International Journal on Recent Researches in Science, Engineering & Technology (IJRRSET)
A Journal Established in early 2000 as National journal and upgraded to International journal in 2013 and is in existence for the last 10 years. It is run by Retired Professors from NIT, Trichy. Journal Indexed in JIR, DIIF and SJIF.
Available online at: www.jrrset.com

ISSN (Print) : 2347-6729
ISSN (Online) : 2348-3105
Volume 6, Issue 12
December 2018.
JIR IF : 2.54
SJIF IF : 4.334
Cosmos: 5.395

Received on: 04.12.2018 Published on: 20.12.2018 Pages : 36-40

DESIGN AND EVOLUTION OF BIO-INSPIRED ROBOTS

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ABSTRACT

Modern engineering problems require solutions with multiple functionalities in order to meet their practical needs to handle a variety of applications in different scenarios. Conventional design paradigms for single design purpose may not be able to satisfy this requirement efficiently. This paper expresses a novel system-of-systems bio-inspired design method framed in a solution-driven bio-inspired design paradigm.

INTRODUCTION

Human inventors and engineers have always found in Nature's products an inexhaustible source of inspiration. About 2400 years ago, for instance, Archytas of Tarentum allegedly built a kind of flying machine, a wooden pigeon balanced by a weight suspended from a pulley, and set in motion by compressed air escaping from a valve. Likewise, circa 105 AD, the Chinese eunuch Ts'ai Lun is credited with inventing paper, after watching a wasp create its nest. More recently, Antoni Gaudi's design of the still-unfinished Sagrada Familia cathedral in Barcelona displays countless borrowings from mineral and vegetal exuberance. Although a similar tendency underlied all attempts at building automata or protorobots up to the middle of the last century [60.1], in the last decades roboticists borrowed much more from mathematics, mechanics, electronics, and computer science than from biology. On the one hand, this approach undoubtedly solidified the technical foundations of the discipline and led to the production of highly successful products, especially in the field of industrial robotics. On the other hand, it served to better appreciate the gap that still separates a robot from an animal, at least when qualities of autonomy and adaptation are sought.

As such qualities are required in a continually growing application field – from planetary exploration to domestic uses – a spectacular reversal of interest towards living creatures can be noticed in current-day robotics, up to the point that it has been said that natural inspiration is the new wave of robotics. Undoubtedly, this new wave would not have been possible without the synergies generated by recent advances in biology – where so-called integrative approaches nowproduce a huge amount of data and models directly exploitable by roboticists – and in technology – with the massive availability of low-cost and power efficient computing systems, and with the development of new materials exhibiting new properties. This will be demonstrated in this chapter, which first reviews recent research efforts in bio-inspired morphologies, sensors, and actuators. Then, control architectures that, beyond mere reflexes, implement cognitive abilities – like memory or planning – or adaptive processes – like learning, evolution and development – will be described.

In fact, these two terms characterize, respectively, the extremities of a continuum in which, on the one side, engineers seek to reproduce some natural result, but not necessarily the underlying means, while, on the other side, they seek to reproduce both the result and the means. Thus, bio-inspired robotics tends to adapt to traditional engineering approaches some principles that are abstracted from the observation of some living creature, whereas biomimetic robotics tends to replace classical engineering solutions by as detailed mechanisms or processes that it is possible to reproduce from the observation of this creature.

BIO-INSPIRED MORPHOLOGIES

Although not comparable to that of real creatures, the diversity of bio-inspired morphologies that may be found in the realm of robotics is nevertheless quite impressive. Currently, a huge number of robots populates the terrestrial, as well as aquatic and aerial, environments and look like animals as diverse as dogs, kangaroos, sharks, dragonflies, or jellyfishes, not to mention humans. In nature, the morphology of an animal fits its ecology and behavior. In robotics applications, bio-inspired morphologies are seldom imposed by functional considerations. Rather, as close a resemblance as possible to a given animal is usually sought per se, as in animatronics applications for entertainment industry. However, several other applications are motivated by the functional objective of facilitating human–robot interactions, thus allowing, for instance, children or elderly people to adopt artificial pets and enjoy their company. Such interactions are facilitated in the case of so-called anthropopathic or human-friendly robots, such as Kismet at MIT or WE-4RII at Waseda University, which are able to perceive and respond to human emotions, and do themselves express apparent emotions influencing their actions and behavior. The android can make facial expressions, eye, head, and body movements, and gestures with its arms and hands. Touch sensors with sensitivity to variable pressures are mounted under its clothing and silicone skin, while floor sensors and omnidirectional vision sensors serve to recognize where people are in order to make eye contact while addressing them during conversation. Moreover, it can respond to the content and prosody of a human partner by varying what it says and the pitch of its voice. Another active research area in which functional considerations play a major role is that of shape-shifting robots that can dynamically reconfigure their morphology according to internal or external circumstances. Biological inspiration stems from organisms that can regrow lost appendages, like the tail in lizards, or from transitions in developmental stages, like morphogenetic changes in batrachians. For instance, the base topology of the Conro self-reconfigurable robot developed in the Polymorphic Robotics Laboratory at USC-ISI is simply connected as in a snake, but the system can reconfigure itself in order to growa set of legs or other specialized appendages.

BIO-INSPIRED SENSORS

Vision

Bio-inspired visual sensors in robotics range from very simple photosensitive devices, which mostly serve to implement phototaxis, to complex binocular devices used for more cognitive tasks like object recognition. Phototaxis is seldom the focus of dedicated research. It is rather usually implemented merely to force a robot to move and exhibit other capacities such as obstacle avoidance or inter-robot communication. Several visual systems calling upon optic-flow monitoring are particularly useful in the context of navigation tasks and are implemented in a variety of robots. This is the case with the work done in Marseilles' Biorobotics Laboratory that serves to understand how the organization of the compound eye of the housefly, and how the neural processing of visual information obtained during flight, endow this insect with various reflexes mandatory for its survival.

Audition

Like vision, the sense of hearing in animals has been implemented on several robots to exhibit mere phonotaxis behavior ormore complex capacities such as object recognition. At the University of Edinburgh, numerous research efforts are devoted to understanding the sensory–motor pathways and mechanisms that underlie positive or negative phonotaxis behavior in crickets through the implementation of various models on diverse robots such as the Khepera. In particular, an analogue very-large-scale integrated (VLSI) circuit models the auditory mechanism that enables a female cricket to meet a conspecific male or to evade a bat (by the calling song or the echolocation calls they produce, respectively). The results suggest that the mechanism outputs a directional signal to sounds ahead at calling song frequency and to sound behind at echolocation frequencies, and that this combination of responses simplifies later neural processing in the cricket.

Touch

It is often asserted that, of all the five senses, touch is the most difficult to replicate in mechanical form. Be that as it may, a passive, highly compliant tactile sensor has been designed for the hexapedal running robot Sprawlette at Stanford, drawing inspiration from how the cockroach Periplaneta americana uses antenna feedback to control its orientation during a rapid wallfollowing behavior. Results on the stabilization of the robot suggest that the cockroach uses, at least in part, the rate of convergence to the wall – or tactile flow – to control its body orientation. To make it possible to detect the point of greatest strain, or to differentiate between different shapes the sensor is bent into, more advanced versions of the antenna are currently under development.

Smell

The way the nematod Caenorhabditis elegans uses chemotaxis – probably the most widespread form of goal-seeking behavior – to find bacterial food sources by following their odors has been investigated at the University of Oregon. This worm has a small nervous system (302 neurons), whose neurons and connectivity pattern have been completely characterized, so the neural circuit controlling chemotaxis is well known and, when implemented in a robot, proves to be able to cope with environmental variability and noise in sensory inputs. The long-term objective of such work is to design a cheap, artificial eel that could locate explosive mines at sea. Other bio-inspired systems for odor recognition are under development in several places. For instance, the chest of the humanoidWE-4RII robot of Waseda University is equipped with two mechanical lungs, each consisting of a cylinder and a piston, thanks to which the robot breathes air. Being also equipped with four semiconductor gas sensors, it recognizes the smells of alcohol, ammonia, and cigarette smoke.

Taste

A first robot with a sense of taste has recently been developed by NEC System Technologies, Ltd. Using infrared spectroscopic technology, this robot is capable of examining the taste of food and giving its name as well as its ingredients. Furthermore, it can give advice on the food and health issues based on the information gathered. The latest developments afford the robot with the capacity to distinguish good wine from bad wine, and Camembert from Gouda

Internal Sensors

Whereas the previous external sensors all provide information about an animal’s or a robot’s external world, internal sensors provide information about a creature’s internal state. Although such so-called idiothetic sensors are widespread in robotic applications, measuring variables such as temperature, pressure, voltage, accelerations, etc., they are seldom biologically inspired, but in the implementation of a variety of visual–motor routines, like those that are at work in the humanoid Cog robot mentioned later.

BIO-INSPIRED ACTUATORS

Crawling

Because they are able to move in environments inaccessible to humans, such as pipes or collapsed buildings, numerous snake-like robots have been developed for exploration and inspection tasks, as well as for participation in search-and-rescue missions. The Salamandra Robotica developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland extends these approaches because it is the first robot that combines the three modes of locomotion – serpentine crawling, swimming, andwalking – in a single robot.Being inspired by central pattern generators (CPG) found in vertebrate spinal cords, this work demonstrates how a primitive neural circuit for swimming, like the one found in the lamprey, can be extended by phylogenetically more recent limb oscillatory centers to explain the ability of salamanders to switch between swimming and walking.

Walking

Eight Legs. Joseph Ayers has developed a biomimetic robot based on the American lobster at the Marine Science Center of North Eastern University. Capitalizing on recent advances in microcontrollers, smart materials, and microelectronic devices, this eightlegged ambulatory robot is intended for autonomous mine countermeasure operations in rivers, harbors, and/or the littoral zone of the ocean floor. Its control architecture supports a library of action patterns and reflexes – reverse-engineered from movies of lobsters behaving under the target conditions – that mediates tactile navigation, obstacle negotiation, and adaptation to surge. The robot will have the overlying motivation to navigate on a specified compass heading. When encountering an obstacle, it will attempt to ascertain whether it is a mine candidate or not through dedicated sensors like an electronic nose, an acoustic hardness tester, or an active electric field perturbator. If the robot determines that the obstacle is not a mine candidate, it will decide whether to climb over the obstacle or to go around it using information supplied by its antennal sensors and claw-like surfaces. If climbing appears to be unfeasible, the robot will use a wall-following algorithm to go around the obstacle until it can resume its predetermined heading.

Six Legs. In the performance energetics and dynamics of animal locomotion (PolyPEDAL) Laboratory at Berkeley, the observation that many animals self-stabilize to perturbations without a brain or its equivalent because control algorithms are embedded in their physical structure is widely exploited. Shape deposition manufacturing has allowed engineers to tune the legs of the SPRAWL family of hand-sized hexapedal robots inspired by the cockroach that are very fast (up to five body lengths per second), robust (hip-height obstacles), and that self-stabilize to perturbations without any active sensing. A cricket-inspired robot, approximately 8 cmlong, designed for both walking and jumping is under development at Case Western Reserve University. McKibben artificial muscleswill actuate the legs, compressed air will be generated by an onboard power plant, and a continuous-time recurrent neural network will be used for control. Additionally, front legs will enable climbing over larger obstacles and will also be used to control the pitch of the body before a jump and, therefore, aim the jump for distance or height.

Wall-Climbing

In the Biomimetic Dextrous Manipulation Laboratory at Stanford University, researchers areworking on a geckolike robot, called Stickybot, designed to climb smooth surfaces like glass without using suction or adhesives. Geckos can climb up walls and across ceilings thanks to roughly half a million tiny hairs, or setae, on the surface of each of their feet and to the hundreds to thousands of tiny pads, or spatulae, at the tip of each hair. Each of these pads is attracted to the wall by intermolecular van derWaals forces, which allowthe gecko's feet to adhere. Conversely, if the hair is levered upwardat a 30◦ angle, the spatulae at the end of the hair easily detach. The gecko does this simply by peeling its toes off the surface. Inspired by such structures and mechanisms, the Stickybot's feet are covered with thousands of synthetic setaemade of an elastomer. These tiny polymer pads ensure a large area of contact between the feet and the wall, thus maximizing the expression of intermolecular forces. In the same laboratory, a six-legged robot called Spinybot climbs vertical surfaces according to similar principles.

Swimming

Several biomimetic robots are being produced that emulate the propulsive systems of fish, dolphins, or seals, and exploit the complex fluid mechanics these animals use to propel themselves. A primary goal of these projects is to build machines that can maneuver by taking advantage of flows and body positions, leading to huge energy savings, and substantially increasing the length of swimming time.

Jumping

In the perspective of environment exploration and monitoring, Scarfogliero et al. [60.40] describe a lightweight microrobot that demonstrates that jumping can be more energetically efficient than just walking or climbing, and can be used to overcome obstacles and uneven terrains. During the flight phase, energy from an electric micromotor is collected in the robot's springs, and is released by a click mechanism during take-off. In this way the instantaneous power delivered by the rear legs is much higher than that provided by the motor.

CONCLUSION

This chapter has reviewed numerous recent applications of bio-inspired solutions to robotics. It seems likely that such solutions will prove to be even more useful as future robots are confronted with similar survival issues to those experienced by animals in unpredictable environments.This will require subsequent progress in the corresponding biological knowledge, a process to which tight collaboration between numerous disciplines, including robotics, may well critically contribute.

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