Towards Biomimetic Locomotion in Robotics

Eva Schindling
Art & Technology,
Dept. of Applied Information Technology,
Göteborg University and Chalmers University of Technology,
417 55 Göteborg, Sweden

Locomotion in nature fairly exceeds locomotion of human-made devices. Biomimetics now tries to copy and imitate materials, mechanisms and processes found in biology to overcome the limitations of traditional mechatronical robotics. By investigating muscle-like polymers, imitating nerve-wiring in animals or evolving motion patterns on the computer several research labs worldwide are producing promising results.

Keywords: biomimetics, robotics, locomotion, artificial muscles, evolutionary robotics

I. INTRODUCTION

After three billion years of iterated trial-and-error processes nature has shaped itself towards perfection. The survival of the fittest favors adaptations that show better behaviors than others. A perfection that seemingly should be hard to beat. But the Wright brothers have proven that mankind actually is able to overcome nature. It started with their analysis of bird flight that became the basis for their airplane structure. Through improvements in technology we are now able to traverse long distances at a speed of 250 m/s and take off into outer space with about 8000 m/s. No flying, running or swimming creature on earth has ever knowingly reached such a rate. Humans have certainly taken over when it comes to maximizing velocity, but what human-made locomotion lacks is its flexibility/adaptability. We have to overcome that fact by providing a perfect artificial environment for our devices - an environment that supplies energy whenever needed and prevents errors whenever the possible maneuverability reaches its limits. Therefore we build networks of roads and trails so that vehicles don't have to slow down or get stuck in uneven terrain. We supply external control systems that feed back information to the devices or their operators so they don't cause accidents or enter dangerous zones. And we supply maintenance and repair services when the damage of one component causes the whole system to fail. All this is unnecessary for biological organisms. They gain energy through chemical reactions, their body is able to heal by itself and their musculoskeletal system allows more coordinated, powerful and energy-efficient movement. Animals are able to locomote without any support network. They move on rough surfaces, climb over obstacles and reach areas that are difficult to reach. Some of them even combine several mobility options and are able to locomote in water, air and on land.

Building robotic systems with the help of principles of motion that are used in nature would open up many new possibilities. Most of robotic research projects are funded by US institutions like DARPA (Defense Advanced Research Projects Agency), NASA (National Aeronautics and Space Administration), ONR (Office of Naval Research) or NSF (National Science Foundation). They envision robots that navigate on Mars on their own, that perform military tasks or search for trapped humans after earthquakes [1]. Research projects worldwide pursue different approaches by focusing on specific principles of animal locomotion. Commercial and non-commercial institutions in the US and Japan investigate polymers that show certain muscle-like characteristics. Many laboratories focus on constructing robots that draw inspiration from the morphology and operating mode of specific animals like cockroaches, crabs or tunas. Other research aims at imitating the process of finding adequate motion control systems by simulating evolution. This paper gives an overview on each of these research areas and then reviews several specific projects in more detail.

II. DIFFERENT BIOMIMETIC APPROACHES

A. Artificial muscles

Controlled motion is the key to producing robust, flexible and powerful robots. Controlled motion in robotics depends highly on the choice of actuator. Big and heavy actuators have an impact on shape, size, weight and strength of the robot. Response time, accuracy, force and velocity of the actuator are major criteria for the robots performance and power output. Characteristics like the stiffness and damping quality of the actuator influence the general stability and robustness of a robot. Power consumption and durability of the actuator are important factors for the efficiency of the robot.

Manhood invented the wheel and further the rotary motor which produces powerful and fast motion but also shows stiffness, high energy costs and a lack in flexibility. It lays great constraints on the robot's potential ability. Strangely the rotary joint doesn't exist in nature. Evolution over millions of years decided to base biological locomotion on linear motors - muscles. Biological muscles primary function is to contract and exert force controlled by electric stimulation. Further they operate as brakes, shock absorbers, springs and struts. Muscles that act as springs are able to store potential kinetic energy. This can be observed in the wing flapping of insects and small birds, the hopping of kangaroos or even the running of humans beings [2].

The multifunctionality of the biological muscle seems to be the key to successful locomotion in nature. Developing a material that emulates the desired abilities of natural muscles would mean a big step forward towards stable and robust robotic locomotion [3]. Several technologies have emerged in the last years and some of them claimed the title 'artificial muscles'. Mostly they only show a few muscle-like characteristics, like pneumatic or hydraulic actuators that have a high power density, but on the other side need a large and heavy support system of pumps and regulators. Or like shape memory alloys that are very light-weight and easy to control, but lack in operation speed and possible displacement. Other materials like electroactive polymers produce a large actuation strain with a high response speed, but require high voltage actuation or wet environments, which still limits their employment in robotic projects. A more detailed description of the advantages and disadvantages of several muscle-like actuator systems follows.

1. *Shape memory alloys*

Shape memory alloys like Nitinol, which are made from a metal combinations that include Nickel Titanium, have a special crystalline structure that allows stress- or temperature-induced phase transformation. When trained at high temperatures around 500 degrees the material gains a thermal memory of the physical shape it is in. At normal room temperature the metal is in its martensitic crystalline state and therefore easy deformable by an increased stress-level. The material can stretch to plus eight percent of its original length and maintains this shape even when the stress is reduced. The shape memory effect (SME) sets in when Nitinol is heated to its transformation temperature and undergoes a crystal transformation into its austenite state. The produced strain in the metal lets it transform into its pretrained shape. No stress-induced transformation is possible until the temperature is decreased, the material cools and changes back into its martensitic crystalline formation.

The shape transformation ability of Nitinol when heated shows similarities to the contraction of biological muscles when activated by neural stimulation. The possibility to heat a Nitinol wire by letting electric current run through it make shape memory alloys easy-to-use actuators for robotic projects. Their light weight, small size and smooth and silent operation shows many advantages to traditional actuators. Though only a strain factor of about five to eight percent can be achieved, the actual force output is quite high. One of its disadvantages is its slow contraction and relaxation speed. The relaxation speed is highly dependable on the surrounding temperature conditions. Cool surroundings like water support a faster crystalline phase transformations and are therefore favored in robotic applications. Nitinols energy consumption is linear proportional to the wire's diameter and length. The metal has a limited cycling-life time and its performance can be effected by too extensive strain-activation in its history [4] [2].

The fact that shape memory alloys are readily available and very easy to control speaks for the materials use in robotic applications despite its many disadvantages. With proper heat conductions and careful avoidance of too high strain-factors it can be employed as linear actuator as in Ayers underwater robots based on lobsters and sea-lampreys.

2. *Pneumatics*

Pneumatic actuators expand and contract through pressurized air. When filled with air they increase their stiffness and exert a high force. They are only able to change from the 'on' to the 'off' state and don't offer the ability to control the range in between. Due to their very high force-to-weight ratio and their easy controllability with digital valves they are in use in the automation industry. Here it doesn't matter that the pump system and its supply add a heavy weight to the construction [3].

Braided pneumatic actuators - or air muscles as they are often called - offer a light-weight alternative to pneumatic cylinder systems. They were developed by McKibben in the 1950s and consist of a soft stretchable inner rubber tube and a braided polyester mesh sleeve. When the rubber tube gets pressurized with gas air, it expands in diameter and therefore shrinks in length. This produces the air muscles contractive force. They can contract approximately 25 percent of their stretched length [5]. Like biological muscles and shape memory alloys air muscles are pull-only devices. A bias force must be provided to return them to their non-contracted state. Because of the damage-causing friction force between the mesh and the rubber tube, air muscles have a quite short life-span.

The Festo corporation recently developed a similar product which they introduced as *fluidic muscle* and employed in their *Airacuda* underwater robot. Here the fiber mesh is impregnated inside the expandable rubber tube and therefore more resistant against friction forces. Their actuators service life on the order of 10.000.000 life cycles exceeds that of normal air muscles by the factor of 1000 [18].

Robotic projects like CWRU's *Robot III* or Standford's *Sprawlita* select pneumatic actuators because of their high power output. The attempts at CWRU to overcome the steplike activation mode of the cylinders with pulse width modulation failed as the robot was not able to produce smooth motion actions. More recent projects at the CWRU like *Robot V* and the microcricket series use braided pneumatic actuators to achieve more lightweight and versatile locomotion control.

3. *Hydraulic actuators*

Instead of gas hydraulic actuators pressure fluids and make cylinders expand and contract. They offer an even higher power output than pneumatic actuators and have been in use in factory automation and aerospace for a long while. Their need for a heavy and large pump generally restricts their use in autonomous robotics. The tuna-inspired *VCUUV* robot constructed at the Draper Laboratories overcomes those disadvantages and uses an onboard pump for its hydraulic driven locomotion system [3].

4. Piezoelectric actuators

Piezocrystals like quartz, lead zirconate titanate or lithium niobate react to changes in the applied electric field with deformation and relatively high force output at a fast response rate. Though the maximum strain it reaches is only 0.1 percent, this behavior can be useful when high precision placement is needed. Like biological muscles it also shows certain elastic characteristics. Vibration of the piezoelectric material can be used to cause robotic movement by exciting another material at its natural resonance frequency. Its light weight, small size and dynamic elastic abilities make piezoelectric actuators favored in mesoscale insect-inspired robotics. A disadvantage of piezoelectric actuators is, that they need high-voltage actuation. The autonomous mesoscale robot developed at the Center for Intelligent Mechatronics needs special onboard power conversion electronics to transduce the 3 Volt of the battery to the required 240 Volts. [2].

5. Electroactive polymers

Recent artificial muscle research focuses on several electroactive polymer (EAP) technologies that promise a wider range of muscle-like abilities. They respond to electric stimulation with a substantial shape and size change and large actuation strains. Additionally they show pliability, elasticity and fracture tolerance like biological muscle material. Based on their activation mechanism EAPs can be grouped in two categories.

Electronic EAPs include dielectric elastomers, ferroelectric and piezoelectric polymers, electrostrictive graft elastomers and liquid crystal elastomers. They are driven by applied electric fields with relatively high voltage rates and therefore need a high-security testing environment. Their response rate is fast and their force output high. They are able to hold the induced displacement with almost no current.

SRI International and its spin-off company Artificial Muscle Inc. investigate the muscle-like behavior of dielectric elastomers with the help of fundings from DARPA and ONR. Elastomers such as silicones and acrylics exhibit the phenomenon called Maxwell's stress - electric field pressure on the surface induces stress on the elastomer and lets it contract in the direction of the electric field lines. Dielectric elastomer film gets coated with elastic electrode material on both sides. When exposed to high-voltage electric fields of about one to five kilovolts the opposite charged coatings attract each other, press down on the elastomer and let it expand in area. This mechanism exhibits high actuation force and fast response times. Through special prestraining the material is able to show strains greater than 100 percent [7]. SRI developed several small-scale actuators that exhibit linear or bending motion and employed them in their hexapedal walking robot, flapping wing robot, and inchworm robot.

Ionic EAPs include ionic polymer gels, conductive polymers, carbon nanotubes and ionic polymer metallic composites. They consist of two electrodes and an electrolyte. A low voltage applied electric field causes a movement of ions and material deformation. The main disadvantages of ionic EAPs are its requirement of a wet environment, a relatively low actuation force and a slow response speed.

Conducting polymers are being developed by the japanese EAMEX corporation. The polypyrole actuators expand and shrink when electrically stimulated. They produce large stress and strain factors and only need a low voltage actuation of 1-2 Volts. The material shows softness similar to biological muscles.

Though EAPs match many aspects of biological muscle behavior, their use in robotics is still constrained by their need for either high-voltage activation or a wet environment and their lacking long-term reliability. But the ongoing investigations in this field promise further improvements by inventing new polymer-combinations and finding better fabrication modes that might diminish those disadvantages in the future [3][2][6].

6. Reciprocating chemical muscles

The reciprocating chemical muscle (RCM) technology was invented and patented by Michelson at the Georgia Tech Research Institute (GTRI) as an energy and actuator system for their *Entomopter*. The RCM can operate with different fuel sources, retrieves energy through chemical reactions and converts these mainly into motion. This mechanism is a close analogy to the chemical reactions in biology that cause muscles to move. Besides outputting motion, the RCM can be used to produce small amounts of energy. The noncombustive chemical reaction produces gas as a waste product which can be of further use as well.

Energy obtained from chemical reactions has a much higher density than stored electric energy. Autonomous self-contained robots would survive much longer on chemical fuel than on energy stored in batteries of the same weight. Additionally the usage of chemical fuel would lighten the vehicle during operation and enable even better performances at the end of each mission [19].

B. Biomimetic design

Another approach towards biomimetic locomotion is the imitation of biological structures and mechanism. Locomotion in nature is based on three major components: the sensors, the actuators and the connecting control system. Living organisms are able to sense their physical environment. The sensing information gets fed into the central nervous system which inhabits the central pattern generators (CPG). Those neurons control the electric stimulation and activation of muscles and cause rhythmic motion behaviors such as walking or flying. A constant monitoring of the resulting behavior through stretch sensors in the muscles affects the output of the CPGs through feed-back loops. This allows precise control over contraction speed and tension of the muscle and produces smooth elegant movements. An update of the environmental sensors also gets fed back into the CPG, this allows the animal to constantly adjust itself to environmental perturbations through reflexes[2]. MITs *RoboTuna*, Fraunhofer Institute's *Scorpion* and CWRU's microcricket series all use closed-loop control systems that allows the robots to adept their movements based on sensor-feedback.

Though research in neurobiology constantly produces new insights in biological mechanisms, we still don't have full insight into the operation mode of nature. This makes it impossible to successfully copy the complexity of nature's neural networks. And even if it would be possible the mismatching characteristics of materials and designs used in robotics would cause direct adaptations to fail. A control architecture modeled closely after biological CPG systems heavily relies on actuators systems similar to biological muscles, because the CPG network has evolved within its biological body. Small differences in response time and power output of the actuators would cause a perfectly working control system to fail. Converting physiological mechanisms into electro-mechanical systems naturally arises several problems. Robots are controlled by an electric and digital circuitry. Sensors and actuators are connected to a computation unit that generates control-signals. Though control systems are programmed to simulate nervous systems they still depend on their non-chemical environment. The inability to reach natures complexity usually causes robots to perform their typical stiff and jerky movements due to a lack of circuitry and feedback loops. But a careful studying of animal design and behavior may allow to create mechatronic and software solutions that produces intelligent behavior closer to natures role models [2].

Well thought-of abstractions of nature's complexity might not limit a robots performance that much. For the microcrickets project at CWRU software analysis showed that the crickets many degrees of freedom don't all have the same impact on the animals behavior. By reducing the amount of joints to those most important almost all the crickets freedom of locomotion could be preserved [27].

Biological phenomena like reflexes arise from a short coupling of sensors and actuators. Traditional robotic systems are usually controlled by one computational center, in the master/slave mode. Animals distribute these responsibilities onto every part of their body. Every leg has his own control system and is able to react to its own sensory inputs. This method supports stable locomotion gaits by the cooperative interaction between each individual component. The whole system becomes more flexible and therefore more robust [8]. The Fraunhofer Institute's scorpion robot owns a CPG control system that is distributed into one main unit for behavioral actions and several local units responsible for individual leg movement. This partitioning allows faster processing speed of the individual control segments and therefore a higher response rate for reflex behaviors [2].

Biological creatures enhance their performance in the natural world through experience. Giving robots the ability to learn will prepare them for unpredictable events and so increase their chance of survival. Through a constant interaction with a real-world environment they can adapt their set of behaviors and rules according to positive or negative feedback [2].

Another design consideration that can be found in nature is that of fault-tolerance. Nature is prepared for failure by multiple independent actuators and processors and communication redundancies. This allows a system still to function even when single components failed [2]. Projects like the self-modeling robot developed at the DEMO lab are programmed to overcome sudden hardware-changes due to damage by constantly experiencing their own morphology. In an iterated process the robot creates its own self-model through comparing predicted with actual sensor values. This allows the creation of new compensatory behaviors when individual components fail [23]. This evolutionary approach overcomes the inability of artificial materials to heal. As long as robotics is unable to employ materials that can grow back, software solutions have to make up for this handicap.

Biomimetic robotic projects are usually highly interdisciplinary as they bring together people from biology, mechanics and computer science. The biologist Ayers spent years studying the nervous systems of underwater creatures before he was asked to develop robots based on these observations. Many projects like the Ayers' robotic lobster or the cockroach-inspired *Robot V* rely on intensive video analysis of biological role models to obtain detailed movement characteristics. In a reverse-engineered process the monitoring of specific joint motions allows the set up of a behavior library that will control the robots locomotion.

Observations of the cockroaches leg thrust production showed that animal's high robustness and dynamic stability is reached by a inefficient force cancellations. The forces generated by the front and the rear legs oppose each other and partly don't contribute to the animal's forward locomotion. Applying this approach at Standford's *Sprawl* robots shows that the internal forces are very important to stabilize the robot while maneuvering or acting against external perturbations [25].

Various flying robots are based on the energy storing mechanism observed in insects and birds. The springs-like behavior of muscles and exoskeleton allows storing and recovering of elastic potential energy for wing-flapping actions. By choosing a flapping rate close to the materials resonance frequency even more energy can be saved. A clever copying of designs found in nature can even lead to outreaching solutions. The *Entomopter* uses a hawkmoths wing shape to take advantage of insects successful aerodynamics, but further development has reshaped the artificial wing to achieve even better results than observed in nature.

C. Evolutionary robotics

As mentioned earlier we don't have full insight into biological mechanisms yet. The attempt to imitate those underlying principles like sensor-feedback-loops and CPG activation might be negatively effected by missing knowledge. Also the fact that robotics uses different materials than nature might interfere with the blind copying of studied behavior. Even though some newly discovered materials might exhibit similar qualities to biological muscles, those materials still operate on different activation modes and produce different output behaviors. Even if we were able to successfully copy one animals complete control system, its employment with human-made electromechanical sensors and actuators would produce results that are far from the animals behavior.

An interesting approach towards overcoming those limitations is evolutionary robotics. Instead of focusing on similar materials and mechanisms, this rather new field imitates the design-process of nature - evolution. The morphology and control system of biological creatures have been shaped over millions of years. The survival of the fittest constructed muscles, bones, tissue and neural networks towards optimal solutions. The way legs, fins and wings of living creatures are built is the result of fighting against nature, for food and for reproduction. Each animals particular pattern of movement increases its fitness, as it catches prey at high speed, escapes predators by swerving actions or long endurance, or even obtains adequate stability while walking slowly [10].

Evolutionary robotics follows the traditional steps of evolution. It evaluates performances of robots based on a chosen fitness value, selects the best among them and replicates them by adding small changes through genetic crossover and mutation operators. Repeating those steps over many generations usually produces a gradually increasing maximum fitness value.

The robotic hardware consists of input (sensors) and output devices (actuators). The control architecture that causes the behavior of the robot is hidden between those components. Artificial neural networks have proven to be adequate computation systems for the control of robots, because they provide parallel computation and allow flexible evolution through weighted connections. They consist of a set of neuron-like units that use their connections to transmit signals. Hidden neurons can have several input and output connections from and to other neurons in the network. Specific output and input units link the network to sensors and actuators of the external environment. The output of each unit is dependent on the sum of its weighted incoming signals. Signal travel on the connections and cause the units to update their state in parallel. Neural network that are simulated in the computer often include threshold parameters, that causes signals to be send when the input sum is over a specific threshold value. The output of the neuron-units can be digital, linear or sinusoidal. When simulating CPG's oscillating output values are used.

The architecture of an artificial neural network can be optimized through tasks like Hebbian and reinforcement learning or through simulated evolutions. The characteristics of each neural unit are usually stored in its genotype, which includes information about all its connections, the synaptic weight of its connections, and further threshold or delay parameters. The genetic algorithms performing crossover and mutation operations can now change the weight of connections, dis- and reconnect different neurons, combine the characteristics of two parent units or even add new units to the network. Successors of successful solutions might fail because of sudden missing connections whereas successors of averagely performing solutions might suddenly show surprising behaviors due to the fine-tuning in its parts. Numerous projects like MIT's *RoboTuna*, CWRU's microcrickets, the *Random Morphology Robots*, CCSL's *Nonaped*, DEMO Lab's *Genobots* or the robots *Rodney* and *OCT-1b* use the many advantages of genetic algorithms to tune their locomotion control architecture.

When the design process of the control architecture is done by evolutionary algorithms the need for the humans to understand the resulting design is diminished. Evolution of neuron-like computation units and interconnectivity between them can produce complex results that are beyond those of traditional hand-made design architectures. This method overcomes certain human design constraints and is therefore able to find new successful solutions. At Sony they were able to evolve the control for a pace gait of their quadruped robot that was more effective and almost twice as fast as former hand-designed solutions. Often control system evolutions find solutions that can be found in nature as well. Gomi and Ide's evolution of the walking pattern for an octopod produced tetrapod gait and wave gate, both locomotion behaviors that are common for biological walking organism [9].

A successful fitness value for evolutionary robotics is often very hard to obtain, especially when the evolution starts from a random setup of configurations and parameters. Then first try-outs often stumble into the 'bootstrap problem', which is the situation when all individuals of one generation produce a fitness value of zero. When the control solution that is looked for is a combination of several behaviors and therefore very complex an incremental evolutionary approach is used. This means that the fitness criteria the simulation is looking for changes at certain intervals. The task the individual solutions have to accomplish gets more complex at every step. So simple behaviors can be adapted first and evolved further at the end. When evolving walking patterns for robots the evolutionary process is mostly divided into first finding the optimal control architecture for one leg, which is replicated then for every other leg, and then the optimal connections among those leg controllers for coordinated movement. This approach that was used for the *Rodney* robot, diminishes of course the range of possible solutions, but has proven to accomplish more successful results in shorter time [9].

Usually the evaluation of evolved control architectures is carried out in physical-world simulation programs. Testing every generation of new solutions on the real physical robot would costs enormous amounts of time and wear out the robot hardware. Additionally real-world testing would require constant human supervision while a computer simulation can run on its own. But as software programs are unable to simulate the behavior of hardware components and environmental conditions to a certain extent, evolved software behavior often fails when finally tested on the physical robot. Often the evolved behaviors don't regard noisy sensor behavior or demand too much from the mechanics and actuators. Simulations are often not able to take every electromechanical characteristic into account and therefore don't match the constraints of the physical hardware [9]. The locomotion controllers of CCSLs *Nonaped* and *Self-Modeling Robot*, MITs *RoboTuna*, the german *Random Morphology Robots* and Gomi and Ide's *Oct-1b* were evolved on the physical robot. The settings of the embodied evolution, like population size and mutation rate, are carefully chosen to reduce the duration and reach successful solutions faster. The optimal control parameters for the *RoboTuna's* forward locomotion through propagating axial wave motions were found with genetic algorithms. During evolution the mutation rate dropped after each generation to ensure variety at the start and finetuning at the end even with a small population size.

Most evolutionary robotic projects only adapt the software running in their processor. The behavior of a robot strongly depends on the physical interaction between its hardware and the environment. Physical properties of circuits, sensors, actuators or the overall shape of the robot influence and limit the possible software solutions. By including those properties in the evolutionary design process more suitable design solutions can be found. When evolving only the control architecture of already existing complex hardware systems, it was hard to find good solutions at the beginning of the evolutionary process. Through co-evolution of body structure and control system the complexity can be increased suitably through the whole process. The nonexistence of suitable evolving materials destroys the possibility of evolving these robots in real life. The evolutionary process is limited to exist in simulations and its results can be used to construct the evolved body morphology in hardware. The *Golem* robots by Pollack are structures of bars, joints and linear actuators that were evolved for straight navigation in computer simulations and later rebuilt out of thermoplastic material with a 3D printer. Modularity in robotic components permits a simpler co-evolution of body and control system. The *Random Morphology Robots* by Dittrich consisted of a set of arbitrarily connected servomotors that could be re-connected by humans throughout the evolutionary process. Also DEMO Lab's *Genobots* consist of simple modular components that enable easy morphology changes.

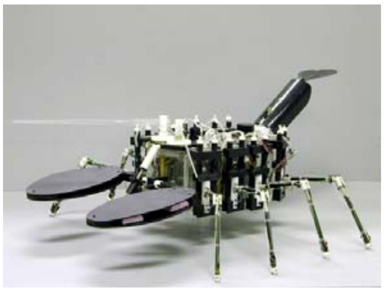

FIG. 1: *Robotic lobster* [28]

III. EXAMPLES

The following robotic examples employ one or several of the above mentioned biomimetic approaches. Though some of the evolutionary robotic projects might focus on simulations on the computer, all the examples were selected according to the requirement that they include a functioning hardware device.

1. *Robotic lobster*

The robotic lobster is a collaboration of biologist Ayers with the University of California, San Diego's Institute for Nonlinear Science and the Department of Biology and Marine Science Center at the Northeastern University in Boston. The goal is to create a sophisticated biomimetic underwater robot that is based on the American lobster *Homarus Americanus.* Ayers devoted his career to the study of the nervous system of lobsters and crayfish and was approached by DARPA to build a robot. The project is funded by a variety of institutions and aims at producing autonomous mission-capable robots for military underwater purposes like detecting mines.

The focus lies on remodeling the underlying control signals of actual lobsters. As the timing of control signals in the nervous systems has evolved together with the response capabilities of the animal's muscles, it was necessary to employ actuators that match their biological models. The SMA Nitinol with its stress-strain relationship, contraction and relaxation velocities was chosen as an adequate actuator despite its high power consumptions and heat dissipation cutbacks. Using Nitinol underwater with additional thermal insulation improves the metals relaxation speed.

The robots eight legs each provide three degrees of freedom, actuated by pairs of antagonistic Nitinol wire that are able to rotate the leg joints in both directions. Besides elevation and swing the robots legs own a extension-flexion joint that makes the lobster typical sideways motion possible. The control signals activate the Nitinol with pulse width modulation and take a precautious relaxation time span in to account to enhance the metals durability by keeping it from

FIG. 2: *Lamprey-based undulatory vehicle* [28]

overheating or overloading.

Behavior of lobsters is a set of dynamically changing command states, that give information about the lobsters walking direction, walking speed, and position and orientation of its body parts. A reverse-engineered behavior library for the robot is based on the detailed study of video material showing a biological lobster. The control architecture of the robotic lobster is constructed of CPG networks consisting of oscillating neurons, command neurons and coordinating neurons. The control system chooses different behaviors according to sensor-input and supervised motivation of the robot; the behavioral sequence of different command states is then fed into the command neurons of the neural network. The pattern generating neurons adept to the commands and produce the current pulse modulation that controls the individual leg movements [2].

The robotic lobster is one of the most complex biomimetic projects that addresses biomimetic issues on several levels. In a reverse-engineering approach sensors, control systems and actuators are designed after their biological counterparts.

2. Lamprey-based undulatory vehicle

The lamprey-based underwater robot comes from the same team around Ayers that developed the robotic lobster. Both projects share the use of Nitinol as actuator and a control architecture that is based on detailed study of their biological role models. Lampreys swim by rhythmical wave movements that propagate along their body axis. Alternating muscles contractions on the sides of the body axis make the lamprey bend in S-shaped waves. As those propagate from nose to tail while increasing in amplitude the produced thrust makes the lamprey move forward. The efficient and highly adaptable swimming locomotion of the lamprey makes it an interesting role model for robotics.

The underwater robot consists of three parts: a rigid hull that houses the processor and further necessary electronics, the flexible plastic notochord and a passive tail segment. The main axial body of the robot is built from 6 vertebrae elements with Nitinol wires attached on both sides. Activation of the SMA wires allows axial bending movements around 5 joints.

Detailed study of video material of lampreys led to a kinematic model for the animals swimming behavior. A CPG control architecture has been built based on neural studies and outputs alternating PWM pattern signals for the Nitinol actuators. The robot is able to produce robust autonomous forward swimming motion by sequentially contracting its artificial muscles [2].

FIG. 3: CWRU's *Robot V* [29]

3. SRI robots

SRI International employed their dielectric elastomer technology and actuator design to a variety of robotic applications. Their six-legged autonomous walking robot is loosely inspired by the cockroach. 2 degrees of freedom for each leg are controlled by SRI's double bow-tie actuators in combination with opposing spring forces. Though the hexapedal robot is only able to walk slowly over even terrain it is believed to be the first self-contained walking robot using the dielectric elastomer technology.

SRI's flapping-wing robot is based on the mechanism of flying insects that operate their wings indirectly by muscles located in the thorax. The robotic body contains 4 silicon bow-tie actuators that are actuated in a frequency that responds to their own resonance. This elasticity allows the storage and release of potential energy and therefore decreases the power requirement for the wing flapping mechanism. The robotic prototype flaps its wings at a resonance of 18 Hz. To be able to lift itself into the air it would need more muscles actuated in parallel operating at a resonance frequency of 40 Hz.

SRI's inchworm robot consists of a 16 mm long rolled actuator made from dielectric elastomer. Electrostatic clamps at each end of the actuator allow the miniature robot to propagate in a inchworm style on vertical and horizontal surfaces. While constantly expanding and contracting the robot reaches maximum speeds of about 10 cm/s. Though the robot does not carry his power and control circuits it exhibits that robots based on soft artificial muscles could be build without rigid skeleton-structures [2].

4. Robot III + robot V

At the Biologically Inspired Robotics Lab at the Case Western Reserve University the results from insect locomotion studies guide the design of legged robots. The video analysis of leg joint movements of running cockroaches were transferred into dynamic computer simulations, where the animals up to seven degrees of freedom (DOF) for each leg were limited to those most useful. The results were used for the construction of *robot III*, a 75 cm long hexapod with aluminum tube legs that were modeled closely after the cockroaches morphology. The front legs inhibit five, the middle legs four and the rear legs three joints. The total 24 degrees of freedom of the robots legs are actuated by double-acting pneumatic cylinders.

The control architecture for the locomotion of *robot III* acts on three levels. The posture control moves the device's center of mass to ensure stability. To reach a certain desired body position and orientation the system calculates the necessary forces for the robots legs. Reflexes seem to be a resulting behavior of posture control in the central nervous system. The swing control is responsible for positioning legs before their stance phase. The starting position of the leg cycle depends on the current movement of the robot. Climbing, turning or walking require different leg positioning. The swing control is in charge of calculating the necessary joint angles for every DOF of the leg to position the foot at the desired location. The stance control is responsible for developing the necessary ground reaction forces for legs to be able to lift the body. Load sensors let the controller calculate how much more forceful extension of joints is necessary until a desired leg position and orientation is reached.

The control system determines motion caused by the pneumatic actuators based upon the posture, swing and stance controller. To overcome the steplike manner of pneumatic devices the valves are controlled with a 80 Hz pulse width modulation [2]. Nevertheless the robot failed at demonstrating smooth locomotion [18].

Though the use of a pneumatic actuator systems significantly adds to the weight of the robot (75 percent of the robots 15 kg are due to actuators and valves), it also makes it really powerful. The robot is able to lift payloads similar to its own weight. But because of the inability of the pneumatic cylinders and the control system to deal with load changes due to locomotion, the robot was not able to produce a stable walking pattern [18].

The successor of the device, *robot IV*, uses braided pneumatic muscles in place of the pneumatic cylinders. The air muscles allow a behavior more similar to that of biological muscles and are significantly lighter than standard pneumatic cylinders. Their flexibility provides compensation for instabilities caused by the control system or external perturbations. Though the air muscles make the robot much easier to control, it fails at its force-to-weight ratio - the robot is barely able to lifts its own weight [18].

As its predecessors *robot V* (also called *Ajax*) is non-autonomous and relies on external power supply and control. Each of its 24 joints is controlled by an opposing set of air muscles that allow controlled joint motion in both directions. Through varying the pressure in the antagonistic muscle pair different compliance/stiffness factors can be achieved. The adding of a torsion spring to support the actuators responsible for the stance force production reduces the necessary force for lifting and locomotion the robot body. Therefore *robot V* is capable of supporting its own weight of 15 kg with an additional payload of 5 kg. The robot is able to produce a tripod walking pattern though the results are not close to the stable locomotion that is desired. Through the implementation of the improved control architecture that was developed for *robot III* and the addition of force sensors *robot V* is expected to produce more robust locomotion [18].

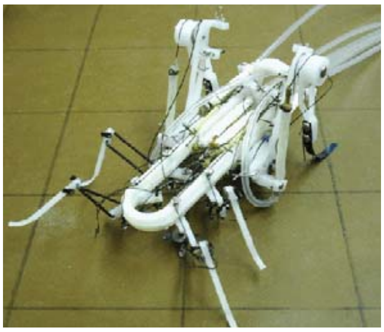

FIG. 4: CWRU's *Cricket microrobot* [1]

Supported by grants from ONR, DARPA, NSF and NASA the projects main goal is the development of mission-capable legged robots. Though not fully functioning yet the robots complex control architecture and hardware design show first promising results very close to biological motion capabilities.

5. *Cricket microrobot*

Another project in development at Biorobotics lab at the Case Western Reserve University is the cricket microrobot series. The small sized autonomous robot designed after a cricket is meant to fit into a 5 cm cube and is build to locomote by walking and jumping. After studying the kinematics of cricket legs simulations showed that reducing the animals many DOF for practical use wouldn't effect the locomotion abilities much. The smaller flexible front and middle legs each have three and the larger powerful hind legs each two DOF. The joints are actuated by custom made braided pneumatic actuators in combination with spring bias forces and are monitored with angle sensors. The actuator system consists of an onboard air compressor that operates the 16 air muscles through 32 valves. The three possible actuator states - inlet valve open, outlet valve open or both closed - are determined by a neural network control architecture. The parameters and thresholds of the neural network have been trained to develop oscillatory motion pattern by using genetic algorithms. As a closed-loop controller it includes the feedback from the angle sensors to adjust the activation patterns. The final robot should be able to use walking patterns for maneuvering and slower locomotion and jumping for traversing difficult terrains [27].

6. *Sprawl*

The *Sprawl* robot family built as collaboration project between the Center for Design Re-

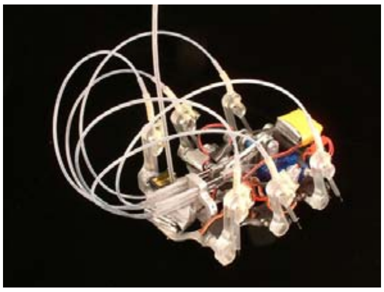

FIG. 5: Standford's *iSprawl* [30]

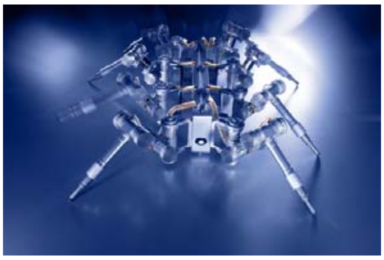

FIG. 6: Fraunhofer Institute's *Scorpion* [31]

search (CDR) at the Standford University and the PolyPEDAL Lab at the University of California, Berkeley draws inspiration from cockroachs to achieve fast and stable locomotion. The cockroachs ability to transverse uneven terrains in velocities up to 50 bodylengths/second while climbing obstacles without excessively slowing down makes it an ideal role model for hexapedal robot design. Several characteristics of the cockroachs mechanical design have been adopted for the design of the *Sprawl* robots.

The dynamic stability of the cockroach can be explained by the large internal forces that are generated by the decelerating thrust of the front and the powerful accelerating thrust of the hind legs. Though inefficient due to canceling of opposing forces this behavior enhances the robustness and copes with dynamic instabilities due to external perturbations or rapid turning maneuvers. The earlier *Sprawl* generations use implemented pneumatic pistons as main actuator system to produce the necessary force for the robots accelerating thrust. Rotation joints activated by servo motors enable to set the main angle for each leg to define if the force output accelerates or decelerates the forward movement of the robot.

The high elastic properties of the cockroachs muscles and exoskeleton have been imitated by including a compliant passive hip joint and using shape deposition manufacturing (SDM) for fabricating the body and legs of the robot. This prototyping method allows layers of polymers with different material properties to be formed as needed. While soft and highly elastic materials are used for the flexible hip joints, stiffer materials are employed for the structural leg components.

Studies show that the tripod locomotion pattern of a running cockroach only changes minorly when the animal has to deal with unexpected perturbations as it transverses uneven terrain. There is no need for a careful closed-loop activation of changing locomotion patterns as the visco-elasticity of the mechanic system respond to perturbations immediately. This so-called *preflexes* are faster than reflexes that influence the neural stimulation of muscles. Compliance and damping of limbs and joints enables a stable locomotion through open-loop control. Tryouts of different activation patterns and angle values produced a maximum velocity of 7 bodylengths/second (1 m/s) for the pneumatic actuated non-autonomous *Sprawlita* robot [25].

The youngest member of the robot family - *iSprawl* - was freed from the weight of the pneumatic actuator system to achieve autonomy. A redesign of the legs based on new motor actuators lead to a push-and-pull cable system to achieve linear motion. Springs, flexible tubes and careful leg extension control enable smooth compliant motion similar to that produced by the pneumatic systems before. The smaller and more lightweight *iSprawl* performs stable dynamic locomotion at velocities of over 15 bodylengths/second (2.3 m/s) [26].

The *Sprawl* robots are a good example where a sophisticated hardware design supports the development of biomimetic locomotion. The SDM fabrication method brings many advantages for robotics. The use of polymers with different compliant values allows components to reach elasticity characteristics closer to their biological counterparts. This reduces the need for complex control signals to mimic these properties in software.

7. *Scorpion*

Researchers at the Fraunhofer Institute are focused on building a biomimetic legged robot that is based on the design of a scorpion. First they implemented a full model of the robot in a simulation environment, where they tested different design solutions and control architectures.

Each of the robots eight legs has three joints which are actuated by DC-motors and allow protraction/retraction, elevation/depression and extension/flexion motion. By using high-ratio gears in combination with the DC-motors each leg is able to lift 8 times its own weight. This is important because the robot is intended to climb high obstacles and this creates the requirement for combinations of legs to push or pull the whole robots weight. To weaken the stress that acts upon the mechanical design through the environment they have used compliant materials in the leg design. Those elastic components are meant to absorb high energy impulses. Also the lowest leg part includes a spring mechanism that acts as a damping component when the leg hits the ground. An included potentiometer makes it possible to measure contact and load of each individual leg. Relative joint angle sensors and motor current sensors allow a more flexible locomotion control based on feedback information.

The control system is based on the CPG model and is distributed to one global and several local computing units. On the global level the neural network sets

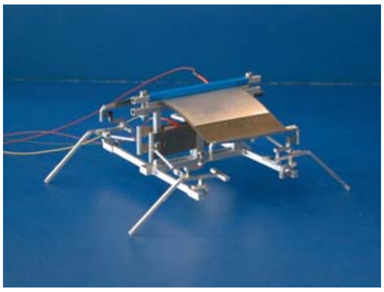

FIG. 7: *Mesoscale robot quadruped* [32]

FIG. 8: Snake robot *S7* [33]

basic locomotion behaviors, like if the robot is performing forward, backward or lateral walking. The local units feed those global behaviors into three oscillator networks that control the three joints of one leg. The oscillators produce rhythmic motion patterns that have been mimicked after real scorpions walking. 2 Groups of 4 contralateral adjacent legs move in the same motion pattern but shifted 180 degrees in phase. Additionally the legs in each group have a delay between their phase timing, whereupon the hind leg is the first to start moving.

The local units are also responsible for reading in the sensors values and performing reflex tasks for each leg. The reflex control consists of a fixed set of actions that overwrites the signals from the CPG when certain sensor values occur. The overwriting happens for a short predefined amount of time. When the current values for a motor are increasing while no angular displacement is reported, the reflex system assumes that something is blocking the way of the leg. This triggers the reflex action of moving the leg backward and upward for a while and then forward with high speed to overcome the obstacle. This combination of CPG and reflex-control should enable the robot to deal with uneven terrains.

8. *Mesoscale robot quadruped*

The goal to construct a self-powered mesoscale robot originates constraints concerning the size, weight and power consumption of the device. The mesoscale quadruped robot developed at the Center for Intelligent Mechatronics at Vanderbilt University measures 9 x 6.5 x 5 cm and employs an elastodynamic locomotion approach that causes it to locomote by vibrationally exciting the light skeletal structure at its resonance frequency. The robot is driven by two piezoelectric actuators that are excited at the same sinusoidal voltage rate, but shifted 90 degrees in phase. The phase-shifted displacement of the two piezoelectrical actuators drives the two-degrees-of-freedom mechanism of each leg in parallel and causes elliptical foot motion. Exciting the legs of the robot at their resonance frequency causes rhythmic smallscale motion that causes the robot to propagate. The elasticity of the vibration motion stores energy and makes the device highly energetically conservative. The use of legs with different resonant frequencies eliminates the need for independent actuators. By shifting the excitation frequency the resonance amplitudes of individual legs can be increased. This allows the control over turning movements of the robot. A straight forward motion can be caused by exciting the structure at a rate that lies between the resonance frequency of left and right legs.

The high voltage actuation requirement of the piezoelectric actuators demands an efficient onboard power conversion. The robot carries an electronic circuit that alters the high-current power of a 3 volt battery to low-current 240 volt power and generates a sinusoidal output. Exciting the actuators at different frequencies shows that the walking speed of the robot and its average power consumption increases with the excitation frequency. When excited at 32 Hz the robot is able to reach velocities of 30 cm/s. By shifting the excitation frequency the robot is able to turn with a minimum turning radius of about 5 cm. The frequency range for left or right turning of the robot depend on its payload [2].

Locomotion through vibration at a specific resonance frequency is a different approach for robotics.

9. *Snake robots*

Snakes employ a variety of effective limbless locomotion strategies that helps them move through narrow tunnels, climb on trees and swim in water. Especially the ability to move underground makes them good biological models for search-and-rescue robots. Miller envisions a autonomous snake robot that - equipped with a range of sensors - is able to locate trapped humans under earthquake ruins. In his quest he has constructed a series of snake robots that are self-contained and allow radio control. He tries to imitate several snake locomotion strategies like sidewinding, rectilinear motion or horizontal undulatory progression.

The first prototype *S0* was constructed out of 12 segments connected with servomotors and performed rather disappointingly due to a false weight distribution and the enormous loss of energy due to friction. The addition of supporting wheels for the following prototypes improved the robots performance. The segments of robot *S3* were equipped with two servomotors and the two degrees of freedom for each joint allowed the robot to undulate vertically and also horizontally. Robot *S5* had 32 joints which made it pos-

FIG. 9: *RoboTuna* [34]

sible to fit two wavelength of undulation within the length of the robot. The most recent prototype *S7* eliminates again the wheels from the design, propagates in a rectilinear motion and includes compass, sonar and heat sensors.

10. RoboTuna

MITs *RoboTuna*, a project of the department of Ocean Engineering, is modeled after the sea's fastest fish - the bluefin tuna. The development of the autonomous underwater vehicle started in 1993 and is based on fish performance studies and rigid flapping foil investigations. The main interest area is the body movement of the tuna and its generation of efficient propulsion force and maneuverability. An understanding of the hydrodynamics in fish swimming, how they position their bodies and flap their tails to recover energy from vortices and turbulences in the ocean, was transferred to the robot. A precise timing in tail oscillation makes it possible to oppose incoming vortices and therefore increase the efficiency of the propulsive motion.

The first robotic prototype was built in 1995 by Barrett, its descendant *RoboTuna II* was developed in 2000 by Beal and Sachinis. The 1.25 m long underwater robot consists of an aluminum skeleton and a hull of ribs wrapped in lycra skin. The undulatory movement of the backbone is based on a eight-link mechanism driven by six external servo-motors that provide the force through a cable-and-pulley system. Sensors mounted on its ribs allow the robot to detect flow pressure changes and adjust its motion through feed-back information. When performing in the MIT's testing tank the robot is supported by a tow carriage, that contains all the motor control and communication equipment [16].

The undulatory motion of the robot is caused by a traveling body wave that can be described by seven characteristic parameters: forward speed, strouhal number, angle of attack, phase angle and maximum excursion of the robots tail and wavelength and amplitude of the body wave. All the possible combinations of different parameter settings create a experimental space that is impossible to explore by hand-tuning. Barrett employed genetic algorithms to search for the parameter settings that allow the best performance of the robot. He carefully designed the external settings of the process to allow an efficient online artificial evolution. Motion criteria were evolved in populations of 10 and tested on the *RoboTuna* in the water tank. The fitness value was measured as the ratio of thrust to power input. After each evaluation the genetic algorithms chose the top 50 percent of the population, replicated them, crossed their genes at the midpoint (keeping grouped parameters together proved to allow a faster approach of optimal values) and mutated individual parameters. A decrease of the mutation rate during the ongoing evolution allowed a wider range of possible solutions at the start and a fine-tuning without losing too many characteristics at the end [2].

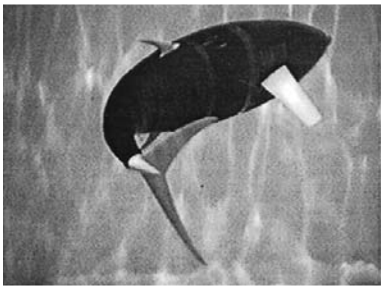

FIG. 10: *VCUUV* [17]

11. VCUUV

The Vorticity Control Unmanned Undersea Vehicle (*VCUUV*) is a direct descendant of MIT's *RoboTuna* and is named after the vorticity control flow mechanisms that is used by fish to maneuver and propel. Developed by at the Charles Stark Draper Laboratory in Cambridge the *VCUUV* performed its first swim tests in 1998. The form and movement of the 2.4 m long robot are modeled after the morphology and kinematics of the yellowfin tuna. In contrast to the *RoboTuna* the *VCUUV* is constructed to be fully autonomous. It carries its energy source, hydraulic actuator unit and control circuits in its rigid fore body. The second half of the robot consists of a freely flooded articulated tail construction that terminates in a caudal fin. The tail structure allows the individual control of three joints and the fin with hydraulic cylinders. An exoskeleton of rigid foam ribs and flexible spines allows smooth bending motions of the robots tail.

Stabilized by the caudal fin the *VCUUV* propels and maneuvers steady in the horizontal plane. By employing variations of the best motion control results from the *RoboTuna* project the robot reaches velocities of up to 1.2 m/s at a tail oscillation rate of 1 Hz. The *VCUUV* is able to turn at rates of up to 75 degrees/s, which is a drastic improvement to the 5 degrees/s turning rate of traditional unmanned underwater vehicles. Tests of the maneuverability of the vehicle show that its performance matches those of real tunas [2][17].

FIG. 11: Georgia Tech's *Entomopter* [35]

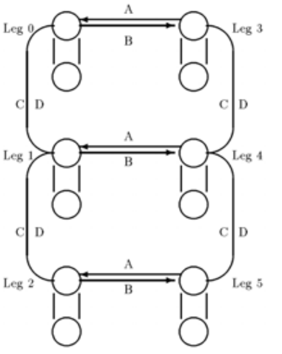

FIG. 12: Neural oscillator control network for *Rodney* [11]

12. Entomopter

The *Entomopter* in development at the Georgia Tech Research Institute is a mesoscaled aerial robot (MAR) that tries to emulate many of the locomotion strategies of insects - crawling, flying fast and maneuvering while flying slowly. Their special aerodynamic design allows insects wings to produce two to three times more lift than wings from birds or bats. The sharp leading edge of thin insect wings causes air flow vortices that give high lift to flapping wings. The *Entomopter* project tries to extend the performance of its biological role models. The wing-flapping robot started from biomimetic principals and copied its wing aerodynamics from the hawkmoth *Manduca sexta*. During development the wing has been reshaped to achieve better flight control and easier manufacture possibilities.

The morphology of the *Entomopter* consists of two wing pairs that are located on the front and rear end of the robots torso and are operated 180 degrees out of phase. Torso and wings are constructed as one piece to enable the recovery of flapping energy from the resonating torso of the robot. The constant frequency of wing-flapping is caused by the reciprocating chemical muscle (RCM) that operates on chemical fuel sources. Developed and patented at Georgia Tech the RCM uses chemical reactions to produce energy and motion. The waste gas produced by the RCM is used to pneumatically modify the lift generation of each wing. Individual lift control for every beat enables sophisticated flight control and stability. Special hollow microchannels in the ribs of the wings enable the modification of the wing shape according to pneumatic control. This allows obtaining positive lift on downbeat and upbeat flapping and is more efficient than biological wings. This flapping wing mechanism exceeds traditional fixed wing and rotational wing mechanisms in maneuverability.

The *Entomopter* design is not in full operation yet. Individual components are being tested and show promising results. As a micro air vehicle it is designed for indoor missions. Equipped with an ultrasonic range-finder it should be able to navigate autonomously based on an obstacle avoidance behavior. With a wingspan of 15 to 20 cm and a flapping frequency of 20 to 50 Hz the robot should be able to carry its 50 g weight. With its ability for speed-independent controlled flight and additional legs for ambulatory locomotion it can navigate in hallways or navigation systems, crawl through narrow pathways or under doors and quickly change from one form of locomotion to the other. Being able to carry additional payloads it can be used to place or retrieve payloads like sensors on/from remote hard reachable locations.

Funded by DARPA and the Air Force the development on the *Entopmopter*, its flying mechanism and the RCM continues. A NASA funded research tries to adept the Entomopter design in a larger scale for potential Mars fliers.

13. Rodney

Early walking pattern evolutions were conducted by de Garis (biped) and Beer and Gallagher (hexapod). They all based their artificial evolutions on simple models that only exist in the computer. Inspired by their work experiments were undertaken at the University of Southern California to evolve locomotion control for a hexapod robot called *Rodney* in 1992. Each leg of the robot could be actuated by two servomotors to produce limb lift and swing. The robot was unable to sensor his environment. The control architecture for the servomotors of the robot was designed as a simple neural oscillator network with weighted connections. The information for the synaptic weights in between the control units were stored in genetic code, which was evolved in populations of 10 individuals. In an incremental evolution they first concentrated on finding the oscillator circuit for single leg movements by evaluation on the computer. In the second step they evolved also the connections for coordination between the individual legs controllers. The output of the neural network activation was then downloaded into the physical robot and its fitness value was measured by human experimenters. Afterwards the two best results of every generation were selected and their genetic code was fed back to the computer for genetic reproduction. After 10 to 35 generations the experiment always leads to the tripod gait as an efficient walking pattern for the robot. Encounters of wave gate propagation in earlier generations disappeared due to their slower speed and therefore lower fitness [11].

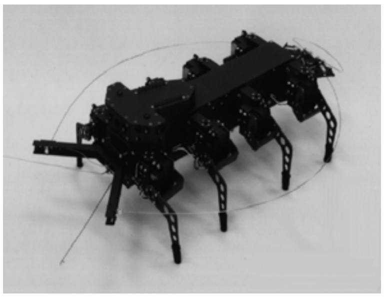

FIG. 13: *Oct-1b* [12]

14. OCT-1b

The octopod robot *OCT-1b* is designed after the body of a lobster. Its eight metal legs are each actuated by two servomotors that cause them to lift and swing. The robot was used for different walking pattern evolutions that were carried out in 1998.

Gomi and Ide designed an automated evolution process that was entirely carried out on the physical robot. Due to reading motor current sensors the robot is able to know the load on the horizontal and vertical axis of the leg and can therefore identify if strokes of the leg are effecting forward locomotion or not. Two touch sensors on the belly of the robot can determine if the robot falls down. The genotype for the motion control contains individual control signals for each of the eight legs. The information encoded gives the delay time before the leg starts to move, the current status of the leg, its maximum swing positions and its vertical and horizontal angular speed. The genotypes are evolved in populations of 50 and get tested by the robot for 40 seconds each. By individually evolving the leg controllers it takes over 100 generations to find effective forward walking patterns [12].

Jakobi evolves the control architecture for the *OCT-1b* for more advanced behavior. He includes the robots infrared and bumper sensors to make it avoiding obstacles while wandering around its environment. He chooses a neural network control architecture that consisted of 6 neuron units for every leg and the sensor neurons connected to the environment. He evolves the synaptic weight for the neuron connections in a computer simulation that tests the robots ability to walk forward when no obstacle is in sight, avoid obstacles by turning to the other side or backing off. Successful control systems emerge within 3500 generations and are downloaded onto the processor of the *OCT-1b*. The robot is able to successfully avoid obstacles in his environment by locomoting in a tetrapod gait [13].

When comparing the results of both approaches Gomi and Ide find that their controller produces more efficient and reliable locomotion control due to its evolution on the physical robot. Jakobi's control system evolved in simulation and therefore doesn't take hardware sensibilities like mechanical stress or motor wear into account [9].

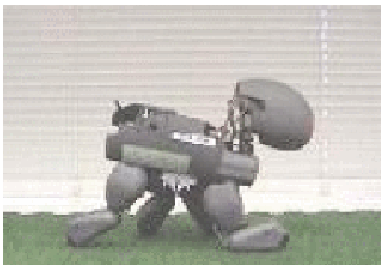

FIG. 14: *Sony quadruped robot* [14]

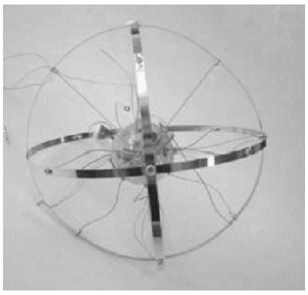

FIG. 15: *Koharo* [21]

15. SONY quadruped robot

In 1999 researchers at the Sony Corporation developed pace and trot gaits for their quadruped robot in the shape of a dog. The robots four legs each have three degrees of freedom. Additionally the robot is able to move his head and tail. Inbuilt infrared sensors and a camera for fast color detection enabled the process of an online evolution. The sensor values are not included in the evolved locomotion control, but are used to account the fitness-values by measuring the traversed distance. Preprogrammed procedures help the robot to stand up and reposition itself to the start position. Generations of locomotion controllers can so be tested without extensive human supervision. The locomotion controllers for the robot dog are predefined modules that are tuned by 20 evolvable parameter values. These parameters specify general body position and orientation, swing speed and trajectories and body oscillation factors. The researchers decided to limit the range of possible values to realistic locomotion behaviors to narrow the search space. After evolving those parameters with genetic algorithms for about twenty generations of populations of 30, stable trot (6.5 meters/minute) and pace gaits (10.2 meters/minute) can be found. Compared to prior hand-designed solutions the found pace gait locomotion control is almost twice as fast, which speaks for the success of this experiment [14].

16. Koharo - Crawling and Jumping Deformable Soft Robot

The *Koharo* project uses deformation as an alternative approach for locomotion over rough terrain. A soft robot can produce gravitational potential energy through deforming itself from a stable to a unstable

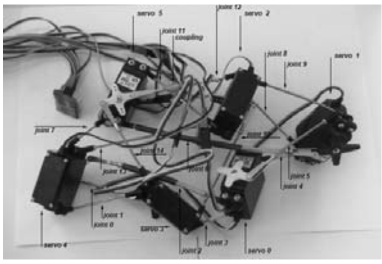

FIG. 16: *Random morphology robot* [22]

shape. Then the gravitational energy sets the robot into motion.

Circular and spherical robots have been constructed out of elastic shells and shape memory alloy actuators. The spherical crawling robot consists of three orthogonally intersecting circular shells, a core containing driving and control circuits and 18 SMA coils connecting the core and the shells. The robot has a diameter of 20 cm and weighs 137 g. The SMA coils are actuated with periodic voltage patterns and cause the spherical robot to deform by contracting. By repeating the deformation process the robot can achieve a stable locomotion pattern to achieve forward locomotion and hill climbing.

A similar yet smaller spherical robot contains four additional SMA coils that enable it to jump. By contracting the additional coils elastic potential energy gets stored and if released fast enough makes the robot jump a distance twice its diameter [21].

17. Random morphology robots

The *Random Morphology* project conducted at the Universitt Dortmund addresses the possibility of evolving control systems for robotic hardware for that no descriptive model exists, either because the design is too complex or because the structure has been built in a random process. The lack of a model usually makes it hard to derive the optimal control architecture because of a missing understanding of all the interdependencies between each of the structures components. Applying genetic algorithms to create an automatic learning and adaptation process eliminates the need for a complex hand-designed control system.

Dittrich, Bürgel and Banzhof performed the evolutionary process of finding a control architecture for their *Random Morphology Robots*. The *RM-robots* consist of 6 randomly arranged servo-motors linked together by thin metal joints in arbitrary connections. The goal of the experiment is to find a control program that is able to move the structure fast in one straight direction.

The genotype for the control program consists of a string of commands and parameters. The set of possible functions includes simple mathematical operations, delay functions, conditional operators and position commands for the individual servo motors. The evaluation of each control program is performed on the physical robot. The fitness value is measured by the input of a computer mouse that is tied to the *RM-robot*.

FIG. 17: *Self-modeling robot* [36]

Evolutionary runs with different population sizes, different sets of functions and different maximal program lengths have been conducted. After each evaluation the fittest genotypes are selected and reproduced with a mutation probability of 0.13 and a crossover probability of 0.86. The results show that success of the experiment, as the control architecture learns to cope with its unexpected morphology and develops locomotion patterns that propagate the random structure. The analysis of the best control programs shows that faster forward locomotion is usually reached by a more complex and therefore longer program [22].

18. Self-modeling robot

This evolutionary robotics project developed at the Dynamical & Evolutionary Machine Organization (DEMO) Lab at Brandeis University aims at generating control architectures for robots that lack any internal model of themselves. Traditional robotic systems own a hand-designed mathematical model of their dynamic capabilities on which they base their actions. This project created a robotic system that is able to experience its own morphology from scratch and update its self-model after unexpected damages to its structure. Tests were taken with a four-legged robot with eight degrees of freedom. Joint angle sensors and tilt sensors are included for the necessary feedback.

The process that helps the robot find its own self-model is based on algorithmic evolution. As a first step the physical robot performs a random motor action and monitors its sensor data at the same time. Then it tries to map the sensor data to the performed actions and synthesizes 15 possible self-models that could have caused the observed actuation-sensation relationship. Afterwards the robot performs another motor action that is likely to interfere with most of the predicted models. Now the model-synthesis step is repeated with more available information based on the new recorded action-sensor sequence. The discrepancy between the predicted sensor values and the actual observed values creates the inverted fitness value. Iterating the modeling-and-testing process for 16 cycles produces a model that represents most accurately the robots dynamic abilities. This final model is used to create a forward locomotion behavior for the phys-

FIG. 18: *Golem* [37]

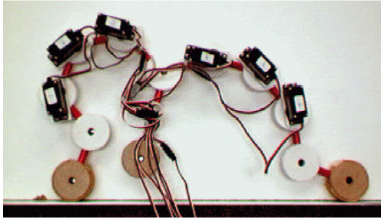

FIG. 19: *Genobots* [24]

ical robot.

When damage occurs to the morphology of the physical robot the system acknowledges differences between the observed and the predicted behavior and restarts the model-finding process. Instead of starting from random self-model predictions it uses its own previously inferred model as a starting point and applies length changes to the limbs or takes individual components away. After several cycles of testing and remodeling the system is able to discover the point of error and creates a new best locomotion behavior to compensate for the physical damage [23].

19. Golem

The *Genetically Organized Lifelike Electro Mechanics* project is a co-production between researchers around Pollack (DEMO Lab, Brandeis University) and Lipson (Computational Synthesis Lab, Cornell University). They claim that not only power and behavior of robots should be subject of evolutionary design, but also the bodies and their fabrication. *Golem* combines evolutionary computation of designing simple electromechanical systems with autonomous physical construction using rapid prototyping technologies.

Bars, actuators and artificial neurons are the elementary building blocks for the evolutionary design process of dynamical three-dimensional structures. Body structures are made by random connections of bars to each other. The evolutionary design process connects bars to each other through ball-and-socket joints and allows rigid or flexible forms to emerge. The control architecture for the behavior is made from random connections between artificial neurons. Synaptic weight and threshold parameters define the behavior of the neurons. By connecting the output of a neuron to a bar, the bar becomes a linear actuator that can be controlled by the signal of the neuron. The lack of constraints for connections between neurons and bars allows the emergence of several different control architectures.

A simulation program on the computer constructs the body and control architecture for 200 individuals and determines their fitness through testing their forward locomotion ability in a simple physical environment. Genetic algorithms select fitter machines and create new generations by adding, modifying or removing some of their building blocks. As the building code for the individuals doesn't differ between physical and neural entities, body and brain are evolved simultaneously. After 300 to 600 generations of artificial evolution some of the robots were selected for fabrication. The conversion into physical objects was first modeled by the computer that drew accurate three-dimensional plans of the structure and implemented functional ball-joints and accommodations for the motor units. This information was then forwarded to the 3D-printer that generated the entire structure by adding layer by layer. The researchers only needed to put in the stepper motors and the necessary support electronics. After downloading the output of the neural control architecture to the robots microprocessor, the robots were ready to perform their evolved locomotion patterns.

The solutions found by the evolutionary computation show a wide range of possibly body structures and motion controls. Symmetry emerged because symmetrical robots easier perform straight forward locomotion. By comparing the speed of the fabricated robots with their virtual counterparts it was discovered that simulations friction calculation was not realistic. Technological advances that would allow the rapid prototyping of electronic circuits and actuators would greatly enhance the possibilities of a human free design and fabrication process [15].

20. Genobots

The *Genobots* developed at the Dynamical & Evolutionary Machine Organization (DEMO) lab at Brandeis University exhibit a morphology and locomotion control evolved through computational evolution. To overcome the main critic point of evolutionary robotics approach - that it is unable to reach high levels of complexity - they use the generative rewriting rules of the L-system. A set of rewriting rules is applied iteratively in parallel to a string of symbols. This allows the emergence of complexity from a set of simple rules. Using this method for constructing robotic structures allows the creation of simple yet stable components that can be re-used more often in the whole structure. In that way higher efficiencies can be reached than in the much broader search space of direct-encoded genotype mappings.

The building blocks for the *Genobots* are simple bars connected through fixed or actuated joints that have a moving angle of 60 degrees. Frequency and phase offset of the actuators are parameters of the form finding process and ensure the co-development of morphology and control architecture.

The algorithms of the L-system consist of set of pro-

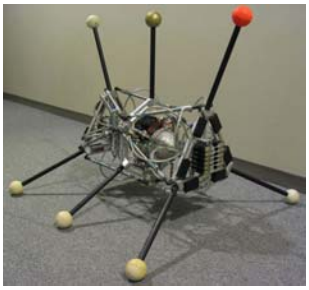

FIG. 20: CCSLs *Nonaped* [38]

duction rules that replace symbols with a strings of new symbols based on certain conditions. The possible symbol language includes commands to add bars or joints, perform rotations, change the phase offset parameter or push and pop the current states.

At first 100 solutions with random sets of rewriting rules are generated. After iteratively applying its rules the morphology and control for each robotic system is derived from its final string of commands. The whole generation gets tested in a physical simulation for the ability to move the robots center of mass forward. Fitter solutions create the offspring of the next generation through mutation and recombination of their rule set. Different evolutionary runs with a maximum of 500 generations produce a variety of creates that evolved successful forward locomotion patterns like crawling, rolling, walking or inching.

Physical robots have been constructed based on successful 2-dimensional and 3-dimensional *Genobots*. The 2D robots are hand assembled out of simple modular components and servo-motors [24].

21. Nonaped

The CCSLs *Nonaped* is a successful attempt to evolve dynamic walking patterns for a physical robot without giving limitations for the desired gait besides that it is supposed to be rhythmic. The robot consists of two Stewart platforms that are connected in series and provide 12 degrees of freedom through pneumatic linear actuators. Three triangular plates with three legs each build the rigid component of the robot. Arranged in front, middle and back plate these are connected with groups of six parallel actuators in between. Each pneumatic actuator is mounted between two platforms with ball-and-socket joints. Individual actuation of the pneumatic piston allows the platforms pitch, roll and yaw freedom.

As leg movement is caused by combined forces of several actuators stable walking gaits are hard to design by hand. Open-loop walking patterns for the *Nonaped* have been found through evolutionary algorithm applied in simulation and on the physcial robot.

Each pneumatic piston reacts according to a pair of binary signals that addresses its four behaviors: either the pistons is locked or passive, pushing or pulling. The genotype for the artificial evolution encodes the main cycle period for the motion pattern and the individual timing for every of the 12 actuators. The genotype contains the initial configuration for every actuator and when in each cycle it is supposed to change forth and back between its possible states.

For the physical evolution the robot is placed in a cage and monitored by a webcam from above that measures the fitness by comparing the placement of the robots colored front foot before and after each test run. At the start of each evolutionary run, random genomes are generated with cycle periods between 10 and 100 timesteps. Initial populations of 30 genomes are each evaluated for forward displacement after 200 timesteps, which corresponds to 5 seconds in the physical evolution. At the end of each generation 22 genomes are chosen for reproduction while the five fittest of them are protected from changes to avoid the loss of good solutions. The genetic codes undergo crossover and mutation algorithms that ensure that genomes with higher fitness are more likely to replace those with lower fitness values.

50 evolutionary runs in simulation and two evolutionary runs on hardware were conducted for about 30 generations. The results show that the fastest gait patterns were independent of their cycle period. Further the dynamic fraction for each gait was evaluated. Dynamic gaits are walking patterns during which the robot is statistically unstable for a fraction of the gait cycle time. The robot is statistically stable when his center of mass lies above the polygon of support formed by foot-to-ground contacts. If the center of mass lies outside this polygon the robot is considered to be in a dynamic transient process. The results show that the fastest locomotion patterns found are also the most dynamic ones.

IV. CONCLUSIONS

One goal of biomimetic design is to develop devices capable of locomoting through nature without necessary human supervision. Nature is full of obstacles and unexpected perturbations. Traditional human-made devices made of stiff materials and rotary motors tend to fail in such environments. They are not trained for every possible incident and don't possess the necessary autonomy to react appropriately on their own. One of the consequences is high stress that acts upon the mechanical components and causes damage to the hardware. And as robots are usually built without unnecessary redundancies, the malfunction of one component causes the whole system to fail. Although the *Random Morphology Robots* and CCSLs *Self-Modeling Robot* project show that a clever control architecture would allow the robot to experience its own morphology and compensate for damages, the main solution for truly biomimetic robots seems to lie in the material question. Biological life is soft and elastic. Compliant materials are damaged less easily and protect the whole system by absorbing high energy impulses through damping. Elastic resonating materials enable high energy savings and motion control at high frequencies. The muscle-skeleton-tissue apparatus of biological creatures is perfectly tuned to cope with external forces. The employment of muscle replacements like shape memory alloys, pneumatic systems or electroactiv polymers provides more compliant yet forceful actuators and therefore more robust locomotion of robots. Sadly most of these actuators have severe drawbacks like a low power output, a heavyweight support system or the need for high-voltage actuation. Still the ongoing research on promising approaches like electroactive polymers and the reciprocating chemical muscle could produce better and easier-to-use solutions in the near future. Also advancements in prototyping methods like shape deposition manufacturing and 3D-printing could allow building robots including their actuators and sensors out of one piece. The ability to use polymers with different material properties makes it possible to achieve the softness and elasticity of biological bodies. But as long as it is impossible to produce and shape materials as wished, robotics has to cope with what is available. Evolutionary robotics is a successful approach of finding the best solutions for systems built from available components. Genetic algorithms form designs until they fulfill a certain goal. Most projects use this approach for an already limited search space like evolving the parameters of the hand-designed CPG network for *Rodney*. This combination of scientific knowledge with evolutionary tuning produces complex and highly competent designs. Other projects like *Genobots* or *Golem*, that allow much more freedom in design of control and morphology, produce results at rather simple levels. But as complexity emerged in nature, evolutionary robotics will be able to show highly advanced results in the future. And then successful robots might employ newly found locomotion techniques instead of copying nature's solutions and even be able to exceed cockroaches, lobsters and tunas in their performance.

---

[1] Paulson, L.D. (2004) 'Biomimetic Robots', *Computer*, vol. 37, no. 9, pp. 48-53.

[2] Ayers, J., Davis, J. L. & Rudolph, A. (2002) *Neurotechnology for biomimetic robots*, MIT Press, Cambridge.

[3] Bar-Cohen, Y. & Breazeal, C. (2003) *Biologically inspired intelligent robots*, SPIE PRESS, Bellingham, Washington.

[4] Gilbertson, R. G. (1993, 2000) *Muscle wires project book*, Mondo-tronics, San Rafael.

[5] Iovine, J. (2002) *Robots, androids, and animatrons*, McGraw-Hill, USA.

[6] Ashley, S. (2003) 'Artificial muscles', *Scientific American*, vol. 289, no. 4 , pp 5259.

[7] Pelrine, R., Kornbluh, R., Pei, Q. & Joseph, J. (2000) 'High-Speed electrically actuated elastomers with strain greater than 100%', *Science*, vol. 287, pp. 836-839.

[8] Beer, R. D., Quinn, R. D., Chiel, H. J. & Ritzmann, R. E. (1997) 'Biologically inspired approaches to robotics', *Communications of the ACM*, vol. 40, no. 3.

[9] Nolfi, S. & Floreano, D. (2000) *Evolutionary robotics: the biology, intelligence, and technology of self-organizing machines*, MIT Press, Cambridge.

[10] Alexander, R. McK. (2003) *Principles of animal locomotion*, Princeton University Press, Princeton and Oxford.

[11] Lewis, M. A., Fagg, A. H. & Solidum, A. (1992) 'Genetic programming approach to the construction of a neural network for control of a walking robot',*Proceedings of the IEEE International Conference on Robotics and Automation*, Nice, France, pp. 2618-2623.

[12] Gomi, T. & Ide, K. (1997) 'Evolution of gaits of a legged robot', *IEEE World Congress on Computational Intelligence*, Alaska, pp.

[13] Jakobi, N. (1998) 'Running across the reality gap: Octopod locomotion evolved in a minimal simulation', in *Evolutionary Robotics: First European Workshop*, ed. Husbands, P. and Meyer, J.-A., Springer-Verlag, Berlin.

[14] Hornby, G. S., Fujita, M., Takamura, S., Yamamoto, T. & Hanagata, O. (1999) 'Autonomous evolution of gaits with the Sony quadruped robot', *GECCO-99: Proceedings of the genetic and evolutionary computation conference*, San Francisco, pp. 1297-1304.

[15] Lipson, H. & Pollack, J. B. (2000) 'Automatic design and manufacture of robotic lifeforms', *Nature*, vol. 406, pp. 974-978.

[16] Triantafyllou, M. S. & Triantafyllou, G. S. (1995) 'An efficient swimming machine', *Scientific American*, vol. 272, pp. 64-70.

[17] Anderson, J. M. & Chhabra, N. K. (2002) 'Maneuvering and stability performance of a robotic tuna', *Integrative and Comparative Biology*, vol. 42, pp. 118-126.

[18] Kingsley, D. A., Quinn, R. D. & Ritzmann, R. E. (2003) 'A cockroach inspired robot with artificial muscles', *Proceedings of the International Symposium on Adaptive Motion of Animals and Machines*, Kyoto, Japan.

[19] Michelson, R., Hemlick, D. & Reece, S. (1997) 'A reciprocating chemical muscle (RCM) for micro air vehicle *Entomopter* flight', *Proceedings of the Association for Unmanned Vehicle Systems*, international, pp.429 - 435.

[20] Zykov, V., Bongard, J. & Lipson, H. (2004) 'Evolving dynamic gaits on a physical robot', *Late Breaking Papers at the 2004 Genetic and Evolutionary Computation Conference*, Seattle, Washington, USA.

[21] Shiotsu, A., Yamanaka, M., Matsuyama, Y., Nakanishi, H., Hara, Y., Tsuboi, T., Iwade, T., Sugiyama, Y. & Hirai, S. (2005) 'Crawling and jumping soft robot KOHARO', *Proceedings of 36th International Symposium on Robotics*, Tokyo.

[22] Dittrich, P., Bürgel, A. & Banzhaf, W. (1998) 'Learning to move a robot with random morphology' in *Evolutionary Robotics - First European Workshop*, ed. P. Husband & J-A. Meyer, Springer Verlag, Heidelberg.

[23] Bongard, J., Zykov, V. & Lipson, H. (2006), 'Resilient machines through continuous self-modeling-, *Science*, vol. 314, no. 5802, pp. 1118 - 1121.

[24] Hornby, G. S., Lipson, H. & Pollack, J. B. (2001) 'Evolution of generative design systems for modular physical robots', *IEEE International Conference on Robotics and Automation*, Piscataway, NJ.

[25] Clark, J. E., Cham, J. G., Bailey, S. A., Froehlich, E. M., Nahata, P. K., Full, R. J. & Cutkosky, M. R. (2001) 'Biomimetic design and fabrication of a

hexapedal running robot', *International Conference on Robotics and Automation*, Seoul, Korea.

[26] Kim, S., Clark, J. E. & Cutkosky, M.R. (2004) 'Isprawl: autonomy, and the effects of power transmission', *Proceedings of the International Conference on Climbing and Walking Robots*, Madrid, Spain.

[27] Birch, M. C., Quinn, R. D., Hahm, G., Phillips, S. M., Drennan, B., Fife, A., Verma, H. & Beer, R. D. (2000) *Proceedings of the IEEE International Conference on Robotics and Automation*, San Francisco, vol. 2, pp. 1109-1114.

[28] http://www.neurotechnology.neu.edu/, accessed 30 December 2006.

[29] http://biorobots.cwru.edu/, accessed 30 December 2006.

[30] http://bdml.stanford.edu/, accessed 30 December 2006.

[31] http://ag47.informatik.uni-bremen.de/eng/pictures.php, accessed 30 December 2006.

[32] http://fourier.vuse.vanderbilt.edu/cim/, accessed 30 December 2006.

[33] http://www.snakerobots.com/, accessed 30 December 2006.

[34] http://web.mit.edu/towtank/www/Tuna/tuna.html, accessed 30 December 2006.

[35] http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/EntomopterProject.html, accessed 30 December 2006.

[36] http://ccsl.mae.cornell.edu/research/selfmodels/, accessed 30 December 2006.

[37] http://www.demo.cs.brandeis.edu/golem/, accessed 30 December 2006.

[38] http://ccsl.mae.cornell.edu/research/nonaped/, accessed 30 December 2006.