Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2016, 3(11): 1-9

Research Article ISSN: 2394 - 658X

A Perspective for Soft Robotics: Bio-Inspired Evolution in Robotics

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ABSTRACT

For the evolution of innovative robots, the method of approach that plays a vital role is biological inspiration. The concept of the Inspire-Abstract-Implement (IAI) design flow as a criterion for innovative, biologically inspired robots are introduced in this article. With the exploitation of their soft structures, animals are able to move effectively in complex natural environments. Taking inspiration from such natural phenomenon, robotics engineers have been inspired to incorporate soft technologies into their design for optimum results. The objective is to equip robots with modern, bio-inspired facilities which permits adaptive, flexible and pliable interactions with unpredictable environments. This paper reviews soft-bodied robotics systems and focuses on the current advancements that has kindled inspiration by soft-bodied animals. Integrating technologies inspired by soft-bodied animals can make mechanical and analytical complexities easier, and can even result in a comparatively more natural outcome. Consolidating this technology might even hasten the improvement of machines, which are able to interact with humans and natural environments without danger. These machines have the ability to achieve deformations to a vast extent and are able to use the compliant distortions of the body to adapt to a particular surrounding. In conclusion, incorporating soft technology with various fields can be done to create hybrid structures for innumerable practices.

Key words: Caterpillars, GoQBot, Inch-worm, Octopus

INTRODUCTION

A famous example in which a bio-inspired design has dramatically altered our daily lives is the development of Velcro., Swiss Inventor George de Mestrel while taking his dog for a walk in the forest was fascinated by the sticky nature of the Burdoch plant seeds that fastened to his dog's fur. After examining the seeds, he found that they were coated with hundreds of miniature hooks that attached itself to fibrous materials with a loop. The simplicity of this biological mechanism urged the inventor to apply the same design to adhere artificial surfaces to each other reversibly. Velcro, now a compelling technology for various consumer product applications and a key demonstrator of a bio-inspired design, was invented.

Once just a theory in science fiction, fortunately for developments in materials like nanocomposites and polymers, such 'Soft Robots' are becoming an increasing possibility. Compliance and distortion capability carries with it significant inhibitions in terms of actuation, power and payload. Thus the responsibility is upon scientists to uncover methods of manipulating systems more efficiently.

Luckily, the environment itself presents several viable prototypes that can be used to our advantage. Among them, many of the large living organisms such as the octopus, caterpillar, fish and insects have played major roles in this field of Robotics. Analysis on how these organisms make use of their soft structure in order to be mobile in complicated, uncertain environments are able to impart extremely useful understanding into evolving soft robotic applications in the search & rescue, fields of medicine, human assistance and disaster response [1][2]. The soft materials adapt to surfaces, spreading stress over a bigger area and increase the time of contact, thus decreasing maximum contact force. Its flexibility and deformability has added functional advantages, such as entry into small openings.

Finally, it is the ecological function that decides the evolutionary likelihood to be rigid or flexible. Animals that do not move quickly need not have a permanently stiff skeleton and can instead develop deformable bodies that allow it to exploit behaviours unavailable to skeletal animals.

The octopus can mimic its surroundings, the caterpillar can conform to their host plants that is enigmatic and they can all push through openings that are tinier compared to their own unconstrained body. Soft animals tend to be small, because they have to bear their own body weight in the absence of a skeleton. The large deformability and energy absorbing capabilities of these soft tissues provide restriction in terms of applying huge forces and limiting how quick soft animals commute from place to place. Octopuses can stretch their limbs quickly by making use of the fixed volume, low-aspect ratio geometry of their arms [3], and carnivorous caterpillars can strike their prey within a few hundred milliseconds [4].

One problem that is faced with developing soft robots is, there is no basic theory on how to manipulate such unrestrained structures. Engineers in the Robotics field have started to advance this particular knowledge by building prototypes based on the neuro-mechanical schemes that soft structured animals use to commute, mainly earthworms and leeches [5], octopus [6] and caterpillars [2].

Rolling Robots Inspired by Ballistic Movements in Caterpillars

The larvae of moths and butterflies are another category of animals that roll. A scheme against prevailing hunters is to move away quickly. There exists a category of caterpillars which when are disturbed quickly curls into a structure that is wheel-like. The technique increases the momentum which is able to transport the animal into a rolling locomotion with a velocity of about 20 cm s^{-1}. Despite the qualitative and detailed descriptions of this behaviour, very little is known about the challenges with respect to its control and mechanics. A caterpillar must make use of certain mechanical manipulation schemes to help the neural motor commands in order to finish the morphing of its structure in less than 100 ms and propel itself into a stable path.

The GoQBot, can crawl around in its conventional work-like morphology and also arch itself into a wheel-like structure in order to improve locomotion velocity over 20-fold. The kinematics closely looks like and replicates the trajectory chosen by the caterpillar during an escape reflex (Figure 1. C). The ground reaction force and the high speed kinematics tracking reveal a variety of important mechanical and analytical concerns. These findings offer help in understanding the neural and mechanical challenges associated with the improvement of body manipulation in caterpillars.

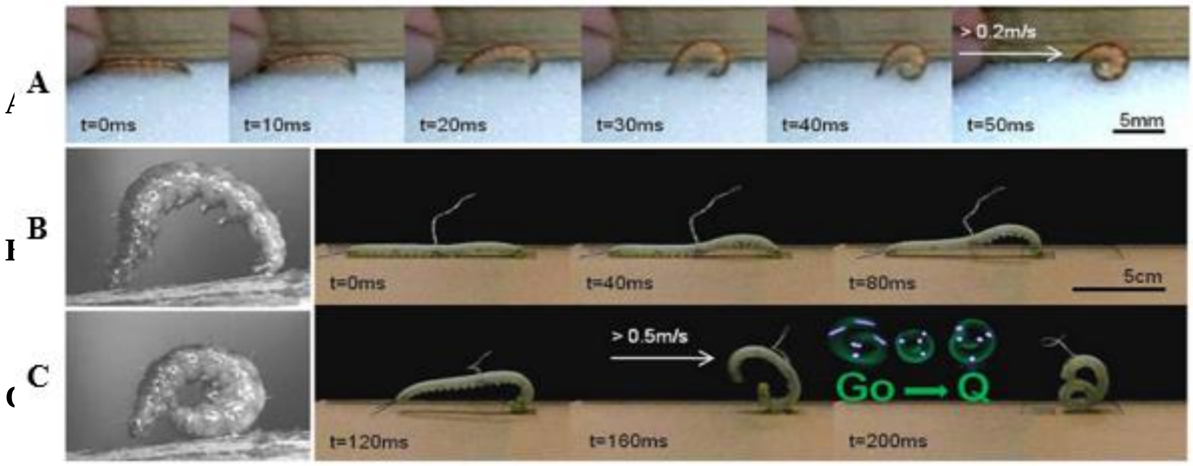


Fig. 1 Robotic simulation and the Ballistic rolling in Caterpillars. A) After receiving a head blow on the ground, caterpillars arch backwards into a wheel-shaped structure in order to escape. This snapshot particularly shows a standard motion cycle from a caterpillar in the family Crambidae. B) This shows the animal uses its terminal prolegs as ground anchor and the thorax as the skid. C) The simulation of the ballistic rolling behaviour in details in the GoQBot is shown. It is approximately five times bigger in size than the actual animal and it takes about four times longer to accelerate the robot into the rolling trajectory. However, it is to be noted that the animal performs the same motion backwards whereas the robot implements the same movement in the onward path for ease [2]

SOFT ROBOT: DESIGN AND METHOD- THE OVERALL SOFT ROBOT ARCHITECTURE

In order to simulate the locomotion of caterpillars in Soft Robots, the caterpillar body is reduced into functional components. There exist two major tensile actuators that allow independent manipulation of anterior and posterior flexion. It also consists of a couple of tail skids that supplies lateral stability for any inching movement. The posterior position of the body flexes to initiate an onward shift in a typical crawling gait. All hierarchical GoQBots maintain same body architecture.

This version of the GoQBot focuses on only straight-line ballistic rolling feature. Firstly, the cross-sectional portion of the Robot was domed. Secondly, tiny segments of wedge shaped legs were forged along the ventral body in order to make possible ventral flexion. Since it is already mentioned above that the GoQBot produces motion in the onward path for the sake of pure ease, thus the hammer head and the pair of tail skids of the GoQBot function like the anal prolegs and the thoracic legs of the animal. GoQBot consists of a hammerhead that is cylindrical in shape with a thin layer of tacky silicone rubber which improves friction. The pair of lateral skids that protrudes from the tail of the GoQBot supplies quite less friction contact to the ground and helps align the body in a ballistic curling movement. These also aid in stabilizing the trajectory of the body particularly during the low-speed initial stage of a ballistic curl [7].

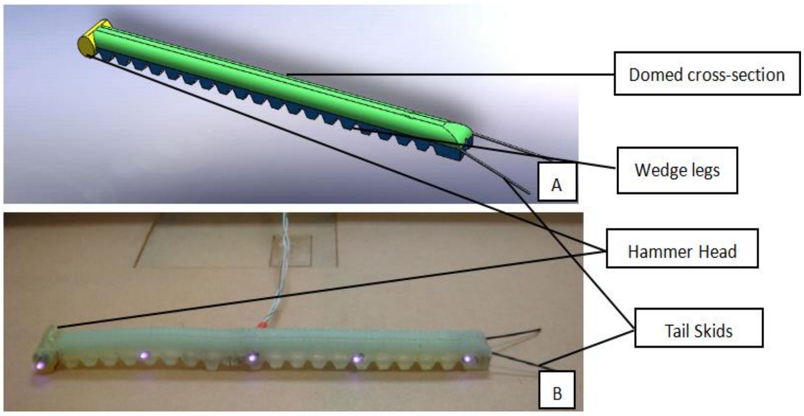


Fig. 2. A) A composite body (GoQBot) consisting of many varieties of silicone rubbers (displayed as various colours in this CAD drawing). B) Five Infrared (IR) LEDs bound on the left side of the body of kinematics tracking [7]

Inch-Worm Based Robots

Numerous studies have been conducted based upon the inchworm and its noteworthy locomotion patterns. The study of inchworms has inspired a new biometric robot known as Omegabot was built. The robot is comprised Smart Composite Microstructures (SMC). An Omegabot can travel in one direction and can approximately travel its body length per stroke along rough surfaces, leaf edges, and boughs of trees. Lee et al also designed a robot with a similar principle as that of the Omegabot. This robot is a motor-actuated, centimeter-scale inchworm with bi-directional claws. Ueno et al [8] developed an inch worm using Electro-Conjugate Fluid (EFC) which is a fluid that flows when subjected to a high DC voltage. The EFC used produces deformation and suction of the robots body. This inchworm is capable of two-way motion. An inch worm robot with one direction of motion made by using glass fiber reinforced plastic was built by Kim et al [9]. The strides of this inch worm is 1/24 of its own body length. Inch worm based robots tend to have relatively small strides and are often only capable of one direction of motion.

An inchworm is larvae of moths of the family Geometridae. Depending on the type of inchworm, the body parts and the location of the true legs tend to differ. For instance, some inchworms have two or three pairs of prologs at the back of its body and its true legs at the front whilst other inchworms have prologs located all along the inchworms body. The figure 3 shows a real inchworm with its longitudinal muscles contracted (top left) and a cross section of its abdomen showing its main muscle structure (top right).

The body of an inchworm shortens when longitudinal muscle fibres contract thus leading to bending deformation of the inchworms body. As a result of leaving both the true legs and the prolegs inactive thus the inchworm uses looping gait for locomotion. The longitudinal muscles fibres on the inchworm can be actuated symmetrically or asymmetrically. When these muscles are actuated asymmetrically, the body of the inchworm undergoes nonsymmetrical deformation which in turn leads to the inchworm using one of its feet as an anchor and turning. However, if the longitudinal muscle fibres are actuated symmetrically, the inchworm will undergo a linear locomotion. If both linear and turning motion are required, then the sequence of motion can be divided into two: an anchor-pull locomotion and an anchor-push locomotion, as shown in the figure 4.

In a study, a robot inspired by bio-mimicking an inchworm was built using SMA-based SSC structures. These structures are capable of mimicking both the linear and tuning motion of an inchworm. Based upon the function of the inchworm, the segments will differ in number. The two main parts being the body and feet. The robot achieved a stride length of 54 mm, which is nearly a third of its' body length, with a linear speed of 3.6 mms^{-1} a linear locomotion efficiency of 96.4%, a turning stride angle of 4.3 degrees, and a turning linear locomotion efficiency of 39.7%. The efficiency of the turning locomotion was compared using different feet configurations to determine the better solution.

The linear stride length and the stride turning angle of an inchworm is much higher than reported in other studies. These robots are simple in their construction, light in weight, don't make noise and can be used when flexibility and deformations is a priority. This robot would be efficacious in rescue and exploration where large robots cannot be used. Increasing the mobility using independent control systems is a field that is currently rising and it would increase the efficiency of mobility.

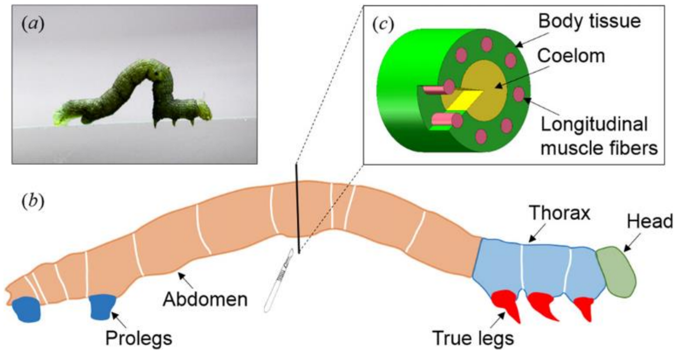


Fig. 3 A) An inchworm. B) Side view of an inchworm. C) Sketch of its main muscular structures

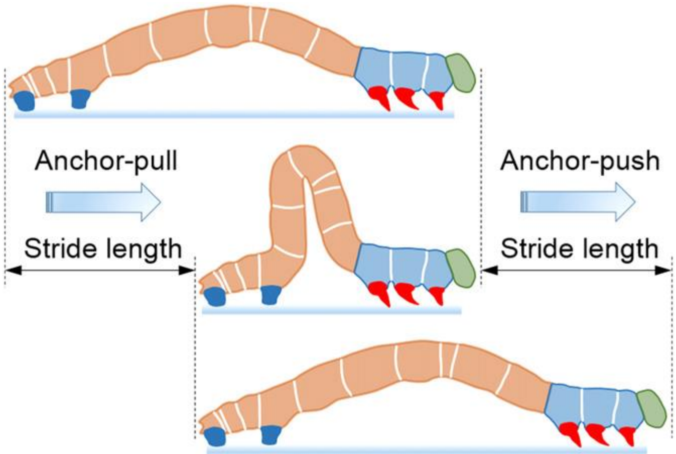


Fig. 4. Locomotion of an inchworm for one stride

Octopus-Inspired Specifications

After further research in the field of soft robotics researchers began focusing more on improvement of a submerged gripper that uses delicate mechanical autonomy innovation to carefully control and test delicate species from the ocean. The outline of an artificial solid hydrostat for soft robotic arm depends on the specific course of action of the octopus' muscles that gives the vital engine capacities by acting equally and filling in as a deformable skeleton ([5], [10]). The morphology and biomechanics of the arm have been depicted in [9] [11] [15].

Octopus's arms lack joints and rigid links, thus, the arms have basically boundless freedom of movement. These flexible appendages exhibit specific biomechanical abilities such as consistence, stiffness control, dexterity, and high adaptability. Instrumentally defined conventions and setups are utilized with a bio-designing way to deal with evaluate the mechanical execution of the transverse and longitudinal muscles [16]. To quantify straightforwardly the dynamic mechanical properties of the arms, focused on instruments were created that would lead the creature to perform the wanted assignment which made it conceivable to gauge arm execution [17] [18]. The setup incorporated a bolster plate that joined a graduated tube made up of transparent Plexiglas. The mechanical assembly is proposed to gauge one arm at once with the bolster plate keeping the octopus body separated and it is adjusted for this reason utilizing sensors (i.e. load cells) and mechanical parts (i.e. springs).

The morphology of the tissue and arm density are assessed in vivo utilizing ultrasound imaging (Esaote MyLabTM-Five VET with a linear transducer LA435, 18 MHz), making it conceivable to investigate the three anatomical planes of the arm quickly and over and again [19]. The octopus is prepared to embed one arm at once into the contraption for the estimations. Food is put inside the tube as a prize. The food hung utilizing a string, moved to acquire the prolongation estimations and appended to a heap cell to gauge the pulling compel or to a spring–sensor framework to quantify shortening and hardening.

Octopus-Roused Answers for Delicate Mechanical Autonomy

The morphological elements uncovered by the top to bottom investigation of the octopus arms have been deciphered into configuration ideas utilized for delicate automated segments. An automated arrangement has been produced for every element of the octopus arm utilizing acceptance test. The consequences of the tests were contrasted with a biomechanical estimation which approves the proposed arrangement. Twisted framework was utilized for development transmission and the control of shape changes. Plaited sleeves are monetarily accessible and it is conceivable to pick among various materials, sizes and meshing strategies.

A specimen of the plate with transverse actuators was tried to assess the vital power for nearby distance across lessening. As an octopus' connective tissue and diagonal muscles, the twisted sleeve is the point between the fibres that make the longitudinal pivot out of the structure and meshed sleeve. Beginning edge of 70◦ is decided for the brain taking into account the point between the mesh fibre and the longitudinal hub of the chamber. Like the connective fibres in the octopus arm [3], the structure is prolonged amid breadth lessening.

On the off chance that the structure is latently discharged, the disfigured point gives back the whole unit to its unique shape as a result of the configuration very still. In this way, the twist is fit for making an interpretation of measurement lessening into stretching comparatively to the connective tissue sheets. In the meantime, the arrival of the structure causes an aloof come back to the first shape. The round and hollow shape is kept up amid lengthening and shortening, and the width lessening has the greatest impact on extension close to the transversal segment of every unit comparing to the area of the transverse actuators; the impact diminishes while moving sideways. The qualities of the structure imitate the part of the connective tissue of the octopus arm. This structure maintains a strategic distance from nearby disfigurement, encourages worldwide lengthening and guarantees a prevalent execution.

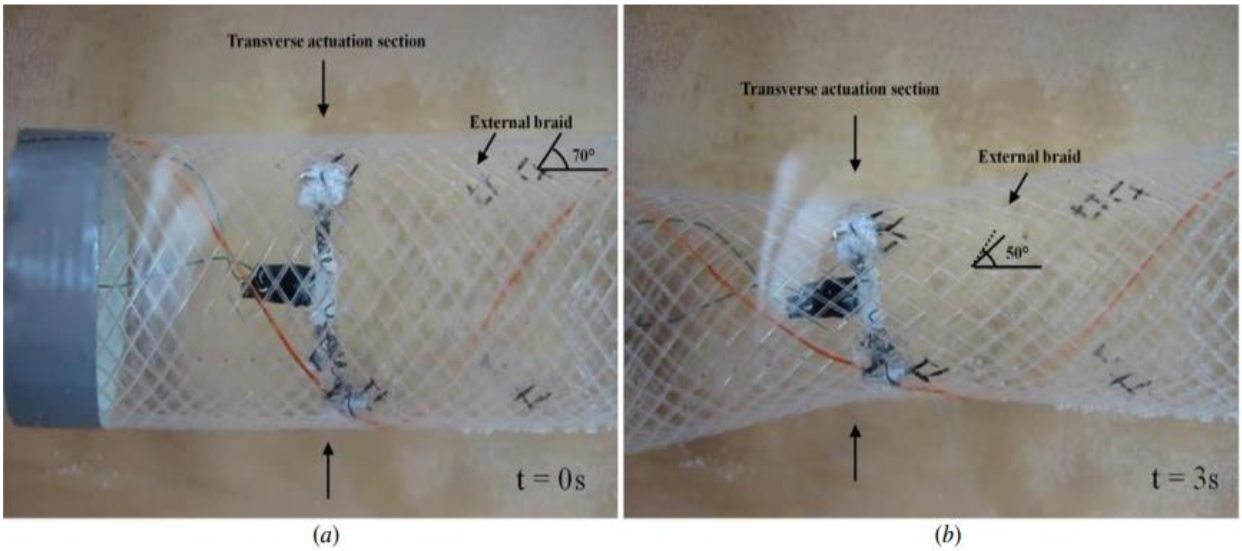


Fig. 5. In view of trial tests and an expository model of an artificial strong hydrostat unit, the distance across of lessening of 20% was found to create a prolongation of 90% with point fluctuating from 70◦ (figure 7(a)) to 50◦ (figure 7(b)) [19]

BIO-PROPELLED IDEAS

Design

Utilizing ultrasound innovation, specialists acquired auxiliary data about the octopus arm, which was moved into the mechanical framework. The transverse muscles recommended that radially organized actuators would be the most efficient component of breadth decrease and significant stretching. The course of action of the longitudinal muscles and insertion focuses proposed the utilization of longitudinal actuators as links along the arm to encourage bowing at different focuses. The sinusoidal plan of the arm nerve line proposed the configuration of electronic materials into wavy shapes in installed stretchable gadgets. [19].

Longitudinal Actuators

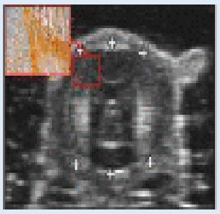
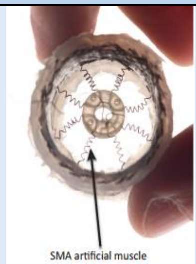
The longitudinal muscles were examined utilizing power and solidness estimations. Links are secured with sheaths to decrease grinding and stay away from silicone harm. The mean pulling power of 40 N with a contracting time of 1–2 s, the control of the grip point position, the shortening strain (20%) and the variability of the solidness are utilized to accept the coupling of the longitudinal actuators and the silicone in element developments [19]. Amid pulling, a grip point position at 75% of the aggregate length was utilized to permit getting a handle on and the distal quarter of the arm was utilized as an end effector.

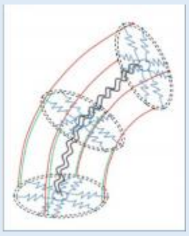
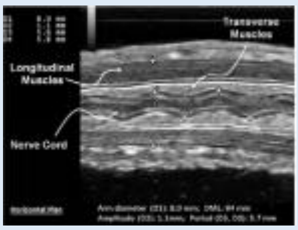
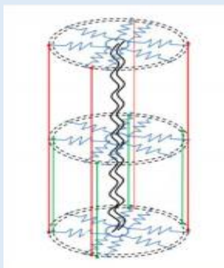
Transverse Actuators

Octopus arms are steady volume structures with high length to width proportion, thus can extend gigantically up to 70%.With the automated framework, specialists got same execution however with 20% lessening in measurement. This specific study speaks to a fruitful case of biomimetic technique, where the extraction of quantitative organic information, measured with building apparatuses, has been used to decide designing determinations and mechanical arrangements, without duplicating however understanding standards and actualizing them.

The proposed mechanical arrangements speak to a decent interpretation of science into apply autonomy, going past the conventional idea of great mechanical frameworks and speaking to a test for delicate apply autonomy and exemplified insight.

Table -1 Summary of Octopus Bio Specifications with Robotic Solutions

<table>
<tr><th>Bio Inspired Ideas</th><th>Design</th><th colspan="3">Bio Specifications (octopus vulgaris)</th><th>Robotic Solution and Performance</th><th>Measuring Method</th></tr>
<tr><td>Mechanical External Interface</td><td>Design</td><td colspan="3">Crosslinked fibres forming 68°-75° angles with longitudinal axis of arm Origin & Instruction of muscular fibres, supporting and energy store structure during the movements of the arm</td><td>Crosslinked fibres allow control in change of shape as well as allow movement transmission by forming 70° angle with longitudinal axis</td><td></td></tr>
<tr><td rowspan="2">Transducer Actuators</td><td>Design Arrangement</td><td colspan="3"></td><td></td><td>Ultrasound
(MyLabFive-VET@18MHz)

Histology
(Milligan-Trichrome straining)</td></tr>
<tr><td>Mechanical Performance</td><td colspan="3">70% of mean arm elongation corresponds to 23% reduction of diameter</td><td>Input to model for design of SMA helix :
• Wire Diameter
• Average spring Diameter
• Number of coils
• NiTi alloy mechanical properties
• Entire spring dimension</td><td>In vivo Biochemical measurement
(24 octopuses,112 max elongations)</td></tr>
<tr><td rowspan="3">Longitudinal Actuators</td><td>Design Arrangement</td><td colspan="3"></td><td></td><td>Histology
(Milligan-Trichrome staining)</td></tr>
<tr><td rowspan="2">Mechanical Performance</td><td>Mean pulling force</td><td>Mean shortening strain</td><td>Time to contact</td><td rowspan="2">• Longitudinal cables
• Calibration parameters(t,F)
• Sheaths to reduce friction & avoid silicon damages</td><td>In vivo Biochemical measurement
(2 octopuses , 928 max pulling force)</td></tr>
<tr><td>40 N with arm length 400mm</td><td>20%</td><td>1-2 sec</td><td>In vivo Biochemical measurement
(1 octopus ,559 measures)</td></tr>
<tr><td>Grasp Point Position</td><td></td><td colspan="3">75% of total arm length</td><td>End effector position & active arm length</td><td>In vivo Biochemical measurement
(2 octopus 928 measures)</td></tr>
<tr><td>Electronic Hardware</td><td></td><td colspan="3">
Sinusoildal arrangement at arm rest length &distension during the elongation process</td><td>
Using sinusoidal arrangement ,large elongations is achieved for electrical cables</td><td>Ultrasound
(MyLabFive-VET@18MHz)</td></tr>
</table>

Soft Robotic Fish

Today there are various type of soft robotic fish have been produced such as Biomimetic Robot Fish [20], Robot Fish FILOSE [21], Aircauda Fish [22], etc. which bring us closer and closer in mimicking the actual motion of a biological fish. Andrew D. et al article on an Autonomous Soft Robotic Fish capable of Escape Manoeuvres Using Fluid Elastomer Actuators [22] shows how far we have come from since MIT's Robotic Fish Robotuna [23] made in 1994.

Construction of Basic Soft Robotic Fish

Soft materials are key empowering agents for making soft body robots. Young's Modulus plays an important role in measurement of rigid Materials that are used for the fabrication of parts of the soft robot. Usually traditional materials such as hard plastics, metals, etc. tend to have a moduli on the order of 109 –1012 Pa. Natural organisms tend have a moduli of 104 -109 since they are made up of muscle tissues, ligaments, skin, etc. [24] Hence soft robots materials mainly consist of materials that whose moduli coincide with that of natural organisms for the fabrication of soft biological materials which aid creating systems capable of autonomous behavior.

Soft Robotic Fish has all the subsystems of an ordinary robot present in it. These include a computing and control system, an actuation system, end effectors, driving hardware components and a power system. Previous approaches to build fish like robots resulted in robotic fish bodies which were hard i.e. composed of finite joints and rigid links. Soft body robots provided an alternative which provided continuous deformation of the bones and infinite degree of freedom theoretically [20].

The mechanical design of general soft robotic fish functions on three important functional components, which are: i) Using the Soft Tale of the robotics fish for forward drive and yawing motions. ii) Pitch control by waterproof servo actuated drive planes. iii) Actuation of tail via waterproof gear pump.

A Fluidic Actuation Source is required to enable the smooth and sleek movement the soft robotic fish. In early soft robotic fish designs, compressed gas cartridges were used, for fast propulsion, as an energy source as pneumatic actuation. Due to the limitations faced by the pneumatic actuators, fluidic elastomer actuator is now used as a better alternative. A closed circulation actuation approach utilizing an incompressible fluid like water and gear pump (included with actuating DC motor) to move it forward and backward. The premise of proprioceptive sensors for a soft robot is typically either non-contact sensors or low modulus elastomers consolidated with liquid phase material. Since soft robots are impelled by producing shapes, proprioception depends on curvature sensors. The low modulus of proposed elastomer sensors, which have moduli in the scope of 105- 106 Pa, cause insignificant changes on the impedance of the basic structures. These sensors for the most part have layered structures, where various flimsy elastomer layers are designed with microfluidic channels by delicate lithography. The channels are in this way loaded with a fluid conductor, such as gallium-containing composites, for example, eGaIn). Hence this makes it possible for tailor sensors in measuring of different strains including elastic, shear, or curvature.The Control System in a basic Soft robotic Fish consists of a MCU, PLD, Motor Drives and Wireless Module as seen in Figure 9. The Microcontroller unit is able to communicate with other devices via Wireless module. Once the Microcontroller unit receives and input, it sends a pulse-width modulation signal to the motor drive to control the tail motors speed thus controlling the oscillating frequency of the tail. The PLD controls the servo actuator of the fins via pulse –width modulation which cause the fins to perform the required motion.

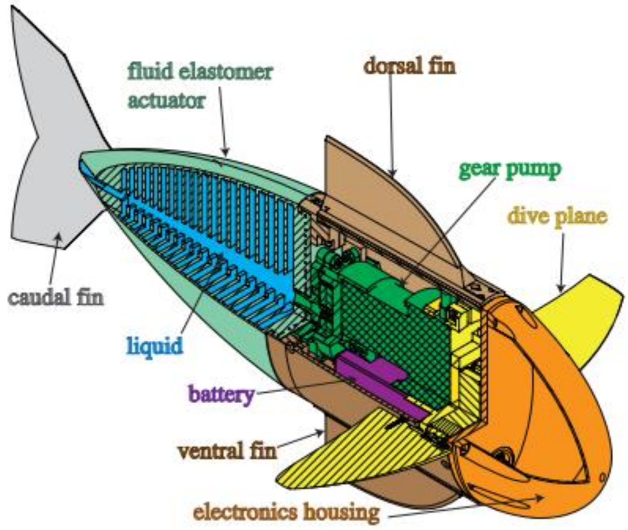


Fig. 6. Soft Robotic Fish

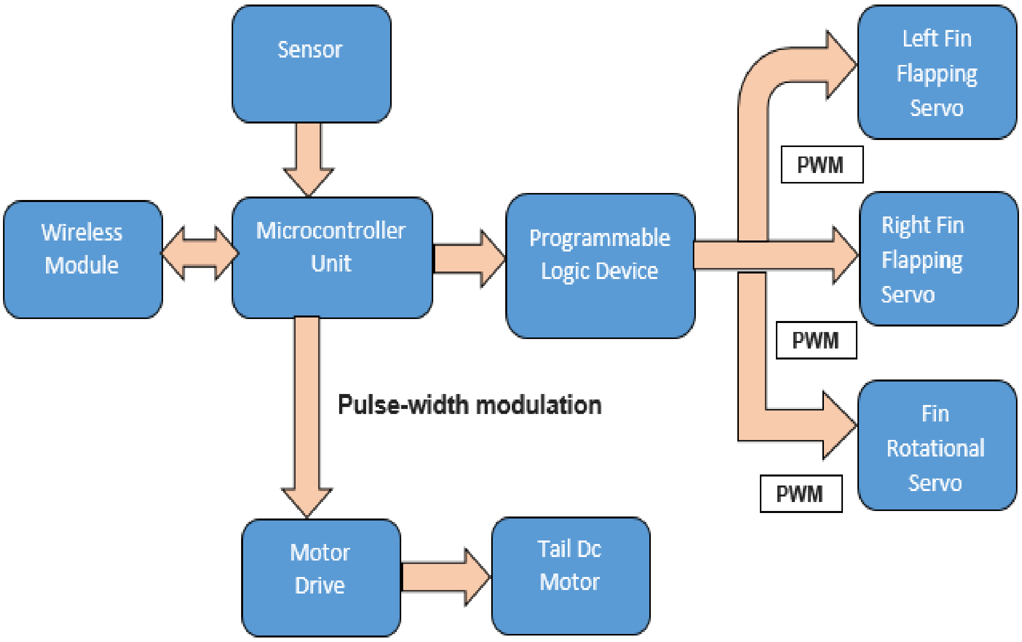


Fig. 7. Block diagram of a Control system

The Soft Robotic Fish may make intelligent decisions and take the necessary actions based on the information's provided by the sensors. Infrared sensors are used to detect obstacles. In the Biomimetic Robot Fish [20], three sensors were mounted on the right, middle and left sides of the robotic fish. According the input given by the three sensors the robot fish made necessary decisions and carried out necessary actions. Increasing or decreasing swimming speed, avoiding obstacles, swimming to safety are a few examples of the real time actions taken by the Soft robot.

CONCLUSION

Everyday there are new fields in science that arise and that are currently being explored. SOFT Robotics is among one of this field. The exploration of this field can have vast reaching advantages in mimicking biological species down to their amorphous structures. Soft Robots will greatly help in the improvement of robots fit for interaction with human and the environment by giving more secure and robust interactions than currently accessible with routine apply autonomy, versatile practices that utilize mechanical knowledge also, thus streamline the controllers required for physical communication and give rise to cheaper and less complex comments of robots .To make an era of SOFT robots in certifiable circumstances requires consistent incorporation of different various fields, for example, bioengineering, medication, mechanical, electrical and material science. This enables the creation of robots that can be as small as inch worms to as large as an octopus and these robots can have the same fluid motion as the species they mimic. Although SOFT Robotics could explore an untapped field that is ready to be explored, it also suffers from certain drawbacks. Currently, there is no robot that has been built with the ability to mimic a living organism completely due to neural computations required in order to perform certain complex tasks. However, advances in SOFT Robotics are promising and hopes to be able to reproduce effects similar to those in organisms, in robots are endless.

REFERENCES

[1] E Brown, N Rodenberg, J Amend, A Mozeika, E Steltz, MR Zakin, H Lipson and HM Jaeger, Universal Robotic Gripper Base on the Jamming of Granular Material, *Proceedings of the National Academy of Sciences*, USA, **2010**,107(44), 18809–18814.
[2] HT Lin, Gary G Leisk and Barry Trimmer, GoQBot: A Caterpillar-Inspired Soft-Bodied Rolling Robot, *Bioinspired & Biomimetic*, **2011**, 6 (2), 026007.
[3] WM Kier and KK Smith, Tongues, Tentacles and Trunks - The Biomechanics of Movement in Muscular-Hydrostats, *Zoological Journal of the Linnean Society*, **1985**, 8(4), 307–324.
[4] SL Montgomery, Carnivorous Caterpillars: The Behavior, Biogeography and Conservation of Eupithecia Lepidoptera: Geometridae in the Hawaiian Islands, *Geo Journal*, **1983**, 7, 549–556.
[5] S Seok, Cagdas D Onal, and Robert Wood, Peristaltic Locomotion with Antagonistic Actuators in Soft Robotics, *IEEE International Conference on Robotics and Automation*, **2010**, 1228–1233.
[6] Cecillia Laschi, Matteo Cianchetti, Barbara Mazzolai, Laura Margheri, Maurizio Follador and Paolo Dario, A Soft Robot Arm Inspired by the Octopus, *Advanced Robotics*, **2012**, 26, 709–727.

[7] RL Caldwell, A Unique form of Locomotion in a Stomatopod - Backward Somersaulting, *Nature*, **1979**, 282 71–3
[8] G de Croon, M Groen, C De Wagter, B Remes, R Ruijsink and B van Oudheusden, Design, Aerodynamics and Autonomy of The Delfly, Bioinspiration and Biomimetics, **2012**, 7 (2), 025003.
[9] Cuvier G Memoires Pour, Servir a lhistoire et a lanatomie des, mollusques Memoires sur les Cephalopodes et sur leur ´Anatomie Paris: Deterville, **1817**.
[10] C Laschi, B Mazzolai, V Mattoli, M Cianchetti and P Dario, Design of a Biomimetic Robotic Octopus Arm *Bio inspiration & Biomimetics*, **2009**, 4, 015006.
[11] G Colasanti, Anatomische und physiologische untersuchungenuber den arm der kephalopoden, Archiv für Anatomie, *Physiologie und wissenschaftliche Medicin*, **1876**, 9, 480–500.
[12] WM Kier and KK Smith, Trunks, Tongues and Tentacles: Moving with Skeletons of Muscle, *American Scientist*, **1989**, 77, 28–35.
[13] Y Yekutieli, R Mitelman, B Hochner and T Flash, Analyzing Octopus Movements using Three-Dimensional Reconstruction, Journal of Neurophysiology, **2007**, 98 1775–90.
[14] Y Yekutieli, R Sagiv-Zohar, R Aharonov, Y Engel, B Hochner and Flash T, Dynamic Model of the Octopus Arm: I. Biomechanics of the Octopus Reaching movement, Journal of Neurophysiology, **2005**, 94 1443–58.
[15] Y Yekutieli, R Sagiv-Zohar, B Hochner and Flash T, Dynamic Model of the Octopus arm: II. Control of reaching movements, Journal of Neurophysiology, **2005**, 94 1459–68.
[16] L Margheri, C Laschi and B Mazzolai, Soft Robotic Arm Inspired by the Octopus: I. from Biological Functions to Artificial Requirements, Bioinspiration & Biomimetics, **2012**, 7, 025004.
[17] L Margheri, B Mazzolai, M Cianchetti, P Dario and C Laschi, Tools and Methods for Experimental In-Vivo Measurement and Biomechanical Characterization of an Octopus Vulgaris Arm, Proceedings of 31st *IEEE International Conference on Engineering in Medicine and Biology Society*, Minneapolis, MN, **2009**, 7196–9.
[18] L Margheri, B Mazzolai, G Ponte, G Fiorito, P Dario and C Laschi, Methods and tools for the Anatomical Study and Experimental in Vivo Measurement of the Octopus Vulgaris Arm for Biomimetic Design, *3rd IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, Tokyo, Japan, **2010**, 467–72.
[19] L Margheri, B Mazzolai, M Cianchetti, P Dario and C Laschi, Soft-Robotic Arm inspired by the Octopus: II. From Artificial Requirements to Innovative Technological Solutions, IOP Publishing Ltd Bioinspiration & Biomimetic, **2012,** 7, 025005.
[20] Chao Zhou, Min Tan, Nong Gu, Zhiqiang Cao, Shuo Wang and Long Wang, *The Design and Implementation of a Biomimetic Robot Fish*, Laboratory of Complex Systems and Intelligence Science, Institute of Automation Chinese Academy of Sciences, Beijing 100080, China School of Engineering and IT Technology, Deakin University, Geelong, VIC 3217, Australia.
[21] H El Daou, T Salumae, A Ristolainen, G Toming, M Listak and M Kruusmaa, A Bio-Mimetic Design and Control of a Fish-Like Robot using Compliant Structures, *15th IEEE International Conference on Advanced Robotics*, **2011**, 563–568.
[22] Andrew D Marchese, D Cagdas Onal and Rus Daniela, Autonomous Soft Robotic Fish Capable of Escape Maneuvers using Fluidic Elastomer Actuators, *Soft Robotics*, Mary Ann Liebert, Inc, **2014**, 1 (1).
[23] Jamie M Anderson and Narender K Chhabra, Maneuvering and Stability Performance of a Robotic Tuna, *Oxford Journals*, **2014**, 42(1), 118-126.
[24] Daniela Rus and Michael T Tolley, Design, Fabrication and Control of Soft Robots, *Nature*, **2015**, 521, 467-475.
[25] Robert K Katzschmann, Andrew D Marchese and Daniela Rus, Hydraulic Autonomous Soft Robotic Fish for 3D Swimming, *Experimental Robotics*, **2015**, 109, 405-420.
[26] Y Zhong, C Chong, C Zhou, GG Seet and K Low, Performance Predict Model for a Body and Caudal Fin BCF Biomimetics Fish Robot, *IEEE International Conference on Advanced Intelligent Mechatronics*, **2009**, 1230–1235.
[27] J Liu and H Hu, Biological Inspiration: From Carangiform Fish to Multi-Joint Robotic Fish, *Journal of Bionic Engineering*, **2010**, 71, 35–48.
[28] L Wen, T Wang, G Wu and J Liang, Hydrodynamic Investigation of a Self-Propelled Robotic Fish Based on a Force-Feedback Control Method, *Bioinspiration & Biomimetic*, **2012**, 73,036012.
[29] Hongli Liu, Yufeng Tang, Qixin Zhu and Guangming Xie, Present Research Situations and Future Prospects on Biomimetic Robot Fish, *International Journal on Smart Sensing System*, **2014**, 7(2), 458-480
[30] Kevin C Galloway, Kaitlyn P Becker, Brennan Phillips, Jordan Kirby, Stephen Licht, Dan Tchernov, Robert J Wood and F David, Soft Robotic Grippers for Biological Sampling on Deep Reefs, *Soft Robotics*, **2015**, 3(1), 23-33.