SOFT ROBOTICS
Volume 3, Number 2, 2016

DOI: 10.1089/soro.2016.0001

ORIGINAL ARTICLE

Versatile and Dexterous Soft Robotic Leg System for Untethered Operations

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Abstract

In this study we show the design and construction of an efficient soft robotic leg system, capable of generating large amounts of force with three degrees of freedom. The legs are inexpensive and easy to construct with forms created from PVC pipe and aluminum rod available at any hardware store. By combining six leg units, we construct a mobile robotic platform which is capable of untethered movement for several hours. Intel's quad-core Compute Stick provides enough computational resources to implement artificial intelligence capabilities, such as navigation, object detection and identification, facial recognition, and even verbal interaction. Additionally, direct control can be accomplished through wireless internet connection to an end user located anywhere in the world.

Introduction

One benefit of soft robots is that, being compliant, they are generally considered safer for human interaction than are their hard counterparts.[1,2] Due to their flexible nature and their ability to apply force in a controlled manner, they are intrinsically better suited to interact with soft tissue. Unfortunately, because of the need for pumps, valves, and electronic controls, it has been necessary to connect soft robots to auxiliary equipment through tube or wires. This results in devices that are immobile, or at best, limits ambulation to areas adjacent to the operator.

We sought to create a soft robot that could overcome those limitations by being capable of untethered ambulation at great distances from the operator, regardless of physical barriers. To carry the weight imposed by all the additional equipment, a highly efficient design was required. We proposed that this efficiency could be achieved through added agility by creating a dexterous leg system.

To explore the advantages of increased dexterity, we designed a soft robotic platform relying on agile leg sections to accomplish untethered mobility as shown in Figure 1. Previous untethered soft robots such as Tolley *et al.*[3] relied on scaling up earlier designs of Shepherd *et al.*,[4] using the same number of actuators and degrees of freedom as their smaller counterparts. We hoped that adding more actuators would result in a device that would be able to carry a box of hard equipment approximately the same size as previous untethered soft robots, but do so with a much smaller footprint.

Dexterity can be increased by adding more actuators within a given space. This will increase the degrees of freedom, which will result in fluid, even lifelike movements. Often, the number of soft actuators can be increased without the need to increase much support equipment or power supplies. Soft robots can be made more dexterous by simply cordoning off a portion of an existing pressure chamber and adding a pair of solenoids to the controller. This is unlike hard mechanical robots, which generally need to be completely redesigned to accommodate more motors, pulleys, and cables. Additionally, work done by a single soft actuator can often be easily split and done by two or more smaller actuators operating side by side, but with the added benefit of being able to apply their force either simultaneously or separately. These additional degrees of freedom come at very little expense, both economically and energetically.

We hypothesized that additional dexterity would allow the building of an untethered robot, which could be smaller yet faster than previously built devices. With this in mind, a prototype was designed which would utilize 18 soft linear actuators. These would be grouped into six individual legs having three degrees of freedom each.

Additionally, the advent of Intel's new Compute Stick microcomputer with preinstalled Windows 8, provided a serendipitous opportunity to include it in command and control

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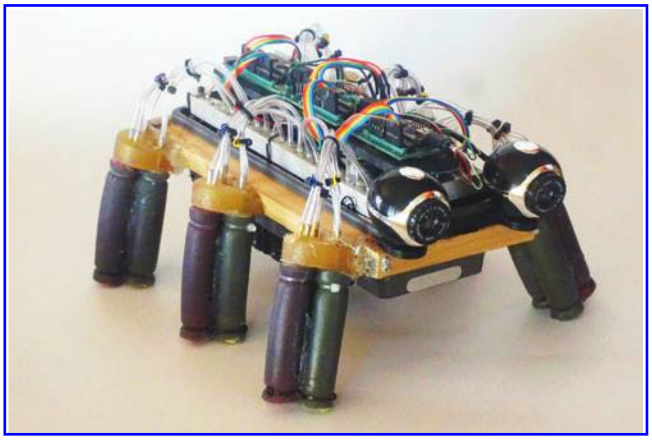

FIG. 1. Untethered soft robot leg system. Color images available online at www.liebertpub.com/soro

structures for the new robot. This allowed us to design and build a system capable of following real-time commands as well as acting autonomously. By connecting to local hotspots, the Compute Stick is able to connect to the internet and send audio and video to its remote operator anywhere in the world. Adding an onboard smart phone, enables communication from anywhere there is cellular phone service of 3G or greater. To allow autonomous behavior, it was necessary to endow the robot with at least a minimal amount of artificial intelligence in the form of navigation, object detection, facial recognition, and verbal interaction using both speech recognition and synthesis.

Materials and Methods

Leg design

Each leg is made up of three individual tubes which are blocked at the ends with the exception of passages to allow the ingress and egress of pressurized air. The conjoined tubes are attached lengthwise so that their centers form an equilateral triangle at any radial cross section. Figure 2 shows a rendering of a completed leg tube. Each tube contains a tri-layered design incorporating a middle layer of twisted nylon mason line (Wellington 10 lb.) sandwiched between layers of Ecoflex 30 (Smooth-On). This spiral wrapped layer limits the tubes ability to expand radially while still providing freedom for axial expansion. Combining three of these tubes results in a one-piece leg joint that can be bent in any direction by expanding any one or two of the tubes. Expanding all three tubes results in an overall lengthening of the leg.

Tethered robots seldom need to assign a high priority to energy efficiency as an abundance of power can be supplied through the tether. Untethered robots, however, have a limited amount of energy stored and, therefore, need to be judicious with its use. Therefore, to carry the necessary equipment, it became obvious that a key goal for leg design must be energy efficiency. Such efficiency was realized by eliminating all unnecessary bending or stretching of the elastomer.

The stretching of the actuator can be modeled by Hooke's law if the speed of the elastomer's expansion or contraction is limited and the temperature disregarded so that the system deforms linearly.[5,6] In that case, the energy $E=\frac{1}{2}kx^2$, where x represents the displacement of one end of the spring/elastomer from its natural unstretched length. This is the case for actuators such as ours, where expansion is restricted to one dimension.

The conservative nature of spring/elastomer systems depends on the constant transformation of potential energy to kinetic and back again, with the potential energy stored in the medium being returned to the system. This is generally not the case with the stretching and contraction used in soft robotic elastomeric actuators. Compressed air within the actuator is usually released back into the atmosphere resulting in the loss of any energy that had been stored in the stretched medium and compressed air. If the soft actuator is used to do work to lift a mass, the energy required can be expressed by equation (1), where the first term represents the energy needed to stretch the elastomer, the second is the energy required to lift the robots center of mass, and the third represents the energy required to pressurize the volume of gas.

$$E=\frac{1}{2}kx^2+mgh+pV \quad (1)$$

With this in mind, three deductions were made in an attempt to increase the energy efficiency of the leg system design. First, mgh only becomes relevant if a leg expands while it is in contact with the ground. Otherwise, no lifting takes place. Therefore, to the extent possible, the body of the robot should remain at the same height during its gait. This suggests that legs should be designed to be lifted, moved, and set back onto the ground to support the structure while the next leg is activated.

Second, $\frac{1}{2}kx^2$ measures x from the actuators natural, unstretched position. Hence larger changes in x require quadratically more energy, most of which, as mentioned above, is eventually wasted. Therefore, we propose that the gait cycle of lift, move and support, be done with the minimal amount of extension needed. This results in the actuator remaining in the energy efficient portion of its range. It should be noted that the spring constant k can be changed by adjusting the overall length of the unstretched tube. Using

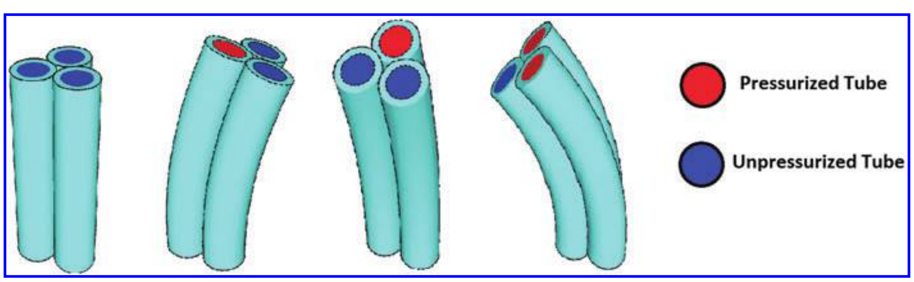

FIG. 2. A complete leg made from three tubes. The leg can be made to bend by pressurizing one or more tubes. Color images available online at www.liebertpub.com/soro

equation 2, where A_0 is the unstretched cross section, L_0 is the unstretched length and Y is Young's modulus, it is obvious that the spring constant k is inversely proportional to the length of the unstretched spring. Therefore, for a given Δx using an actuator with a longer unstretched length proportionally decreases k, and therefore, the total energy required. However, the practical length of the actuator is limited due to its propensity for buckling. The length for the legs was determined experimentally.

$$k = \frac{YA_0}{L_0} \tag{2}$$

A third form of loss results from allowing the expansion of the actuators in directions which do not accomplish any desired work. Figure 3 illustrates such a loss. The leftmost image (A) shows a mass resting on an unpressurized actuator tube, whereas the actuator tube in the center (B) is pressurized. The final rightmost image (C) is a tube with its radial expansion restricted. By comparing (B) to (C), it can be seen that some of the systems' energy is used to stretch the tube walls outward. Thus, the same volume and pressure of air results in a lower amount of useful work being done, that is, the weight is raised less.

With radial expansion/deformation restricted, the previously unutilized energy is harnessed to raise the mass to a greater height. Alternatively, for a given amount of work, a radially restricted actuator requires less compressed air at the same pressure as its unrestricted counterpart.

These considerations guided the prototype's design.

Leg construction

As depicted in Figure 4, a 12-inch length of 3/8 inch aluminum rod was obtained along with an 8-inch piece of ½ inch PVC pipe as well as a pair of ½ inch end caps. Each end cap was drilled in its center with a 3/8 inch drill bit. One was drilled halfway through, whereas the other was drilled completely through. The interior of the pipe and the aluminum rod were both lightly coated with petroleum jelly. Ecoflex 30 (Smooth-On) was then mixed and 30 g was poured into the pipe which had been capped with the half-drilled cap. The aluminum rod was placed into the pipe until it settled in to the half-drilled hole. At this point the fully drilled cap was slid over the rod and onto the pipe. In this manner the aluminum rod was guaranteed to be centered within the pipe and the Ecoflex 30 was allowed to set for $\sim$2 h. The aluminum rod and Ecoflex were removed from the PVC pipe. We found it useful to mount the rod in a vise while the pipe was pulled off. At this point, the resulting Ecoflex tube was removed from the aluminum rod, the rod relubricated and reinserted into the tube. This facilitated the final removal of the finished leg-tube in the final step.

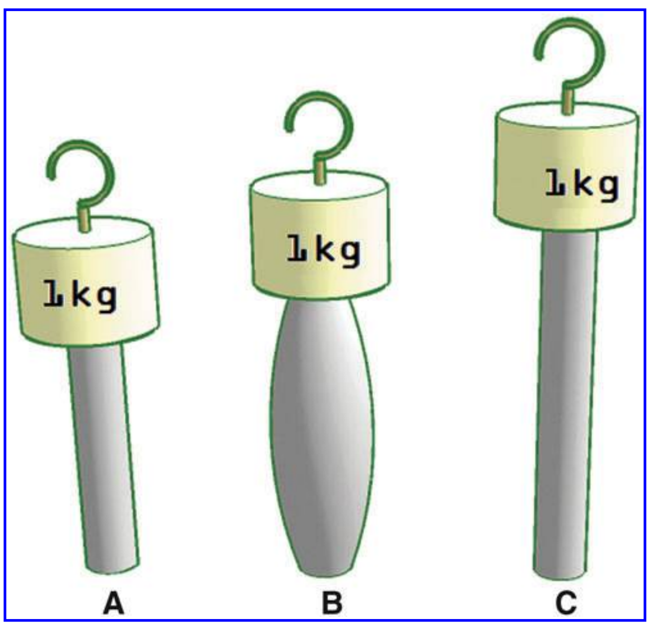

FIG. 3. **(A)** Unpressurized actuator. **(B)** Pressurized unrestricted actuator **(C)** Pressurized and restricted actuator. Color images available online at www.liebertpub.com/soro

The end of the aluminum rod was chucked into a battery-powered drill. Surveyor's string was tied around one end of the Ecoflex tube/aluminum rod assembly and the drill was slowly rotated, uniformly wrapping the string around the Ecoflex layer. No more drag than needed to accomplish an even layering of the string should be applied and the result should be a smooth wrap with no spaces or overlapping. At each end of the wrap, a drop of cyanoacrylate glue was used to hold the string in place while the excess was cut off.

Next, an 8-inch length of ¾ inch pipe and end caps were prepared in the same manner as the ½ inch ones. The pipe was capped with the half-drilled cap and 28 g of Ecoflex 30 is poured into the pipe. The aluminum rod was unchucked from the drill and the rod/Ecoflex/string was inserted into the ¾ inch pipe. Once the end of the rod was seated into the half-drilled hole, the fully drilled end cap was slid over the aluminum rod, again guaranteeing the assembly is centered. This was allowed to cure for $\sim$2 h at which point it was removed from the pipe and slid off the aluminum rod. The finished length of tube was then able to be cut to various lengths as needed.

Three pieces were cut to $\sim$100 mm and glued one to another with parallel axes using a thin bead of Sil-Poxy (Smooth-On). One end of each tube was plugged with a short piece of 3/8 inch aluminum rod, sealed with Sil-Poxy, and secured with a tie wrap.

Body construction

Because the design was focused on the soft robotic leg structures, the body design was viewed as completely utilitarian. A list of equipment was compiled based on the attributes we wished to include in the prototype. The main equipment included 6 pumps (Medo MAP-1704), 36 solenoids (Skoocom SC0411G), six 3.7 V li-ion batteries (Panasonic NCR18650), a quad-core computer with internet connectivity (Intel Compute Stick), a custom control board for each pair of legs, two webcams, and an optional iPhone 5. A final body size of $75 \times 125 \times 200$ mm was judged to be sufficient. A KraftMaid kitchen drawer organizer, which was $75 \times 75 \times 225$ mm, was chosen as a shell. A length of ½-inch square wood was cut and glued to form a 3-inch by 9-inch rectangle. A leg mounting block was created by cutting 3/8 inch hose barbs in half and pushing three of the halves into a sculpted block of clay. This form was then covered with Rebound 40 (Smooth-On) and allowed to cure for 1 h at which point the clay and hose barbs

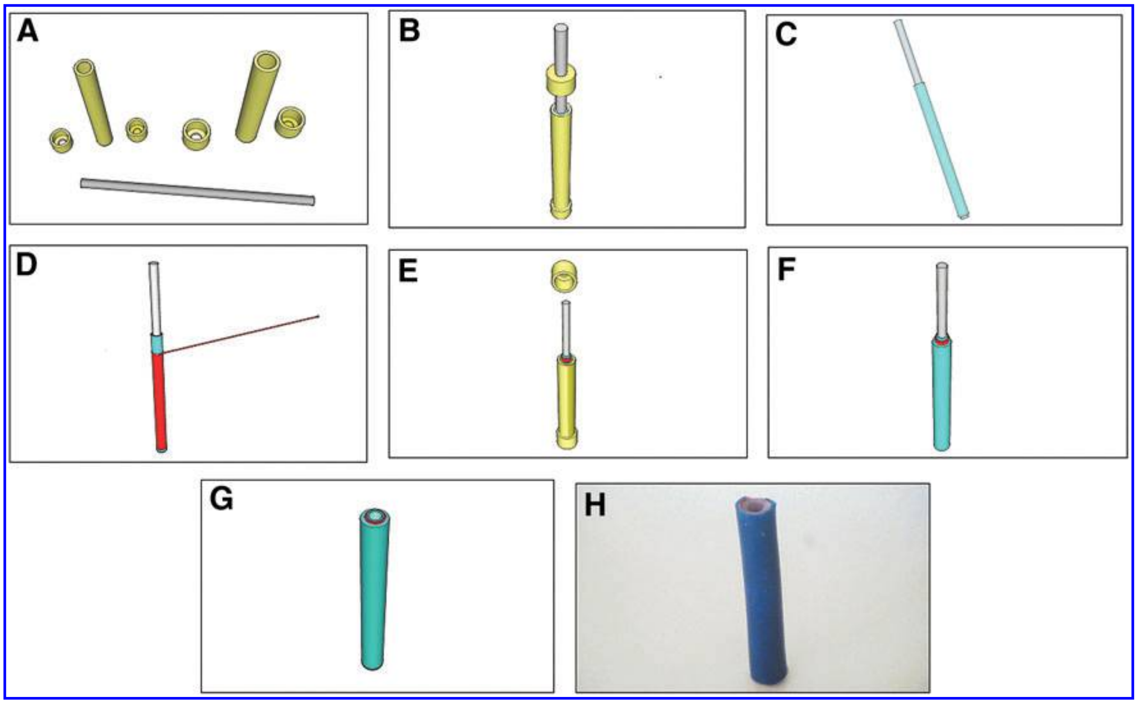

FIG. 4. **(A)** Molds needed for construction. PVC pipes, caps, and aluminum rod. **(B)** Capped pipe is filled with Ecoflex 30 rod is inserted. **(C)** Rod and Ecoflex removed from pipe. **(D)** Tube is wrapped with string. **(E)** Assembly is lowered into ¾ inch PVC pipe. **(F)** Pipe is removed after curing. **(G)** Rod is removed. **(H)** A completed tube. Color images available online at www.liebertpub.com/soro

were removed creating a mold. Smooth-Cast 45 (Smooth-On) was poured into the mold and allowed to cure resulting in a one-piece resin cast leg mount. Six mounts were created in this manner. Each tab was cocked ~30° to the plane of the frame. Finally, a pair of 1/8 inch holes was slowly drilled axially through each of the hose barbs to accommodate a length of 1/16 inch I.D. silicone tubing which was secured and sealed with a small amount of Sil-Poxy. A light coating of Sil-Poxy was also applied onto each trio of hose barbs and the three tubes of each leg were slid on. A Ty-Rap was fastened around the top of each leg tube.

Pneumatics

Compressed air is supplied by six Medo Air pumps. These pumps are inexpensive and lightweight and extremely quiet producing 41 dB of sound at 7.4 V. Measuring 27 mm in diameter and 64 mm long, they are compact with a mass of ~55 g.

Each pump produces ~2 cc's/s at 90 kPa. This pressure is supplied to 36 individual solenoids through a manifold and 1/16 inch I.D. tubing. Two of the tiny solenoids ($10\times10\times11$ mm with a mass of 4.5 g each) are connected to each leg tube opening it to either the atmosphere or to the pressurized manifold. By powering the solenoids each tube can be caused to expand or contract.

Power supply

The system is powered by six lithium polymer batteries which are connected into three separate banks of 7.4 V each. By using three separate banks we are able to adjust voltages as needed and to isolate sensitive computer components from the power buses that are prone to voltage spikes from the solenoids and motorized pumps. The batteries used were Panasonic model number 18650 that provide 3200 mAh each. The three banks are, therefore, capable of supplying about 60 watt-hours. Current draw of the prototype varies depending on how many solenoids are operating at the time, but measurements have shown that when the model is moving at full speed, the current draw is ~3 A at 7.4 V. This allows the prototype to run for ~3 h, however, by using isolated banks, the maximum run time is limited by the bank with the largest power draw. The onboard computer, microcontrollers, USB hubs and cellular hotspot all require a regulated 5 V supply. To accommodate this, two DC to DC buck power converters are employed to drop the voltage from a nominal 7.4 to 5 V. We chose LM2596 (Texas Instruments)-based modules capable of supplying up to 3 A each.

Command and control

Higher level controls were handled by the onboard microcomputer using multiple software packages, including a custom software package nicknamed MIND. Developed primarily in C++, Qt, and Visual Basic, MIND provides interfaces between the user and robot as well as the microcomputer and microcontrollers. Originally designed to biomimic the nervous system of a frog, the software isolates the chores for each component allowing independent autonomic actions by the individual microcontrollers to best accomplish the directives from the somatic control of the microcomputer. It can be used for training initial behavior as well as the implementation of learned routines. It takes advantage of several existing artificial intelligence applications such Micrsoft's SAPI 5 speech recognition and synthesis using an Ivona II voice package named Amy, as well as Intel's OpenCV computer vision for face and object

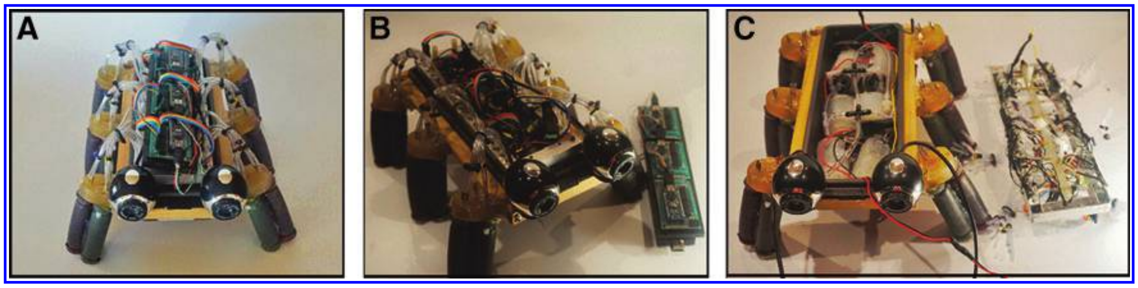

FIG. 5. **(A)** Assembled robot. **(B)** Control board removed. Compute Stick and USB splitters are on the bottom side of the board. **(C)** Solenoids housing removed. Thirty-six solenoids are mounted in the rectangle formed of aluminum channel. Six Medo air pumps can be seen wrapped in Ecoflex sheet. Color images available online at www.liebertpub.com/soro

recognition. Upon booting, MIND automatically uses the microcomputer's built-in Wi-Fi to connect to the Internet using either an external hotspot or its onboard cellphone. The robot has the ability to connect through its virtual private network VPN or using stealthy Linux operating systems Kali and TAILS (The Amnesic Incognito Live System). Once connected, the on-board system can be accessed by the operator using Google's remote desktop from anywhere in the world. A list of the software programs and operating systems is attached below.

While the Intel compute stick provides ample computing power, its single USB Port limits its ability to interact with other electronics. Therefore, it was necessary to build intermediary devices which could control the 36 solenoids as well as reading any data provided by sensors. Two four-port USB splitters were hard-wired together and connected to create seven independently addressable USB ports from the one. Three ports were connected to the Arduino Nanos, one for each one pair of legs. By opening and closing the 12 solenoids associated with the assigned pair of legs, the Arduinos could expand or contract any of the six leg tubes, thereby causing each leg to bend with three degrees of freedom. Six ULN2003 Darlington transistor arrays were used to accommodate the current draw of the solenoids. Figure 5 shows assembled robot as well as the control board and pneumatic system.

Each Arduino was programmed to read the digital stream received from the Compute Stick through its serial port. This data stream represented the status of each solenoid and the length of time each should remain in this state. The Arduinos interpret and execute the instructions by activating and deactivating the solenoids at appropriate times.

Two of the four remaining USB ports were dedicated to two webcams mounted on the front of the robot, whereas a

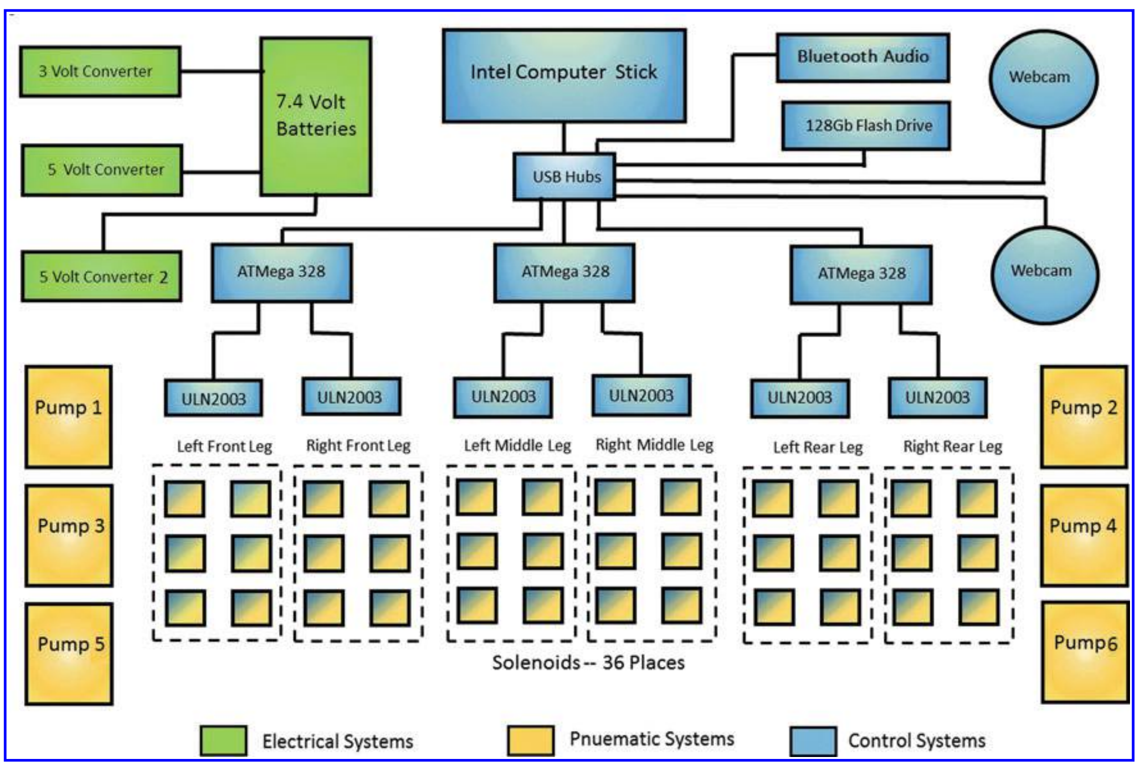

FIG. 6. Schematic overview of the power, pneumatic, and command/control system. Color images available online at www.liebertpub.com/soro

third USB Port contained a 128 GB flash drive. Combined with the 32 GB of internal memory and a 64 GB SD card, the system contained a total of 224 GB memory for data storage and software. A diagram of the complete control system is shown in Figure 6.

Results

The MIND software is bimodal, with separate learning and execution routines available to the user. During the learning mode, the individual leg tubes may be controlled by the operator through a graphical user interface, allowing the optimization of a particular gait. Once a satisfactory gait is obtained, the routine can be saved into memory making it accessible for use in the robot by a single button-push, function call or verbal command.

Upon booting into windows, the custom software automatically loaded, connected to the internet using a predetermined hotspot and waited for instructions. Connection to the robot was established through the internet using an HP EliteBook 8530p laptop running Google Remote Desktop in Windows 7. From the laptop we implemented a series of preloaded gates that were stored in the memory of the robot. These included walk forward, backwards, turn left, turn right, and rotate left and right. These were first preformed using voice commands and then initiated through an internet link. These are demonstrated in our Supplementary Video S1 (Supplementary Data are available online at www.liebertpub.com/soro).

Our first attempts at walking resulted in a speed of over 40 m/h, which is more than double the previous untethered soft robot by Tolley *et al.*[3] It should be noted that manifold pressure was affected by the number of input solenoids open at a time, as would be expected. We found that pressurizing more than four actuator tubes simultaneously resulted in enough pressure drop to cause notable slowing in inflation. Thus, if a multitude of input solenoids were opened concurrently, the length of time they were left open would need to be increased slightly. This adjustment can be easily accomplished by changes in the algorithms, however, for initial trials, we simply limited the number of opened input actuators to four. While this allowed better synchrony, it does not allow the full optimization of gaits. For this reason, we expect that adjustments to our existing software will allow the robot's top speed to be more than doubled from its current limit of 40 m/h.

While we succeeded in establishing control through internet connection, latency issues became problematic. Ping times between our laptop and robot were usually less than 500 ms, however, delays using Google Remote Desktop were much longer, often more than several seconds. This results in inefficient control routines if a small number of commands are issued by the operator at a time. Therefore, at least short autonomous behaviors become imperative for effective remote control. This issue can be avoided if dedicated software is written to replace Remote Desktop.

While we have performed some basic artificial intelligence routines such as voice commands, speech synthesis, and object recognition, we have only utilized a fraction of the computational resources available with the current platform.

One drawback in the current design is that over half of the power consumed by the device is used to power the control solenoids. This is a common issue in many pneumatic devices, however, the issue becomes critical if the device is reliant on battery power and has size/weight limitations. Our soft robotic leg system, designed to be agile, has more solenoids than most previous soft robotic designs making this an even more important issue. One of the future directions of our work will be to attempt to incorporate a new valve design that, if successful, will reduce valve power consumption and size by an order of magnitude. This reduced power consumption draw, combined with the weight and space savings, would result in a much smaller and lighter device, which, in turn, would require fewer batteries and pumps, thereby making the device smaller still. We hope and expect that these reductions will result in untethered soft robots of similar size to the original design of Shepherd *et al.*

Conclusion

We have demonstrated a soft robotic platform relying on highly dexterous legs to accomplish untethered mobility. The legs are versatile, simple, and inexpensive to build.

We have shown that adding more degrees of freedom through additional actuators, our design was able to carry as much hard equipment as previous untethered soft robots, but do so with a much smaller footprint and a mass of only 2 kg. We have also shown that the number of soft actuators can be increased with only a small resulting increase of support equipment and power supplies, thereby making it both economically and energetically inexpensive.

The inclusion of an onboard microcomputer, interfaced with multiple microcontrollers, allowed the robot to follow real-time verbal commands as well as act autonomously. By utilizing off-the-shelf parts and freely available software such as Microsoft's SAPI5 speech system (through preinstalled Windows 8) and Intel's OpenCV computer vision system, we were able to design a self-propelled device capable of displaying rudimentary artificial intelligence skills for less than $500 (excluding a smartphone).

Software Packages

Operating systems/security

WINDOWS 8 Windows 8 32 bit Operating System.

KALI LINUX Kali 32 bit Linux operating system/Penetration Testing and network security assessments.

TAILS (The Amnesic Incognito Live System) Linux-based operating system provides complete online anonymity.

VIPER VPN A global Virtual Private Network (VPN) with points of presence in the United States, Europe, Asia, and Brazil. 128-bit and 256-bit encryptions.

Artificial Intelligence Packages

SAPI5 Microsoft (*Speech Application Programming Interface*) Provides speech recognition and synthesis systems.

IVONA VOICES IVONA is a multilingual speech synthesis system, which offers a full text to speech system with various APIs. Provides a multitude of voices and languages.

OPENCV (*Open Source Computer Vision*) a library of programming functions for real-time computer vision, developed by Intel research in Nizhny Novgorod (Russia).

MIND Controller package written in C++, Visual Basic, and Qt.

Author Disclosure Statement

No competing financial interests exist.

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