycle of operation. The steps will be repeated and the robot will move up the pole with alternate movements of the upper followed by lower deck. The sequence executed in the reverse order will allow the robot to climb down. The steps described above were programmed using a "STAMP-SX" microcontroller. All the programs were written and compiled on a standard PC and downloaded to the microcontroller. The programs can be easily edited for any fine refinements.

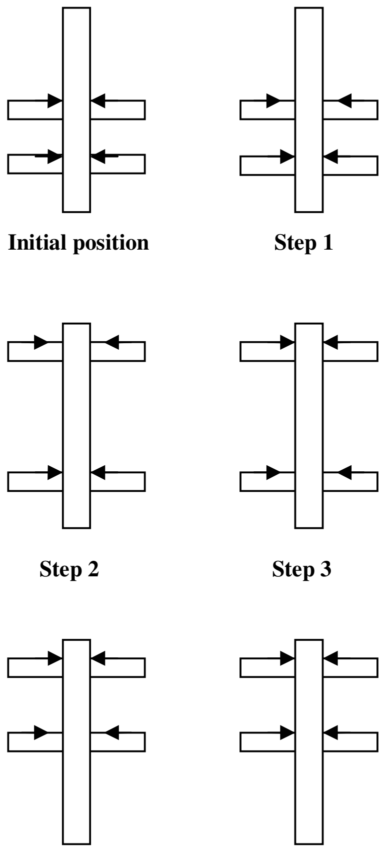


Figure 5: Sequences of steps for climbing

3.2 Tower Crawler robot-Design details

The tower crawler robot was modeled mimicking the motion of a leech. As shown in Figure 6, the robot consists of a central section (trunk) and a head and a tail. The trunk is capable of expanding and contracting and the design is very similar to that of pole climber. Unlike the pole climber design, a single dc motor using similar arrangement of steel wire and compression springs achieves the motion. In order to provide sufficient rigidity to the structure, the trunk has four sets of springs instead of three incorporated in the pole climber. A set of sensors monitor the position of the two end plates with respect to each other. The trunk has two rigid extension links on either side to which the head and tail sections are attached as shown in Figure 6. The head section is capable of independent rotation about a horizontal axis passing through the axis of two actuators, a left head actuator (LH) and right head actuator (RH). The tail section has a similar set of actuator (LT and RT in **Figure 6**). The head and tail sections of the robot also carry the suckers which can be made to release or hold by using an actuator located within the head and tail section. The design is very similar to that of trunk and employs compression and tension elements working in unison. The motors (LH-RH and LT-RT) allow the tail and head section to rotate about their own axis, when the suckers are not holding onto the surface below. They also serve another purpose. When the sucker located on the head section is firmly anchored to the ground and the sucker on the tail section is off the ground, a clockwise motion of motors LH and RH in unison will rotate the entire trunk section along with the tail section. This motion will produce a leaping motion that leeches use to ambulate when seeking a prey. The entire section will rotate through 180 degrees placing the tail section in front of the head section. A reversal in sequence of motion will bring back the robot to its original motion. Thus leaping motions in the forward or reverse directions are facilitated. The trunk section of the robot does not have any grasping pads unlike the one found in the pole climber. When the sucker on the head is firmly holding the surface and the sucker on the tail is in lifted motion, the trunk actuator when powered can allow contraction of the trunk. This can be followed by an expansion of the trunk when sucker on the head is released and the sucker on the tail is made to hold the surface. This type of motion mimics motion similar to that of a worm. This gives the ability to produce small incremental motion that may be required to negotiate obstructions on the surface. The suckers are made up of five 'Neodymium Iron Boron (rare earth) magnets sandwiched between two Perspex plates (Figure 7).

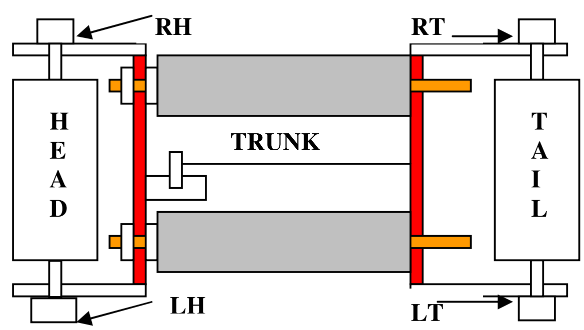
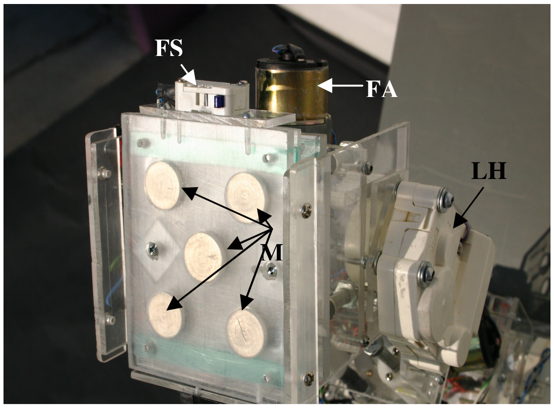


Figure 6: Line diagram of tower climber robot

The suckers provide a strong grip with the surface below when they are lowered within a certain distance from the surface. The lifting and lowering of the feet pads are controlled by a dc motor labeled C in Figure 7 and the mechanism uses the same type of design (tensile wires and compression springs) employed in other parts of the design. The arrangement of actuators for lifting and lowering of suckers in the tail and head section are identical to that of trunk except for the physical location of the motors. A close up view of the trunk and the head section is also shown in Figure 8 and 9. An overall view of tower climber is shown in Figure 10.



M-embedded magnets, LH-left side head motor, FA-foot actuator, FS-sensor to detect foot position

Figure 7: Location of magnetic suckers on tower climber robot

The design of tower climber followed similar steps mentioned earlier in section 2.1. However the design iterations were lot more complex. The synchronization of head and tail motors and the dual role they perform for rotating the entire trunk required more consideration from a control perspective. The design also underwent substantial change when the net weight of the robot had to be minimized for efficient performance of various actuators.

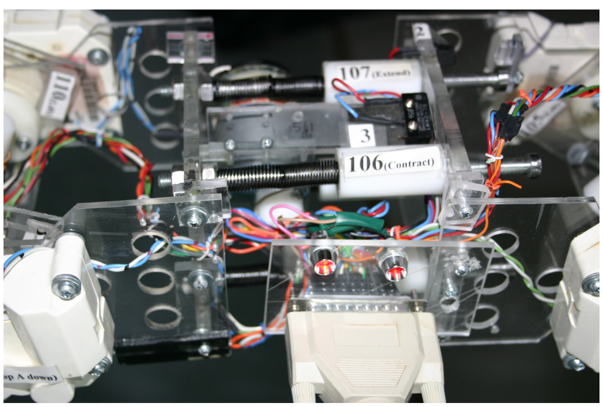


Figure 8: Close up view of Trunk section of tower climber robot

3.2.1 Working Principles

The tower climber robot has two modes of operation. The first one is its ability to crawl using smaller incremental displacements. The sequence of motion is identical to that of a pole climber. By anchoring the head foot and lifting the tail foot, any contraction of the trunk will create a displacement equal to the net contraction of the trunk. What is unique to the motion of the tower climber is its ability to selectively combine the worm like trunk motion and the ability to swing its trunk over a full robot length as would be seen in the motion of a leech. This produces a much larger displacement in one sequence of motion. The full sequence for a combined motion is described below with respect to a starting position. The robot's trunk is fully contracted and both feet are on the ground.

Step1 The head foot is lifted off the ground while the tail foot remains anchored to the ground.

Step2 The trunk section expands to its full length causing the head section to be pushed out by an equal distance. At the completion of this phase, the head foot lowers and anchors the robot to the ground.

Step3 The foot on the tail section is lifted off the ground and at the completion of this, the trunk is made to contract which causes the tail to move forward by an equal distance. At the completion of this phase, the tail foot lowers regaining grip with the surface. When the entire is repeated, the robot moves over the surface incrementally.

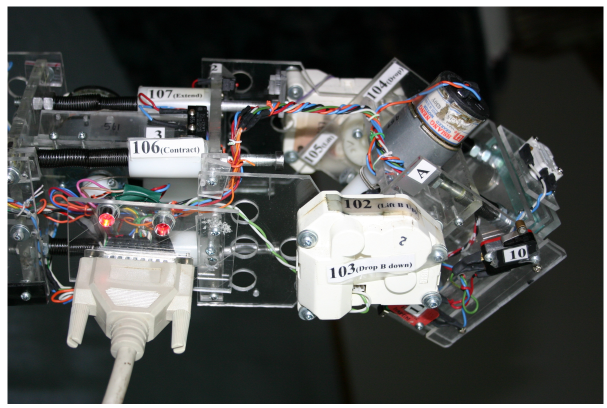


Figure 9: Close up view of Head section of tower climber robot

Step 4 The foot on the tail is lifted. The two rotation motors on the head are activated. Since the head foot is anchored to the ground, rotation of the actuator motors will cause the trunk and tail section as a unit to be lifted off the surface and swing over to the other side. While the robot is swinging over to the other side, the tail rotation motors will also be actuated (after making sure that the tail section is fully off the ground). The tail rotation will stop when the tail section has rotated a full 180 degree rotation.

Step5 The last phase is lower the tail foot onto the surface and regain grasp. At the end of this phase, the robot is fully swung over and the net displacement equals one full length of the robot minus half the width of the tail section. The robot has advanced its position with respect to the initial position.

If the sequence is repeated the robot climbs over the surface much faster than when only trunk is contracted. It should be noted the sequence of motions are reversed the robot begins to descend. The logic for the entire process is shown pictorially in Figure 11 and 12**.**

4 Experimentation

Both the robots were interfaced to a programmable microcontroller. The microcontroller chosen was “STAMP 2sx”. They are tiny microcomputers with “Ubicom SX28AC” processor chip on-board. They were selected since they can be embedded on any control applications that require some

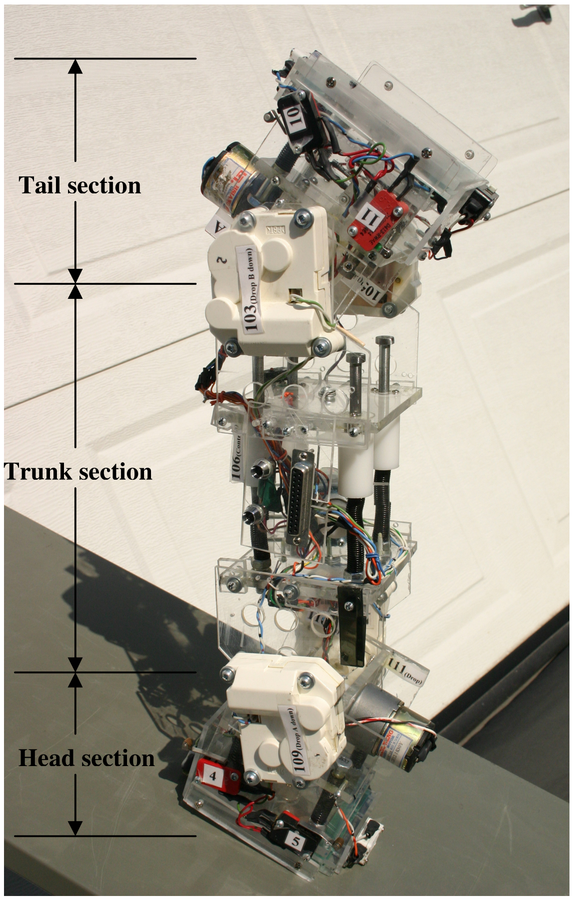


Figure 10: Overall view of Tower climber robot

levels of intelligence. They can be programmed using a wide variety of languages with a processor speed of 50 MHz and the execution speed is close to 10,000 instructions/sec. They have dedicated RAM and are capable of handling eighteen dedicated input/outputs. The size of the controller is 1.2”x0.6”x0.4” and hence ideally suited for this application. They also have a serial interface (9600 baud) and consume 60mA during run time and hence will not drain any portable battery power supply. Customized codes were developed on a pc and downloaded to the microcontroller using serial interface link. The pole climber has five actuators that need to be controlled and six sensors that need to be sampled. These were well within the capability of the microcontroller. The tower climber robot had three actuators, one for contraction/expansion, two additional actuators for lifting and lowering of the two suckers on each side. The rotation of the trunk as well as rotation of the two end sections was controlled by four actuators working in pairs of two. Thus altogether the number of actuators that need to be controlled was five in total. The tower climber had ten sensors that need to be sampled. The microcontroller chosen was quite adequate to implement all of the control actions. The pole climber was tested for its ability to climb a wide variety of surfaces ranging from polished tubes to fairly rough textured tubes. The tests for tower climber robot included crawling and leaping motions on various textured surfaces at inclinations ranging from 0° to 90°. The controller’s capability to execute the custom written software was tested both for fully automated operation as well as speed of execution.

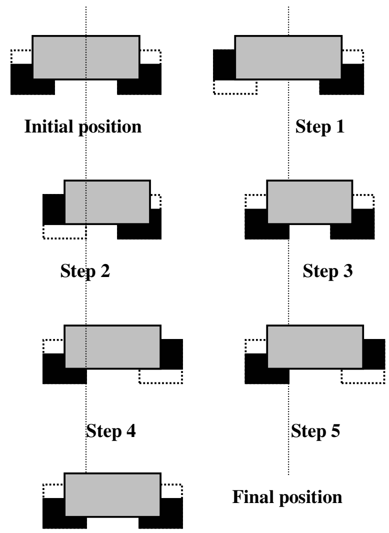


Figure 11: Sequence of movements for crawling motion of tower climber

5 Results and Conclusion

The study undertaken indicates that it is possible to create machines that mimic biological creatures. The design required several innovative applications of linkages, mechanisms, sensors and actuators. The pole climber was able to climb poles as high as 4m (the maximum height available within a laboratory space) without slipping. The feet did not loose their grip even on very smooth surfaces such as those found on metal and PVC pipes. The present design does not permit motions to climb curved tubes. However further design modifications are being implemented to overcome this limitation.

The tower climber performed very reliably in negotiating slopes up to 75°. For inclinations greater than 75°, the magnets employed for grasping were not strong enough to support the weight of trunk and tail section and the foot will loose hold. This limitation can also be overcome by using more powerful magnets. The tower climber robot has a much greater speed of travel in climbing mode in comparison to crawling mode. Further information on the technical specifications of the two robots is shown in Table 1. The two robots were tested in a laboratory environment have several potential applications in the real world. Electrical authorities spend many man powers in inspecting and maintaining their utility poles and transmission towers. Utility poles need to be painted periodically and the pole climber with suitable on-board tooling can easily execute this task in a relatively quick time with minimal manual intervention. The transmission towers need to be inspected often to monitor the quality of insulators and support structures. The tower climber robot has the capability to execute this task. The risk to human life involved in these tasks can be considerably reduced or eliminated using automated robots such as the ones developed in this work. With increased interest in space explorations, robots of this type can be beneficially used for repair and maintenance works in the International Space Station. The robots also have potential applications in exploratory work in Lunar/Martian surfaces. With increased interest for protecting

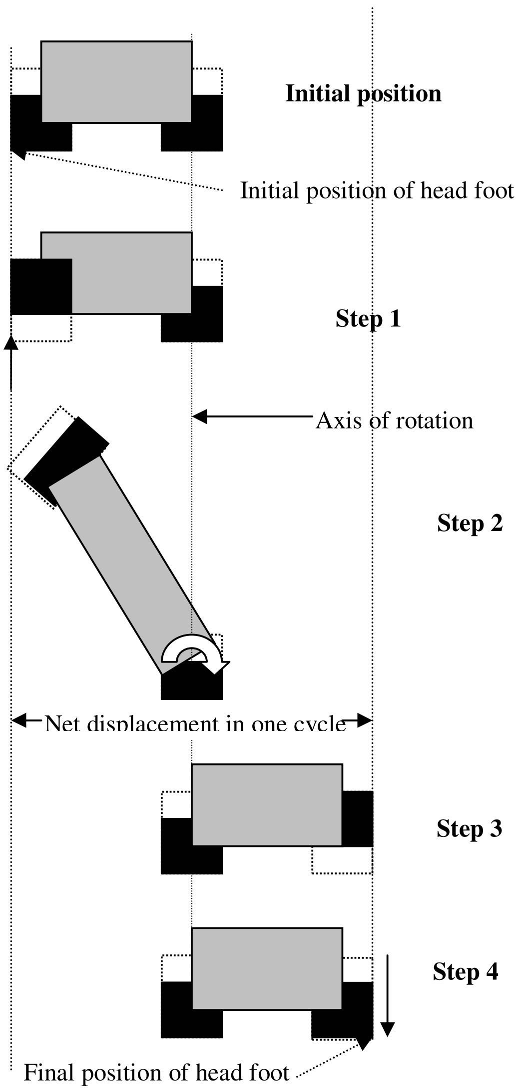


Figure 12: Sequence of movements for leaping motion of tower climber

our environment, the robot could play a key role in remotely monitoring quality of ecosystems for possible forest fires and other environmental problems. The different applications identified will require further modifications in design. For example, the magnetic sucker incorporated in the tower climber restricts its application to ferrous material surfaces. This is not a serious limitation as many other types of foot design using suction cups, claw mechanisms have been developed and they can be easily incorporated in the present design.

The proposed design was evolved after a thorough examination of traditional robot designs. The bio-inspired approach was chosen after determining that conventional robot design would have resulted in a much more complex machine. They will also not produce the type of motions required to climb a vertical surface with ease. The choice of developing a machine that mimics biological motion was found most promising for the type of task considered in this paper. The proposed design was evolved after examining many options for various sub-components of the machine. One that provided great promise is the use of shape memory alloy actuators. This approach had to be abandoned since the contraction and retraction times were of the order of two seconds, reducing the traverse speed considerably. They also require much higher power for actuation and need substantial cooling for them to perform reliably. The tower climber uses a single actuator for contraction/expansion. However, the pole climber utilizes three separate actuators. A single actuator will not allow the robot to twist its trunk as and when needed. A wide variety of gripper mechanisms were also examined and did not perform as well as the one proposed in the current design. The microcontrollers employed in the present design have limited intelligence. More powerful microprocessors are currently available in the market place and use of such microprocessors will enhance the capability of the present design. The robot can also be equipped with vision sensors for enhanced intelligence and enhanced collision avoidance strategies can also be employed. The authors are currently working on incorporating many of these additional tools in the design and it is anticipated that machines with greater capabilities will be made available in the near future.

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Table 1:Technical Specifications of Pole and Tower climber robots

	Pole climber	Tower climber
Number of actuators	7	5
Number of sensors	6	10
Total weight	2.7 Kg	2.5 Kg
Crawling speed	Not applicable	49.4 mm/min
Leaping speed	Not applicable	420.0 mm/min
Climbing speed	76.7 mm/min	49.4 mm/min
Dimensions	300 mm x 300 mm x 300 mm	130 mm x130 mm x 430 mm