Biomimetic approaches to new robotics

Paolo Dario, Scuola Superiore Sant' Anna, Pisa, Italy

Recent advancements of robotics technologies are opening new opportunities for the application of robotics in biological research. [1]. The adoption of bio-inspired approaches in robot design lead to advances in robotics technologies, in terms of more compliant and stable mechanisms, and new developments in materials, fabrication technologies, sensors, actuators and control schemes [2]. Thanks to these achievements, bio-inspired robots also represent a useful scientific tool for studying biological systems and in particular animal forms [3].

In this talk four examples of the application of bioispiration paradigm will be presented, thus exploring different approaches to face different problems related to the locomotion and actuation mechanisms.

In neuroscience, the use of robotics has resulted to be especially significant when models of sensory-motor coordination involving different brain areas are investigated [4], by using bioinspired artefacts. The most effective approach consists of purposely designing and developing bio-robotic platforms replicating the biomechanical and sensorial characteristics of the animal form under analysis [5]. A joint design is required for all system components, in particular the mechanical structure and the control schemes.

According to this biomechatronic approach, a biorobotic lamprey platform has been designed by taking advantage of the extensive knowledge on the lamprey musculo-skeletal and nervous systems and on the CPG and by jointly designing the mechanical structure and the control system. The lamprey-like robot has an elastic notochord made by a steel wire whose flexibility has been set to be the same of the natural counterpart. On the notochord, five segments are placed each with four actuators arranged in ventral/dorsal, left/right configuration; for each segment, 2 optical sensors are positioned to measure flexion. In this case the main aim of the work is reproducing the lamprey neuromuscular system, by relying on the deep knowledge on the CPG and on the behaviour of the lamprey in natural environments. The final objective of this joint investigation of neuroscientists and roboticists is the scientific understanding of basic mechanisms, regarding for example the switching of locomotion strategy depending on the environment and the selection of behaviours [6].

Locomotion strategies in the small scale (millimeter size) in terms of energy efficiency, negotiation of uneven terrains and robustness to disturbances (e.g.: wind) have been investigated: starting from natural observation of small animals, the authors conjectured that jumping could be an optimal candidate as locomotion strategy.
Studies have been carried out in order to better understand the biological mechanisms at the base of jumping locomotion, from an engineering point of view, with the aim of developing new models which improve existing theories on animal locomotion (in particular on the physiology of jumping in small animals). The obtained results have successfully been used for identifying design principles to be adopted for the development of jumping minirobots with onboard power source and ability to travel long distances on uneven terrains (figure 1). Regarding scale effects in micro-robots, several researches have been carried out on system design [7] but the issue of which strategy adopt according to robot size has been explored in authors work for the first time. Attention has been firstly focused on the jump biomechanics in small animals (a particular leaf-hopper, the *Cicadella viridis*, has been chosen). Firstly, observations of the considered insect have been carried out by means of a digital high speed camera, observing and recording the take-off phase of jumping. This high speed recordings have then been exploited for extracting the kinematic parameters (velocity and acceleration) of the insect body and legs. Moreover, scale effects (i.e. body size) on the jump mechanics have been studies for a wider class of animals a model has been developed for relating scale effect to gait switching in animals.
Of notice, the acceleration (i.e. the thrust) of the *Cicadella Viridis* seems to be constant during the take-off phase. Moreover, the aforementioned biomechanical model correctly predicts the effect of animal size on gait switching. In particular, it highlights the fact that for small animals, jumping is a more effective locomotion strategy (compared e.g. to walking, crawling, etc…).

The octopus is an invertebrate sea animal with amazing motor capabilities and intelligent behavior, with respect to its position in the evolutionary scale [8]. Most recognized theories explain that this enhanced behaviour and capability of interaction with the environment is due to the peculiar morphology of the octopus body, and especially to the form and materials of its limbs (tentacles). The motor capabilities of the tentacles are far beyond any existing robots, for their dexterity and for the variability of their stiffness, on a very wide range. Based on this consideration, the authors started an investigation on the octopus tentacle, aimed at: 1) a deeper understanding of the biomechanics, kinematics, dynamics, and control of the octopus tentacle and of their role in the determination of the octopus behaviour and interaction with the environment, and 2) new design principles for actuation, sensing, and manipulation control, for robots with increased performance, in terms of dexterity, control, flexibility, and applicability. The octopus tentacle has served as an inspiration in robotics, to develop the so-called continuum robots, with omnidirectional mobility. Walker and co-workers developed continuum robots that, in contrast to traditional rigid-link robots, feature a continuous backbone with no joints [9]. Potential applications of these robots include navigation and operation inside complex, congested environments in search and rescue operations, or inside the human body in medical applications.

Plants have developed growth responses to deal with the copious and rapid changes in their environment in order to compensate for their sessile nature. The process by which plant roots expand in soil involves water uptake through osmosis, and an overall increase in size by cell division [10]. Each root apex has sensors to get information from the environment, which is then transduced, processed, and used to direct the growth towards regions of the soil with the best minerals and water availability. This knowledge has inspired a novel concept of robotic system and a new actuation mechanism inspired by plant root (see figure 2), leading to a first mechanical design based on several theoretical assumptions and preliminary experimental tests. A parametric model of the system geometry has been developed, in order to obtain an optimal size of the robotic system and to achieve a best compromise between penetration capability and actuation times. A generic and scalable structure of the robotic apex has been fixed following a minimal approach in the design of the robotic root apex.

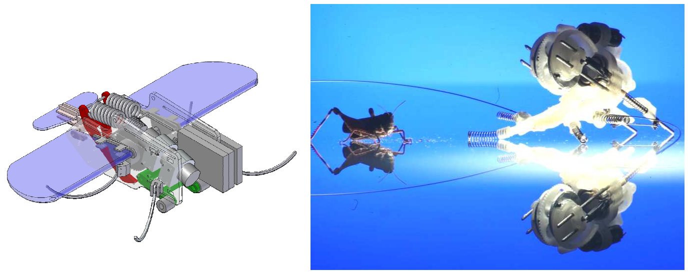


Fig.1: Jumping minirobot

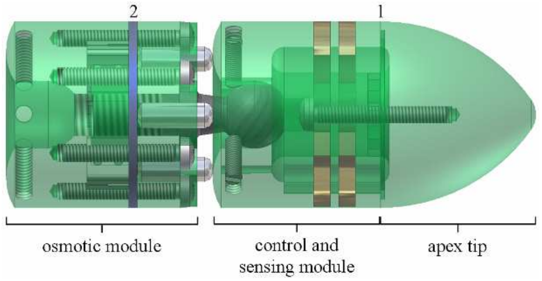


Fig. 2: robotic plant apex

[1] R. D. Beer, R. D. Quinn, H. J. Chiel, and R. E. Ritzmann, “Biologically inspired approaches to robotics”, Communications of the ACM, 40(3):, pp. 30-38, 1997.
[2] V. Durr, J. Schmitz, and H. Cruse, „Behaviour-based modelling of hexapod locomotion: linking biology and technical application”, Arthropod Structure & Development, pp. 237-250, 33, 2004.
[3] B. Webb, T. Consi, Biorobotics: Methods and Applications, MIT Press, 2001.
[4] L. Manfredi, E.S. Maini, C. Laschi, P. Dario, B. Girard, N. Tabareau, A. Berthoz, “Implementation of a neurophysiological model of saccadic eye movements on an anthropomorphic robotic head”, submitted to the IEEE International Conference Humanoids 2006, Genova, Italy, 4-6 December, 2006.
[5] C. Laschi, B. Mazzolai, F. Patanè, V. Mattoli, P. Dario, H. Ishii, M. Ogura, S. Kurisu, A. Komura, A. Takanishi, “Design and development of a legged rat robot for studying animal-robot interaction”, IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, Pisa, Italy, February 20-22, 2006
[6] O. Ekeberg and S. Grillner. Simulations of neuromuscular control in lamprey swimming. Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences, vol. 354, pp. 895-902, 1999.
[7] Kaneko M. et al., IEEE Journal of Robotics and Automation, 1987, 3: 19-30.
[8] Hochner B., Shomrat T., Fiorito G., “The Octopus: A Model for a Comparative Analysis of the Evolution of Learning and Memory Mechanisms”, Biol. Bull. 210: 308-317, 2006.
[9] Walker, I., Dawson, D., Flash, T., Grasso, F., Hanlon, R., Hochner, B., Kier, W., Pagano, C., Rahn, C. and Zhang, Q. “Continuum Robot Arms Inspired by Cephalopods.” SPIE The International Society for Optical Engineering Defense and Security Symposium, Orlando, FL, March, 2005.
[10] Schopfer P Biomechanics of plant growth. Am. J. Bot. 93, 2006, 1415-1425.

Multi Purpose Usage of Artificial Legs in Rough Terrain

Jan Albiez, Dirk Spenneberg, Markus Eich, Sebastian Bartsch, Felix Grimminger and Frank Kirchner
DFKI Robotics Lab Bremen, Germany, jan.albiez@dfki.de

Introduction

Legged robots have moved from the pure academic research are into the more application driven areas. There have also been first attempts to successful commercialise them in the entertainment business, Sony's AIBOs being the best-known example. The causes for this transition are not only the better mechanics but also the improved knowledge of the low-level control of legged robots. CPGs and reflex chains are to well known examples for successful control approaches. In this abstract two extremes of legged systems used in uneven terrain, both using the same CPG approach (see [1] for details), but using them on different robots with different goals.

Legs for walking and grasping

One of the major research areas in the DFKI robotics lab, is the use of legged robots as planetary rovers on space missions. The surfaces of Mars and Moon have been the target during the development of the eight-legged SCORPION [1], the four-legged ARAMIES [2] and the six-legged SCARABAEUS [6]. In the space context, the ability of walking robots for traversing rough terrain or the steep slopes of craters is not the only advantage. The legs of these systems can also be used to grasp objects of interest and to place them into internal laboratories.

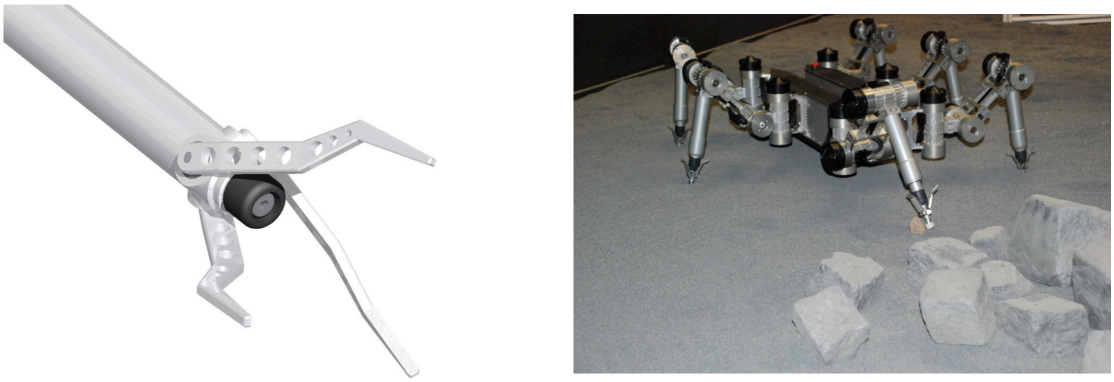


Figure 1 (left) The new gripper design for SCORPION, (right) the six-legged robot SCARABAEUS

To demonstrate this ability we have equipped the legs of SCORPION and SCARABAEUS whit grippers (see Figure 1). The grippers are moved partly away while walking and used when in grasping mode. To integrate them into the control architecture of the robots, we extended our CPG-reflex approach by an inverse kinematic solution. Using the phase-offset input of the CPGs has done this. When the control software of the robots is instructed to grasp an object, the CPGs tonic input is reduced to zero, and the legged is moved by the deliberative control elements of the higher level via the offset input.

Currently SCARABEUS is mainly used as the demonstrator and research platform for this multi-use of legs. We have successfully demonstrated our new approach and are currently enhancing the design in two projects sponsored by DLR and ESA.

Hybrid locomotion

Legs, as biological inspiration for locomotion, can also be used in the other extreme. To generate high speed over flat terrain, combined with a high mobility in uneven terrain and high robustness, wheel-leg-hybrids have been successfully used (see [3] and [4]). The main requirements while designing our new hybrid ASGUARD [5] were the ability to climb stairs, move over uneven terrain and travel relatively fast on flat surfaces. With ASGUARD we use a hybrid system consisting of four wheels, where each wheel consists of five mechanical compliant legs (see **Figure 2**(left)). An additional passive degree of freedom between the fore and the hind section allows for even more adaptivity to rough terrain. The design of the ASGUARD wheel allows the climbing of stairs by gripping the stair corner between to legs.

Figure 2 (left) ASGUARD in a rock channel at the DFKI outdor test facilities, (right) the design of one ASGUARD wheel

The control of ASGUARD uses mainly internal proprioceptive data. An abstract model of Central Pattern Generators controls the locomotion of the robot. The compliant legs of the robot are arranged around four hip shafts, with an angular distance of 2π/5. Because of the symmetry of the legs, we have only to consider the phase between [-π/5, π/5] (see **Figure 2**(right)). The CPG generates a saw-tooth like pattern, which then acts as inputs of four PID-Controllers for the individual motors speed. The motor current and the actual wheel position are used as inputs for the CPG. The robot is therefore able to automatically synchronise the legs which each other concurrent to an overall pattern and to switch between different modes (e.g. flat terrain, stair climbing).

For the directional and speed control of ASGUARD a high level controller, which receives its input via a joystick, sends the parameters for phase, frequency, and direction to the CPGs. ASGUARD has already been tested heavily on different terrains and various set of stairs. Current works mainly focus on improving the mechanical design and implementing autonomous behaviours.

References

1. Kirchner F. and Spenneberg D., and Linnemann R., *A biologically inspired approach towards robust real world locomotion in an 8-legged robot,* in Neurotechnology for Biomimetic Robots, MIT Press, 2002
2. Spenneberg, D. and Albrecht, M. and Backhaus, T. and Hilljegerdes, J. and Kirchner, F. and Strack, A. and Zschenker, H. *ARAMIES: A Four--Legged Climbing and Walking Robot*, In Proceedings of 8th International Symposium iSAIRAS, 2005
3. Saranli, U. and Buehler,M. and Koditschek, D.E., *RHex: A Simple and Highly Mobile Hexapod Robot,* The International Journal of Robotics Research, 20(7), pp. 616-631, July 2001
4. Quinn, R.D.and Offi, J.T. and Kingsley, D.A. and Ritzmann, R.E., *Improved mobility through abstracted biological principles,* In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and System, Volume 3, pp. 2652-2657, 2001
5. Eich, M and Grimminger, F. and Bosse, S. and Spenneberg, D. and Kirchner, F., *ASGUARD: A Hybrid Legged Wheel Security and SAR--Robot Using Bio--Inspired Locomotion for Rough Terrain*, In Proceedings of the IARP/EURON Workshop on Robotics for Risky Interventions and Environmental Surveillance, January 2008
6. Spenneberg, D.; Kirchner, F.: *A Free-Climbing Robot for Steep Terrain*. In In 9th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2008), Los Angeles, California, USA, February 26-29/2008

Challenges for the Development of Robotic Insects

Robert Wood
The Harvard Microrobotics Lab
School of Engineering and Applied Sciences
Harvard University

Abstract: We seek to elucidate how to use biological principles for the creation of robust, agile, inexpensive robotic insects. However, these principles alone are not sufficient to create robots that share these characteristics with their analogs in biology. This is particularly true for insect-scale robots: to create the high performance articulated and actuated components of robotic insects, we must explore novel manufacturing paradigms.

Traditional manufacturing methods are insufficient to produce devices on the sub-millimeter scale, so a novel manufacturing paradigm called “Smart Composite Microstructures”, or SCM, is used. SCM utilizes a flexible thin polymer film sandwiched between two rigid composite layers. This technique enables the creation of flexure joints analogous to macro-scale revolute joints, and the construction of robust microstructures with ultra-high strength to weight ratios. Additionally, the use of electroactive materials within the laminate results in actuated structures.

Now that these fabrication techniques are in place, we must address the remaining issues for creation of autonomous robotic insects: sensing, electronics, power, and control. Microelectronic and microelectromechanical sensors appropriate for small robot proprioception and exteroception are being developed by multiple groups. For example, we have demonstrated ocelli, halteres, and optical flow sensors, all for stabilization of sub-gram flying robots. We are also developing new architectures for high-efficiency, low-weight power electronics to drive the actuators of robotic insects. Power is an essential topic that must be solved for any robot that must carry its own energy. High power density, high energy density LiPoly batteries are emerging that are promising for these devices. Furthermore, energy harvesting techniques are being explored to supplement on-board energy storage. Finally, our group is beginning to explore control strategies for unstable, under-actuated, nonlinear, computationally limited robots.

In March 2007, The Harvard Microrobotics Lab demonstrated the world’s first flight of an at-scale robotic insect. Tethered for stability and power supply, this robot was the first insect-scale flapping-winged device capable of producing enough thrust to lift its own weight. Work on the project continues with the ultimate goal of developing a fully autonomous robot capable of untethered flight. The lab has also demonstrated a biomimetic fish fin capable of undulatory motion mimicking the biomechanics of actual body/caudal fin propulsion. A cockroach-sized biomimetic leg has been built as a step towards producing a hexapedal crawling robot.

The applications for robotic insects are the ubiquitous applications for any autonomous robot. Surveillance, reconnaissance, hazardous environment exploration, search and rescue, and environmental monitoring are just a few examples. Just as with larger devices, robotic insects will be placed in situations that would be dangerous to human operators; however, due to decreased size, increased agility, and decreased cost, these robots will be able to perform tasks faster, more robustly, and in environments that would be otherwise impassible.

Bio: Robert Wood is an Assistant Professor in Harvard's School of Engineering and Applied Sciences (SEAS). Prof. Wood completed his M.S. (2001) and Ph.D. (2004) degrees in the Dept. of Electrical Engineering and Computer Sciences at the U. C. Berkeley. He was a postdoctoral researcher in Berkeley's Biomimetic Milli-Systems Lab for one year before joining the faculty at Harvard. While at Berkeley, he invented the Smart Composite Microstructures (SCM) process for rapidly creating sub-millimeter to centimeter scale articulated, actuated, and rigid micromechanical structures. He has demonstrated both flying and terrestrial microrobots created using this paradigm. At Harvard, he founded the Harvard Microrobotics Lab which contains the world's leading facilities for the SCM process. His current research interests involve the creation of biologically-inspired mobile microrobots for aerial, terrestrial, and aquatic environments, minimal control of under-actuated nonholonomic nonlinear dynamical systems, and decentralized control of multi-agent systems. He is the winner of a 2007 DARPA Young Faculty Award.

Walking, Climbing and Reaching:
News on Kinematics and Dynamics and Questions about the Level of Control

Fischer MS

[4] Institut für Spezielle Zoologie und Evolutionsbiologie, Friedrich-Schiller-Universität, Jena, Erbertstr. 1,
D-07743 Jena, Germany

1. Motivation and scope

The question which is of greatest current interest to me in the field of locomotion is the interdependency of intelligent mechanics and control. The German language distinguishes between “Steuerung” und “Regelung”, that is central and adjustment control. Recently, we started to use photothrombosis in order to selectively eliminate different parts of the motor cortex in rats. To our surprise, our rats show only minor handicaps even after extensive lesions: walk smoothly, groom and reach for food. Thanks to our new biplanar-high-speed-videoradiography we are now able to detect difference with much more precision. We use the same set up to document climbing in various mammals as well as the chameleon to biologically inspire the ongoing work on a climbing robot (see Mämpel et al. this volume).

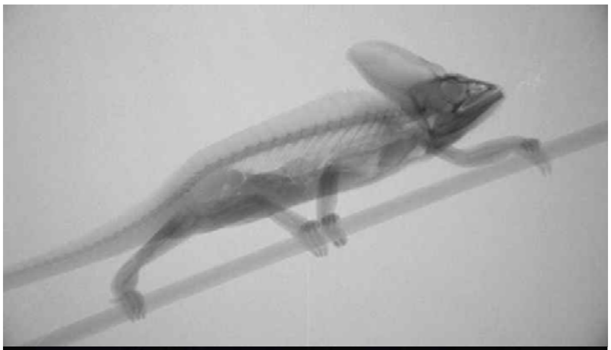
2. Technical advancement

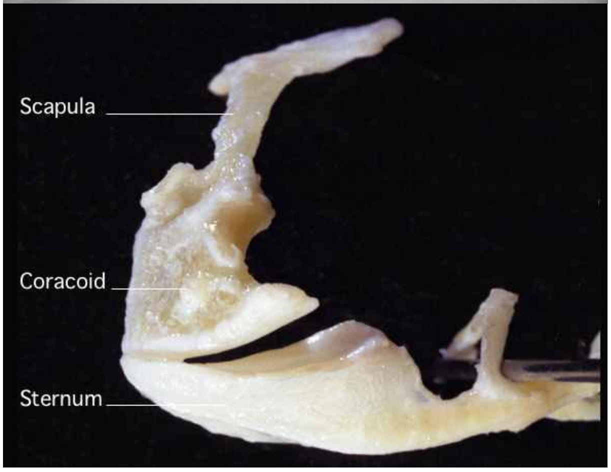
We are proud to announce a new biplanar-high-speed-videoradiography-system And the good news: it will be accessible to the international scientific community at minimum costs. The system is based on the high-end X-Ray system Neurostar from Siemens. For very high frame rates, the use of X-ray Image intensifiers in combination with TV- cameras was required. Two 16 inch Image Intensifiers are available. Depending on the size of the object, different zoom formats can be used. Besides the 16 inch full format, zoom with 11”, 8” and 6” is possible. At the full format of 16 inch the resolution is better than 1.3 LP/mm,. At 6”, we measured more than 3 LP/mm. That means, small structures down to 0.1 mm can be displayed. The selection of the TV- cameras for the Image Intensifiers was critical in order to obtain a superior resolution in combination with very high light sensitivity. For the X-ray channel we selected a first class high speed camera SPEEDCAM visario g2 from Weinberger-Vision Company in Erlangen (Germany). These cameras provide high light sensitivity together with excellent resolution. They can sample at 1000 f/s with a matrix of 1536 by 1024. With some Overframing we can obtain 2000 f/s at 1024 by 768 Pixels. The Nikon Nikkor Optics with a focal distance of 50mm and a maximum aperture of 1:1.2 provides good sharpness and high light transmission. So the system can run in a very Low Dose mode with a minimum of X-ray radiation. The adaptation on the different light levels is done by a remote controlled iris in the optical channel between Image intensifier and TV camera. For scene cameras, we chose the latest black and white cameras, SPEEDCAM MiniVis e2 ECO with an extreme light sensitivity and a resolution of 512 by 512 pixels for up to 2500 f/s. In combination with high aperture Zoom optics, optimal object capture is provided. All 4 cameras are externally synchronized and can run with frame rates from 125 up to 2000 frames per second. They are controlled by the latest high perform software VISART , which provide besides the absolute synchronized operation also the display of the 4 images in parallel and comprehensive image processing features. A high end PC equipped with a Dual Core Processor and Raid 0 got the camera data via a Gigalink network. By external S-ATA hard discs a fast transfer of the high amount of data to other workstations is possible.

Finally, we will present ctx-movies based on biplanar-high-speed-videoradiography from a collaboration with a mediadesigner: Jonas Lauströer (Hamburg)

2. First results: Climbing

Many tetrapod vertebrates are able to move on trees so long as the support diameter is large, but only a few groups have developed specialized adaptations for foraging on small branches. Quadrupeds that climb and walk on such narrow support face two key problems: (1) controlling the gravity-induced momentum imposed on the body axis (balance) and (2) reducing the gravity-induced forces imposed on the limbs (compliance). The combination of prehensile extremities and simultaneous footfalls of diagonally opposite limbs increases the balancing abilities of primates, arboreal marsupials, and chameleons over those of other arboreal vertebrates by allowing them to shift their weight dynamically sideward, or backward and forward. Chameleons, arboreal marsupials, and primates use a crouched limb posture, but only chameleons and primates possess relatively elongated limbs, which increase step lengths and contact times, and thus, reduce the peak substrate reaction forces. So, chameleons and primates display a highly compliant gait. Arboreal quadrupedalism does not necessarily demand three-dimensional limb excursions. videoradiographic analyses show that forelimb abduction results from constraints in shoulder morphology.

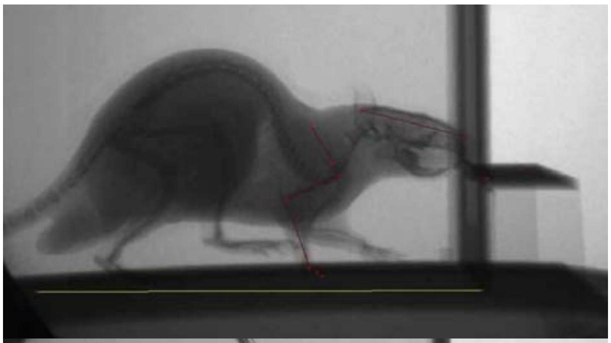


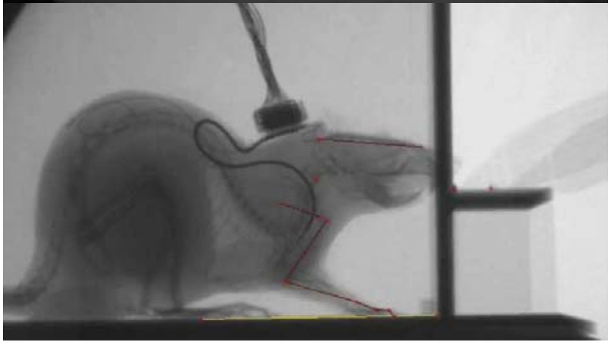


But, because the shoulder morphology differs in chameleons and mammals, each had to find different solutions to overcome these constraints. Chameleons support their parasagittal limb excursions by possessing the most mobile scapulocoracoid among reptiles. In primates, by contrast, the "emancipation" of the arm from the scapula was an important pre-requisite for developing locomotor modes reliant on shoulder joint mobility rather than on scapular excursions. For more details on the climbing robot see Mämpel et al. in this volume.

3. First results: Reaching in rats

Since Whishaw (1991), videorecording and motion analysis is the basic tool for studying reaching and crasping in rats with motor cortex lesions. In our study, we combine the skills of different groups at Jena University.





Training and movement notation analysis is done by the group lead by Prof. Otto Witte (Neurology), EMG-studies by the group of Prof. Scholle, and 3-D kinematics based on videoradiography by our own group.Adult Wistar rats were trained to retrieve food pellets in a skilled reaching task prior to receiving a unilateral cortical infarction induced by photothrombosis in forelimb motor cortex. Animals were continuously tested in the reaching task up to 3 weeks after lesion.

All rats are analyzed prior to photothrombosis and form the control group. A first cohort received photothrombosis, a second photothrombosis plus a 16-channel matrix-electrode subcutaneously impanted onto the long and lateral head of the triceps muscle. So our data set comprises high resolution 3-D kinematics, together with myoelectrical activation patterns in normal and lesioned rats. The end point measures revealed that reaching success rates remained at pre-lesion levels. Analysis of reaching movements indicated only a change in timing of the movement due to paresis in the first ten days but no permanent changes in forelimb movement patterns except for the loss of supination/pronation. Incidentally, we also observed grooming behavior, and, much to our surprise, recorded supination in this context. Locomotion is not handicapped even after 50% of motor cortex lesion. Some ideas on the lower level of control in rats in contrast to primates concerning the absence of monosynaptic cortico-motoneural connections, or the possible higher adjustment control in rats will be presented. It has been documented for the long head of the triceps brachii muscle that its length also serves as a reference system for the activation of almost all monoarticular forelimb muscles (Caicoya et al., 1999). It is likely but never investigated that the same system exists on the hindlimb with both gastrocnemius heads fulfilling the same function as the long head of the triceps muscle. This internal control system has the unquestionable advantage to minimize the effort of supraspinal neural control (Fischer, 2001).

Applying principles from the locomotion of small animals to the design and operation of bio-inspired robots

Mark R. Cutkosky
Professor, Dept. of Mechanical Engineering
Stanford University

Collaboration between biologists and engineers has resulted in a new generation of bio-inspired robots. Drawing inspiration from the locomotion of small animals, these robots are faster, more versatile, more robust and easier to control than their predecessors. The bio-inspired design process begins with identifying exemplars from nature that excel at a particular task, such as running rapidly over rough terrain or climbing vertical surfaces. The next step is to hypothesize design principles that underlie the animals' success. These design principles represent a simplified abstraction of the complex structures and behaviors observed in animal models. The design principles guide the development of small robots, which take advantage of recent developments in rapid prototyping technology to create tuned multi-material structures with embedded sensors and actuators that exhibit the desired characteristics and response. Testing and evaluating the robots reveals where the design principles should be refined or augmented. The resulting insights are valuable to both roboticists and biologists to deepen their understanding about what is important, and why.

The bio-inspired design process will be illustrated with several running and climbing robots from Dr. Cutkosky's laboratory.

Biosketch:

Mark Cutkosky is a professor at the Center for Design Research in the Department of Mechanical Engineering at Stanford University. He formerly was a lecturer and research assistant at the Carnegie Mellon University Robotics Institute and a design engineer at ALCOA. Dr. Cutkosky is the principal investigator of projects on Biomimetic Robotics and Dexterous Manipulation with Tactile Sensing. He has numerous publications in these and related areas and is a former Fulbright Chair and NSF Presidential Young Investigator.

Web site: http://bdml.stanford.edu

==========================

Photos:
* http://www-cdr.stanford.edu/~cutkosky/
* http://soe.stanford.edu/research/layout.php?sunetid=cutkosky

==========================

The higher order control of locomotor behaviors in fruit flies.

Michael Dickinson
California Institute of Technology

Abstract: As researchers analyze the locomotion of insects with ever more accurate methods, they have uncovered a surprising degree of adaptive and flexible motor control. For example, as insects encounter obstacles in their environment, they not only quantitatively alter their locomotor output (i.e. slow down, turn left, etc.), they may also appear to choose one of several alternate strategies to overcome challenging impediments. The apparent sophistication of such behaviors challenges century-old traditional notions that insects operate as complex finite-state automata, Recently, researchers have suggested that insect nervous systems are capable of rudimentary form of cognition and even ‘free will’.

Because of their importance as a model genetic organism, fruit flies (/Drosophila melanogaster/) sit front and center in this debate between drastically opposing viewpoint of animal behavior. Using a neuroethological perspective, I will examine the control of flying and walking in /Drosophila/, with the aim of testing whether insect behavior can or cannot be explained as the output of a complex automaton. I will investigate whether complex sequences of behavior might result from a serial iteration of simpler motor acts, and whether the operant closed-loop behavior of flies can be explained by genetically-preprogrammed open-loop reflexes. I hope that the presentation will stimulate discussion not only on the mechanistic basis of animal behavior but also on robust strategies for the control of autonomous robots.

Neuroprostheses for Movement Restoration

P. Hunter Peckham, Ph.D.
Donnell Institute Professor of Biomedical Engineering
Director, Functional Electrical Stimulation Center of Excellence
Case Western Reserve University and Veterans Administration Medical Center

Abstract: Major advances have been made over the past decade in use of neuroprostheses for restoration of motor function. These advances have been built on the fundamental science of neural excitation and the technologies for implantable stimulation and control. The technologies have advanced to provide operational systems that function in the human body for decades, and include implantable electrodes, stimulation devices, and sensors. The neural interface between the excitable tissue and the delivery electrode are enabling evermore powerful control and precision in the delivery of stimulation, not only providing for excitation but also blocking of neural activity (e.g. for annihilation of pain or spasticity) and selective stimulation. Distributed implantable systems and brain control interfaces are currently in development that will provide greater flexibility in implementation and performance.

The clinical manifestations of these findings are the available systems that have been created, and are being developed, to restore function. These include many areas of the body for people with spinal cord injury, including hand grasp, standing and walking, breathing, and bladder and bowel control. The presentation will provide examples of both upper and lower extremity neuroprostheses to restore full arm mobility and levels of standing and ambulation. Several areas where future advances are likely to meet clinical challenges will be discussed.

Animals as models for robot mobility and autonomy: Crawling, walking, running, climbing and flying

Roger D. Quinn
Case Western Reserve University

The biorobotics program at CWRU has been active for 20 years. This presentation highlights many of the projects undertaken during that time and describes how neuromechanical principles have benefited a number of robots. As this list of principles grows, so does the functionality and performance of the biorobots.

We use biological inspiration to incorporate neuromechanical principles of locomotion and autonomy into robot designs. The dual goals are to develop useful robots and also to develop neuromechanical models of animals to test hypotheses about their design, movement and control. These goals are complementary. Better models lead to more efficient experiments and new neuromechanical knowledge, which points the way to improved robot designs and animal models.

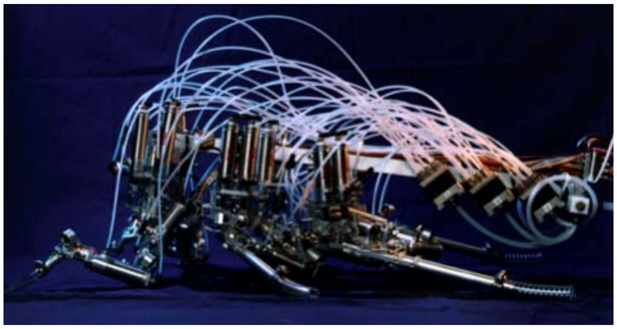


Figure 1. Robot III, a cockroach robot

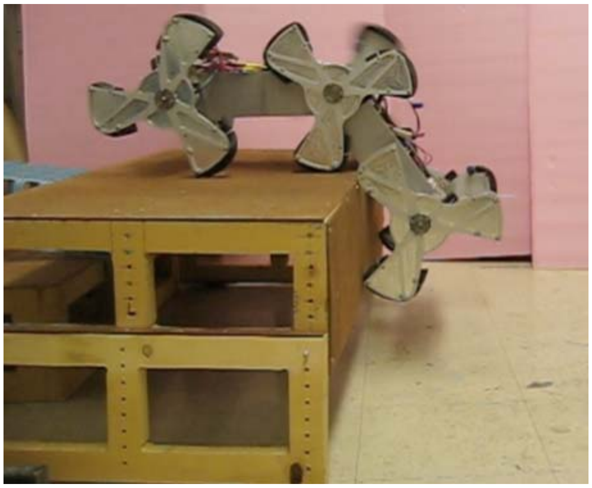


Figure 2. DAGSI Whegs™ climbs a tall step

A robot that captures the leg designs important for cockroach locomotion will be extremely agile and therefore suitable for many missions. For example, the after action report for the robot search and rescue mission at the World Trade Center recommends that legs be used instead of tracks or wheels because they can better adapt to complex terrain. However, before a robot with the intricate leg designs of an animal can be deployed some technical issues must be solved. Therefore, the Quinn-Ritzmann groups are using two complementary approaches to develop mobile robots. Using the direct approach we have developed a series of robots that are each more similar to cockroach. These have multi-segmented legs requiring a controller that captures neurobiological principles. The third robot in this series is shown in Figure 1. Models of insect legs are being used to understand animal leg control circuits and how descending commands from the brain interact with the local circuits to profoundly change leg movement. This knowledge will greatly simplify the control circuits for our legged robots and make them more robust.

In the more abstract biorobotics approach the fundamental principles of cockroach locomotion are applied using existing technologies. Robots called Whegs™ have mechanical designs that passively solve lower level motor control problems and their subsequent agility makes them suitable for many applications in the near term. Whegs™ can climb barriers much taller than their leg lengths (Fig. 2). Small Whegs™ robots called Mini- Whegs™ can run rapidly

Figure 3. Mini- Whegs™ running

Figure 4. Mini- Whegs™ climbing

Figure 5. MALV walks on the ground using Mini- Whegs™ technology

over relatively large obstacles (Fig. 3). A Mini-Whegs™ with specially designed legs and animal inspired adhesive feet can climb vertical glass walls (Fig. 4). It places each of its adhesive feet on the wall, propels itself through the stance phase, and peals its feet from the wall mimicking insect foot motion. Mini- Whegs™ has also been integrated with a micro air vehicle to form MALV (Micro Air and Land Vehicle) shown in Figure 5.

The WTC report also recommended that search and rescue robots should be capable of autonomous locomotion. A long-term goal is to develop an artificial insect head with sensors and a guidance and stabilizing system for implementation in our small mobile robots. Preliminary research resulted in a Whegs™ robot autonomously climbing obstacles using tactile antennae and avoiding obstacles using ultrasonic sensors in a bat-inspired configuration. The Willis-Quinn groups are developing odor tracking behaviors based upon moth behavior. CWRU's Urban Challenge vehicle, DEXTER, and its autonomous lawnmower, CWRU Cutter, benefit from an animal inspired control architecture.

Animals that have soft bodies can very effectively locomote and manipulate materials in their environment. For example, worms, leeches, and slugs are all capable of moving through complex environments. The Chiel-Quinn groups have developed two robotic devices: a peristaltic robot, and a soft gripper device. The peristaltic robot is constructed from a number of specially designed McKibben actuators in series surrounded by a central hollow tube. We have also developed a soft gripper device consisting of a series of four rings, each of which is constructed from four McKibben actuators, arranged in parallel to form a hollow lumen. At the center of the lumen, we have placed a spherical grasper that can open and close on material that is attached to the center of the lumen by a spring.

Mobiligence:
Emergence of Adaptive Motor Function
through Interaction among the Body, Brain and Environment

Hajime Asama
Director of the *Mobiligence* Program
RACE (Research into Artifacts, Center for Engineering)
The University of Tokyo
Kashiwanoha 5-1-5, Kashiwa-shi, Chiba 277-8568, Japan
Tel. +81-4-7136-4255, Fax. +81-4-7136-4242, E-mail asama@race.u-tokyo.ac.jp

1. Introduction

The *Mobiligence* program is a five-year program started from 2005[1], which was accepted as a program of Scientific Research on Priority Areas of Grant-in-Aid Scientific Research from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). This paper introduces the concept of the *mobiligence*, and presents the overview, objectives, and approaches of the program.

2. Objective of the *Mobiligence* program

Human, animals, or even insects have function to behave adaptively even in diverse and complex environment, such as a locomotive behavior in the form of swimming, flying walking, a manipulation behaviors such as reaching, capturing, grasping by using hands and arms, a social behavior to the other subjects, etc. Such adaptive behaviors are the intelligent sensory-motor functions, and most essential and indispensable ones for animals to survive.

It is known that the function of such adaptive behaviors is disturbed in patients with neurological disorders. Parkinson disease is a typical example of disorders on adaptive motor function, and autism or depression can also be considered as a disorder on social adaptive function.

Recently, due to aging or environmental change of society, the population of people who are suffering from these diseases is growing rapidly, and it is urgent to cope with this problem. However, the mechanisms for the generation of intelligent adaptive behaviors are not thoroughly understood.

The objective of the *mobiligence* program is to understand the mechanism on how the adaptive behaviors of the biological systems are generated.

3. Concept of the *Mobiligence*

Such an adaptive function is considered to emerge from the interaction of the body, brain, and environment, which is caused by motion or action of the subject. The environmental information which the subject can obtain is quite limited in the static condition. However, once the subject starts to move or act, the signals to move its body are transmitted from the brain to the body, and the interaction between the body and environment is generated due to the motion or action, and the rich environmental information can be acquired dynamically. From this consideration, we suggest a working hypothesis that the adaptive function is considered to emerge from the interaction among the body, brain and environment, which requires motions or actions of the subject, and name this concept *mobiligece*, which stands for intelligence emerged from mobility.

The information which can be acquired by motions or actions are;

1. diverse information by existing in various locations
2. dynamical information, and
3. experience.

4. Research Approach in the *Mobiligence* program

A large amount of knowledge and findings on function and mechanisms of various neural networks and neural modulator has been obtained so far by the biological research represented by neurophysiology. However, the most of such knowledge was obtained based on animal experiments. The animal experiments can be made in the condition that the body is fixed. In such conventional analytical approach in the biology, the observation is quite limited to the measurement of the simple brain function in stationary state, and function on interaction between brain, body, and environment in dynamic state is difficult to observe.

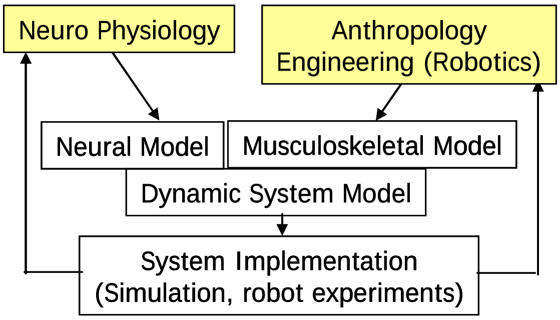
To overcome the problem, a new approach was adopted in the *mobiligence* research. The physiological models or hypotheses can be made from the knowledge obtained by biological studies such as clinical medicine and animal experiments. With the physiological models or hypotheses, the biological models can be derived by integrating engineering technologies and methodologies, such as dynamical system modeling. The biological models or hypotheses can be implemented on a simulator and actual robot systems, and can be verified by realizing the adaptive functions. The biological models can also be constructed by integrating biological elements and mechatronic elements to construct bio-machine hybrid systems.

Such a research approach to understand the mechanisms of emergence of adaptive behaviors can be called a constructive approach by close collaborative research of biology and engineering.

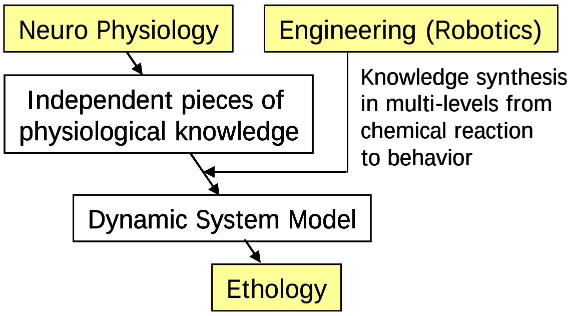
In the *mobiligence* program, three types of methodologies of collaborative research of biology and engineering;

1. system Biomechanics
2. synthetic Neuroethology, and
3. brain machine integrated system.

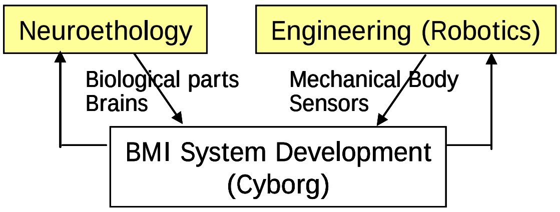
The schematic concept of the methodologies is shown in figure 1.



(a) System Biomechanics



(b) Synthetic Neuroethology



(c) Brain Machine Integrated System

Fig. 1 Methodologies for collaborative research

5. Research Groups of the *Mobiligence* program

The *mobiligence* program focuses on three aspects of the mechanisms generating adaptive behaviors:

1. Mechanism whereby animals adapt to recognize environmental changes;
2. Mechanism whereby animals adapt physically to environmental changes; and
3. Mechanism whereby animals adapt to society.

Research groups for each of the categories listed above are organized.

Group A: Adaptation to environmental change
  discusses investigation of mechanism to generate the information based on cognition of the environmental change

Group B: Physical adaptation
  discusses investigation of mechanism to change and control the body according to the environment

Group C: Social adaptation
  discusses investigation of mechanism to select the behaviors adaptively to other agents and society

While the three groups investigate the specific adaptive behaviors of various biological systems, it is required to seek for the common principle, which underlies the mechanisms to generate the various types of specific adaptive behaviors. The fourth group was organized to investigate the common principle of the *mobiligence*:

Group D: Social adaptation
  discusses investigation of common principle on dynamics in generating adaptive behaviors

6. Expected Impact of the *Mobiligence* Program

Various types of adaptive motor function mechanisms performed by animals are expected to be elucidates. In the medical field, the results of our research will contribute to the discovery of a method to improve motor impairment and develop rehabilitation systems. In addition, in the engineering field, the results of our research will contribute to the derivation of the design principles of artificial intelligence systems. Furthermore, we will explore the new research field, *mobiligence*, establish a research organization that integrates biology and engineering, and implement programs to foster young engineering scientists and biologists to conduct collaborative and interdisciplinary research between biological and engineering research, respectively.

Acknowledgment

The author thanks Prof. Kazuo Tsuchiya, Prof. Koji Ito, Prof. Masafumi Yano, Prof. Kaoru Takakusaki, Prof. Ryohei Kanzaki, Prof. Jun Ota, Prof. Akio Ishiguro, Prof. Hitoshi Aonuma, Prof. Koichi Osuka, and other members of the planned research groups for their cooperation in establishing the concept of the *mobiligence* and the organization of the *mobiligence* program. The author also thanks to Prof. Shigemi Mori (National Inst. Physiological Sci.), Prof. Ryoji Suzuki (Kawazawa Inst. Tech.), Prof. Shinzo Kitamura (Hyogo Assistive Tech. Research and Design Inst.), Prof. Sten Grillner (Korolinska Inst.), Prof. Avis H. Cohen (Univ. Maryland), Prof. Rolf Pfeifer (Univ. of Zurich) for the evaluation of the *mobiligence* program as reviewers.

References

[1]http://www.robot.t.u-tokyo.ac.jp/mobiligence/index_e.html

Title: Synthetic neuronethological approach to understand experience dependent adaptive behavior in the cricket

Hitoshi Aonuma[1] and Jun Ota[2]
[1] Research Institute for Electronic Science, Hokkaido University, Sapporo, Japan
[2] Graduate School of Engineering, The University of Tokyo, Tokyo Japan

Animals have evolved nervous systems to adapt dynamically changing environment. Insects have rather simple and identical nervous systems than mammalian brain. Thus insects must be good model animals to investigate neuronal mechanisms underlying adaptive behavior. They perceive lots of signals as stimulation from environment and they adjust their behavior. They do not always respond same way to the same external stimuli. The state of central nervous system must be dependent on their experiences as well as internal and/or external conditions. These factors would mediate threshold of releasing a behavior or behavioral pattern. Insect neuroethology has already provided valuable insight into how nervous systems organize and generate sophisticated behavior. It has made important contributions to brain research, expanding our overall understanding of sensory and motor systems. However, thousands of mechanisms to understand how adaptive behavior emerges have been still remained unclear. We believe one of the common goals of biologists and engineering researchers must be to understand how nervous systems adapt animal behaviors to the dynamic environments. For further elucidation, we combine neuronethological approaches and engineering approaches by constructing dynamic model to understand neuronal mechanisms of socially adaptive behavior.

Fig. 1. Agonistic behavior of male crickets. Two of males were placed into an experimental arena to observe behavioral response to the cuticular substances that are on the surface of cricket's body. Crickets bit each other until one of then retreat from the opponent.

It is important topic to investigate social adaptation in animal behavior. Previous social behavior such as mating behavior and agonistic behavior must drastically mediate following behavior. We have focused on insect communication behavior using male crickets to understand how animals establish social organization and how they emerge adaptive behavior in the society. Cricket aggressive behavior is one of the pheromone behaviors released by cuticular pheromone on the surface of cricket body. The main components of the cuticular substances are hydrocarbons. The male and female cuticular pheromones introduce different behaviors in male crickets. When male crickets come across a female to perceive female pheromone, they start courtship behavior. When they, on the other hand, come across conspecific male, they start agonistic behavior (Fig. 1). The interaction usually escalated to hard fighting. After the fighting, the dominant (winner) starts aggressive song with chasing after the loser (subordinate). The subordinate crickets wouldn't fight again against other male crickets about 1 hr. This indicates that cricket behavior can be modified by the previous social experiences. How do subordinate animals retain the previous experiences and change their behaviors after they lose fighting? We have investigated neuronal mechanism of the cricket agonistic behavior. Behavioral and pharmacological experiments suggest that NO generation in the brain would play important role on the formation of dominant hierarchy. We also hypothesize that NO system might regulate biogenic amines in the brain to meditate agonistic behavior of crickets. In order to understand dynamic activities of the cricket's brain, we are trying to construct a neuronal circuit model based on biological experiments. We consider neuromodulators in the neuronal model that consists of a diffusion equation for NO level, differential equations for biogenic amine levels and a threshold model for behavior selection.

We have also constructed models of cricket agonistic behavior based on biological analysis. First of all, observation ability and motion ability of artificial cricket are assumed based on animal behavior. The behavior of the artificial crickets was described by using a probability that is defined by the parameter α. A personal field of an artificial cricket was defined and the behavior was simplified to three major primitive patterns that were wandering, avoiding and fighting. Artificial cricket fight each other when they encounter with other one. After fighting, subordinate turns and escapes from dominant opponent and avoid them for a while. On the other hand, dominant retreat others from its personal field. Animals change their behavior based on their experiences. Hence, we need at least one internal state variable for the cricket model. The probability (*P*) of losing at cricket fighting depends on a parameter α that runs from 0 through 1. The parameter α describes an internal state of the cricket. We determined this parameter from the behavior experiments of crickets. The value of α gradually decrease depending on time. Losing at fight increases the value of fight but decreases while winning at the fight.

$$P = \alpha (0 \le \alpha \le 1) \qquad (1)$$

The value of α is revised with the following equation.

$$\alpha_{n+1} = (1-\omega)\alpha_n + \varepsilon_{lose}\eta_{lose} - \varepsilon_{win}\eta_{win} \qquad (2)$$

Here,

$$\eta_{lose} = \begin{cases} 1 & \text{if lose} \\ 0 & \text{else} \end{cases}, \eta_{win} = \begin{cases} 1 & \text{if win} \\ 0 & \text{else} \end{cases}$$

We simulate how crickets change their behavior depending on the density of animal population (Fig. 2). The simulation results are similar to that of behavior observation results of crickets, suggesting that the parameter α would contain internal model that must be neuronal modulation system in animals. Adequate parameter tuning in the simulation model also suggests that the cricket behaviors among males were mainly influenced by the previous fighting experience in the particular previous losses.

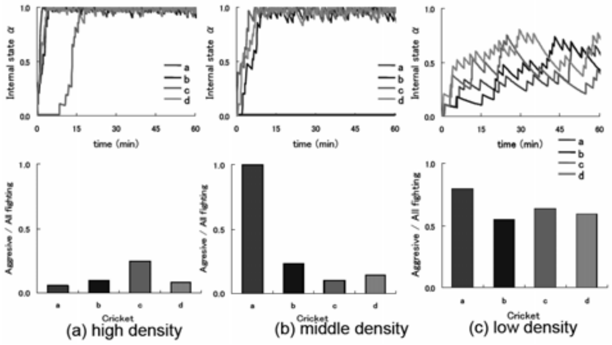


Fig. 2. Simulation results of the artificial cricket behavior. Three kinds of fields (128×128(pix), 256×256(pix) and 512×512(pix)) are utilized for simulations. The number of crickets was fixed to four. In case of higher density, the value of α converged to rather high and most of all avoided each other. In case of middle density, one of the crickets increased its α value to be dominant. In case of low density, α did not converge. The aggressiveness of each cricket was similar and α value is not so low.

Modeling must give us better idea to understand mechanisms underlying adaptive behavior and also give us some hypothesis. Therefore multidisciplinary contributions from neuroethology (analysis) and engineering (synthesis) will be important for a deeper understanding of adaptive behaviors.

Understanding Mobiligence Through Amoeboid Locomotion
– A Case Study with a Modular Robot –

Akio Ishiguro
Dept. of Electrical and Communication Engineering, Tohoku University, Sendai, 980–8579, Japan
ishiguro@ecei.tohoku.ac.jp

The behavior of robotic agents as well as animals emerges through the dynamics stemming from the tight interplay between the control system, mechanical system, and environment. Despite the existence of tight interdependency between control and mechanical systems, traditional robotics have often ignored this and have focused on either mechanical designs or control architectures in isolation. Generally speaking, system enhancement has been achieved normally by increasing the complexity of its control system. This, however, causes serious problems, particularly in terms of adaptivity and energy efficiency.

Under these circumstances, recently the importance of the following suggestions has been widely recognized: (1) a certain amount of computation should be "offloaded" from the control system to its mechanical system; (2) there should be an "ecologically-balanced" task distribution between the control and mechanical systems; and (3) under which one can expect that quite interesting phenomena, *e.g.*, real-time adaptivity and high energy efficiency, will emerge[1][2][3] (see Fig.1). However, there are still a number of issues that remained to be understood about how such task distribution between control and mechanical systems can be achieved so as to emerge useful functionalities[4][7].

Now a question arises. How can we investigate the validity of the suggestions above effectively? One may say that one of the promising ways is to focus on a primitive living system, and to mimic its behavior in a synthetic manner, *i.e.*, building a robotic agent. To do so, we have employed *slime mold* as a model living system[5][6] (see Fig.2), and have modeled this as an "embodied" coupled nonlinear oscillator systems.

In this talk, we introduce our robotic case study underway in the Mobiligence project, dealing with a fully decentralized two-dimensional modular robot called "Slimebot" that exhibits amoeboid locomotion by taking full advantages of the interplay between its control and mechanical systems. Owing to this minimalistic approach, we clearly show that there exists an "ecologically-balanced" coupling, under which significant abilities such as real-time adaptivity effectively emerges.

Fig.3 (a) and (b) show representative simulation results obtained under the condition of 100 and 500 modules, respectively. In these simulations, the task of Slimebot is to move upward. The two thick circles in the figures denote obstacles. These snapshots are in the order of time evolution (view from left to right). As the figures illustrate, the Slimebot can successfully negotiate the environmental changes without losing the coherence. These results provide us the following three points that have to be noted. First, as we clearly see in Fig.3 (b), the traveling wave stemming from the phase distribution created through the mutual entrainment gradually becomes conspicuous (see time step 1000 in the figure), and the right and left outer sections in the module group start moving toward the center. As a result, locomotion is generated by causing the spontaneous connection/disconnection between the modules. It should be noted that this passive/spontaneous connectivity control mechanism provided by the functional materials is fully exploited in the process. Second, the way of negotiating the environment seems significantly different: the Slimebot in Fig.3 (a) passes through the obstacles by narrowing the width of the entire system, whilst the one in Fig.3 (b) negotiates its environment by enclosing the obstacles. Note that these behaviors are not pre-programmed, but are totally emergent. Third and finally, the effect of cohesive force contributes to maintain the coherence of the entire system. Around the time step of 30000 in Fig.3 (a), we temporarily turned off the goal light. As we see from the figure, the Slimebot starts to form a circle in shape. This is due to the cohesive force similar to the effect of surface tension. In order to verify the feasibility of our proposed method, experiment performed with a real physical Slimebot is vitally important. A prototype of the latest version of a module for Slimebot is represented in Fig.4.

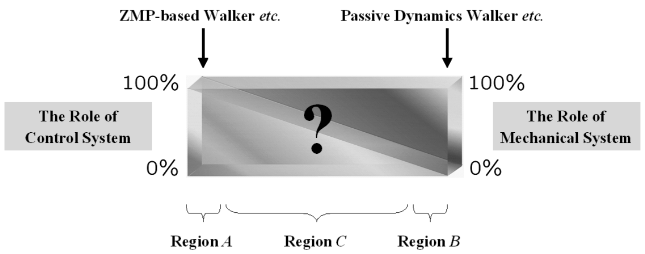


Fig. 1. A graphical representation of possible task distribution between control and mechanical systems in generating behavior. Most of the current robots are driven under the task distribution either around the left or right extremity (Region A or Region B). Our case study strongly supports that in order to emerge mobiligence, the task distribution should be designed around Region C.

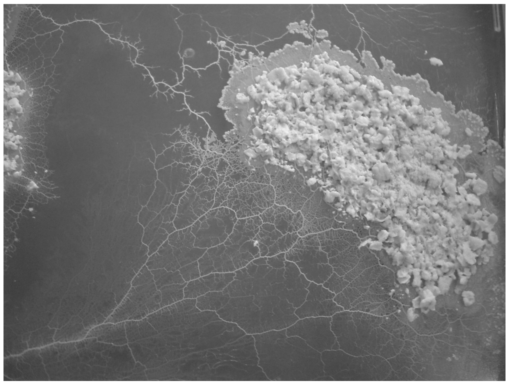


Fig. 2. True slime mold (*Physarum polycephalum*). They exhibit amazing collective intelligence without any centralized control mechanism.

ACKNOWLEDGMENTS

This work has been partially supported by a Grant-in-Aid for Scientific Research on Priority Areas “Emergence of Adaptive Motor Function through Interaction between Body, Brain and Environment” from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

REFERENCES

[1] McGeer, T.: Passive dynamic walking. The International Journal of Robotics Research, **9(2)** (1990) 61–82

[2] Pfeifer, R. and Iida, F.: Morphological computation: connecting body, brain and environment, Japanese Scientific Monthly, **58(2)**, (2005) 48–54

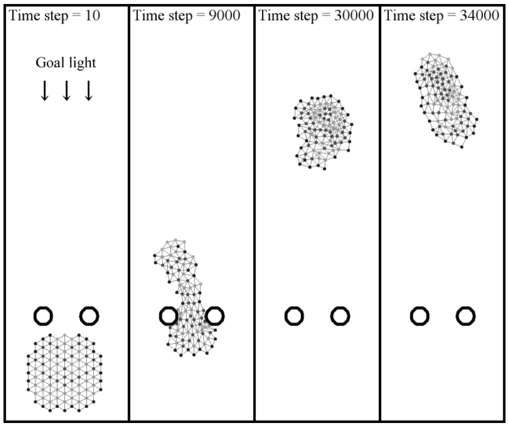
[3] Matsushita, K., Lungarella, M., Paul, C., Yokoi, H.: Locomoting with less computation but more morphology, Proc. of the 2005 IEEE International Conference on Robotics and Automation, (2005) 2020–2025

[4] Ishiguro, A. and Kawakatsu, T.: How should control and body systems be coupled? — a robotic case study —, Lecture Notes in Computer Science (Eds. Iida, F., Pfeifer, R., Steels, L., and Kuniyoshi, Y.), Springer, (2004) 107–118

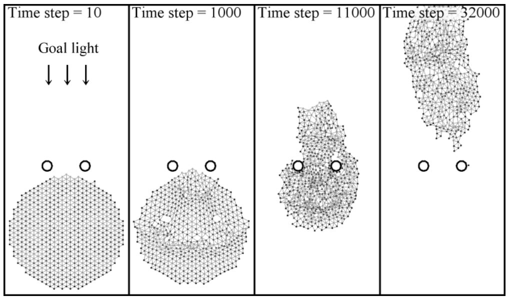
[5] Nakagaki, T., Yamada, H., and Tóth, Á: Maze-solving by an Amoeboid Organism, nature, **407**, (2000) 470

[6] Takamatsu, A., Tanaka, R., Yamada, H., Nakagaki, T., Fujii, T., and Endo, I.: Spatiotemporal Symmetry in Rings of Coupled Biological Oscillators of Physarum Plasmodial Slime Mold, Physical Review Letters, **87(7)**, (2001) 078102

[7] Ishiguro, A., Shimizu, M., and Kawakatsu, T.: Don’t try to control everything!: an emergent morphology control of a modular robot, Proc. of the 2004 IEEE International Conference on Robotics and Automation, (2004) 981–985



(a) The number of the modules: 100



(b) The number of the modules: 500

Fig. 3. Representative data of the transition of the morphology (see from left to right in each figure).

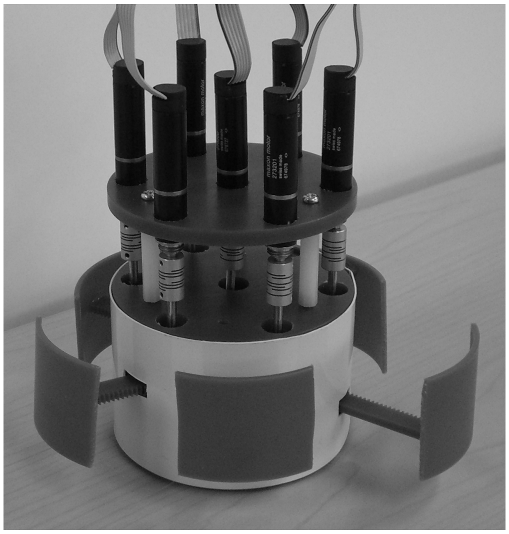


Fig. 4. A prototype of a real physical module of Slimebot.

Synthetic study of quadrupedal/bipedal locomotion in the Japanese monkey

Naomichi Ogihara[1], Shinya Aoi[2], Yasuhiro Sugimoto[2], Masato Nakatsukasa[1], Kazuo Tsuchiya[2]

[1]Department of Zoology, Graduate School of Science, Kyoto University, Japan
[2]Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Japan

I. INTRODUCTION

Animals are capable of generating locomotion adaptive to diverse environments by coordinately controlling complex musculoskeletal systems. Mechanisms underlying the emergence of such intelligent adaptive behavior have often been attributed to the sophisticated control mechanism of a biological sensorimotor nervous system. However, the suggestion has recently been made that animals achieve such adaptive yet efficient locomotion by exploiting intrinsic designs and properties of the musculoskeletal structures acquired through evolutionary history. A fundamental limitation may thus exist in attempts to clarify how the nervous system adaptively functions during locomotion based solely on neurophysiological studies; towards elucidating the mechanisms, the mechanisms of information processing emerging from appropriate dynamic interactions among the neuro-control system, musculoskeletal system and environment must be thoroughly investigated.

We therefore aim to construct a biologically plausible computer simulation of animal locomotion by integrating physiological findings from the locomotor nervous system and the anatomy and biomechanics of the musculoskeletal system, with the aim of illuminating the dynamic principles underlying the emergence of adaptive locomotion in animals. Particular focus was placed on modeling quadrupedal and bipedal locomotion in the Japanese monkey (*Macaca fuscata*), as Japanese monkeys have recently been used for neurophysiological studies on adaptive locomotor mechanism, allowing direct comparisons between experimental data and simulation results. Moreover, the transition from quadrupedalism to bipedalism in Japanese monkeys is regarded to some extent as a modern analogue of the evolution of bipedal locomotion and therefore offers an interesting subject for research in the field of physical anthropology. Furthermore, inferences gained by analyses of phylogenetically close animals such as primates might be more directly extensible to the understanding of human locomotion and associated clinical applications.

II. WHOLE-BODY ANATOMICAL MODEL OF JAPANESE MONKEY

For a realistic representation of body motion, a fresh cadaver of an adult male Japanese monkey underwent whole-body computed tomography, and three-dimensional (3D) morphological data of musculoskeletal system were obtained. Based on this information, the whole-body skeleton was modeled as a chain of 20 bone segments connected by joints (Fig. 1). Each joint was approximated as a combination of hinge joints, joint centers and rotational axes estimated by joint morphology based on joint surface approximation using a quadric function. As a result of morphologically accurate description of the joint kinematics based on quadric function approximation, rotational axes of the joints did not coincide with bone coordinate axes, unlike robots.

To calculate inertial properties necessary for biomechanical studies (i.e., mass, position of the center of mass of the segment, and inertial tensor about the center of mass), the body surface was divided into 20 segments. To mathematically describe the path of each muscle and the associated capacity to generate force, a fresh cadaver of a Japanese monkey was dissected. Each muscle in the fore- and hindlimbs was carefully exposed and points of origin and insertion were observed. The muscle was then removed and mass and fascicle length were systematically recorded to calculate physiological cross-sectional area (PCSA). The path of each muscle was defined using a series of points connected by line segments. Capacity of each muscle to generate force was assumed to be proportional to PCSA.

III. GAIT ANALYSIS USING THE MUSCULOSKELETAL MODEL

Locomotion is an elaborate physical phenomenon generated by dynamic interactions between a complex chain of musculoskeletal elements and the changing outside world. To understand the mechanism underlying the generation of adaptive locomotion, actual locomotion must be thoroughly investigated. For this reason, quadrupedal and bipedal locomotion of Japanese monkeys were videotaped from 4 directions and analyzed. Markers placed at joints were digitized and the coordinates of markers were calculated. If the musculoskeletal model described could be matched to the temporal history of digitized marker coordinates, all body skeletal motion could be reconstructed as in video fluoroscopy. For this, the musculoskeletal model was firstly scaled to the size of the monkey in the video based on segment lengths, and the 47 joint angles of the skeletal system were adjusted frame-by-frame to minimize the sum of distances between corresponding markers while minimizing deviations of joint angles from the anatomically natural position (midpoints of the ranges of joint rotations). The whole-body kinematics of a Japanese monkey walking on a treadmill was successfully reconstructed using an anatomically based musculoskeletal model and the model-based matching technique. From this reconstructed skeletal motion, changes in state variables of muscles such as muscle length and contractile velocity during locomotion were also estimated to help clarifying how morphology and structure of the musculoskeletal system restrict or facilitate generation of adaptive locomotion.

IV. FORWARD DYNAMIC SIMULATION OF LOCOMOTION

Animal locomotion is generally accepted as being generated by a rhythm-generating neuronal network in the spinal cord known as the central pattern generator (CPG). In this study, the CPG was hypothesized to represent a set of oscillators corresponding to each of the limbs and the trunk segment, and oscillator phase was considered to encode global parameters of the limb movement, i.e., orientation and length of the axis connecting the most proximal joint and the distal position of a limb (limb axis), with the spinal circuitry of interneurons somehow generating muscle activation patterns based on output signals from the CPG. For now, we modeled this transformation using a PD feedback control law, and joint torque was applied instead of muscle force to generate locomotion. Orientation and length profiles of limbs were provided based on measured kinematic data. The CPG phase was reset in response to the timing of hand or foot-ground contacts. To realize coordinated interlimb movements, appropriate dynamic interactions among the oscillators were assumed.

Although many problems remain, the results show that locomotion was successfully generated due to dynamic interactions among the body mechanical system, the nervous system consisting of the oscillators, and the environment. The importance of computer simulation studies based on biologically relevant neuro-musculoskeletal modeling has gained particular emphasis in recent years for truly elucidating adaptive mechanisms of locomotion in animals. Based on our current model, we aim to further improve our simulation study, particularly that of the locomotor neuro-control system with the collaboration of neurophysiologists to achieve biologically plausible simulations. We hope to elucidate the dynamic principles underlying the emergence of adaptive locomotion by analyzing the behavior of neuro-musculoskeletal dynamics recreated in a computer from a system engineering perspective.

ACKNOWLEDGMENT

We would like to express our gratitude to all the staff of the Suo Monkey Performance Association for their generous collaborations in experiments. This study is supported by Grant-in-Aid for Scientific Research on Priority Areas "Emergence of Adaptive Motor Function through Interaction between Body, Brain and Environment" from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

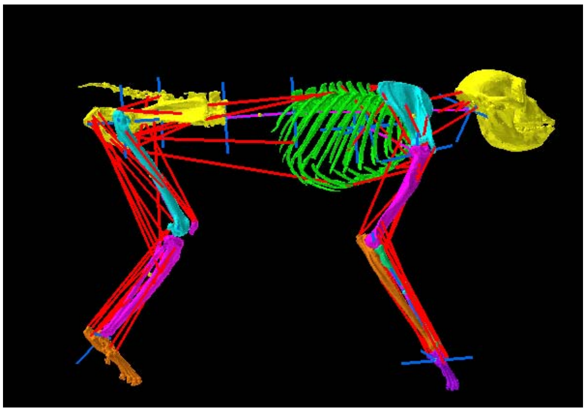


Figure 1. Whole-body anatomical model of Japanese monkey

Insect-Machine Hybrid System
for Understanding an Adaptive Control in Biological Systems

Ryohei Kanzaki

Research Center for Advanced Science and Technology
The University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, JAPAN
TEL: +81-3-5452-5195　FAX: +81-3-3469-2397
kanzaki@rcast.u-tokyo.ac.jp

Adaptability, the capability to behave properly in accordance with ceaselessly changing environments, has been required in robotics. Adaptability is an excellent feature of animals. Insects are the most diverse and abundant animal group representing >70% of all known animal species. They display a diversity of sophisticated behaviors adapted to their environments by the processing of a simple nervous system, a so-called microbrain system. Insects will become an excellent model for understanding adaptive control in biological systems, which will inspire control and communication in engineered systems.

Adaptive behavior appears in the interaction between a body, brain and the environment. Therefore, an experimental system for evaluating and understanding adaptive behavior requires a closed-loop system in which environmental information is fed back to an insect. This system must be capable of optionally manipulating the external environment or the properties of the insect, allowing the adaptive behavior to be manipulated. We have developed an insect-machine hybrid system that acts based on the behavioral or the brain/neural output of an insect, as a novel experimental system that manipulates the interaction between an insect and the real environment in order to evaluate and understand environmental adaptation.

We have used a male silkmoth as a robot controller because the moth exhibits a well-defined pheromone searching behavior, the neural basis of which has been well characterized by our group. The robot measures the behavior of an insect tethered on the robot and moves based on the insect's behavior or the neural activity of the insect brain. Therefore, it is possible to cause changes in the same way as manipulation of the sensory-motor system of the insect by giving arbitrary manipulation to the motion system of the robot.

First in this lecture, as an example of adaptive behavior of an insect, odor-source orientation behavior and its neural basis will be shown. Second, tests of the feasibility of the behavioral strategy based on the neural system, by implementation in robots, will be shown. Finally, I will demonstrate the insect-machine hybrid system that will lead to great insight for evaluating and understanding adaptive behaviors (or mobiligence), which will inspire control and communication in engineered systems.

Robotics as a Tool for Gait AND Posture Study

Hiroshi Kimura
Kyoto Institute of Technology, Matsugasaki-Goshokaidotyo, Sakyoku, Kyoto 606-8585, Japan
kimura@mech.kit.ac.jp

I. INTRODUCTION

The gait (rhythmic motion) and the posture in animals or human have been studied independently for decades as far as the author knows, since it is difficult to measure the activities of posture control exactly while walking. In order to understand the relations between rhythmic motion control and posture control, it is useful to construct the control model of animals or human walking, simulate it using a musculo-skeletal model and compare the simulation results with the results of animals or human experiments. But since it is difficult to simulate friction, collision with ground, effects of elastic materials and so on, we would like to employ experiments using a real machine (robot) in addition to computer simulations. In this article, we discuss the relations between rhythmic motion control and posture control while introducing our studies on quadruped and biped robots. Of course, in order to confirm those hypotheses obtained in robot experiments, we have to arrange animals or human experiments of walking in future.

II. ROLLING MOTION FEEDBACK TO CPGS IN QUADRUPED

In our studies of Tekken series[1], [2], an oscillator-typed CPG (Central Pattern Generator) generated the rhythm of a single leg, and rolling motion of the body was one of feedback signals to CPGs. As a result of this feedback, the timing of landing and lifting in each leg was adjusted and posture of the robot in the lateral plane was well controlled, since the stiffness of joints was high in stance legs and low in swing legs. This could be the first result indicating that posture can be controlled by the adjustment of gait (rhythmic motion generated by CPGs). But since leg loading (ground reaction force) information was not fed-back to CPGs and posture control in low speed walking was not sufficient, Tekken could not walk slowly with long cyclic period.

III. INTEGRATION OF RHYTHMIC MOTION AND POSTURE CONTROL IN QUADRUPED

This study aims at the design and implementation of a general controller for quadruped locomotion, allowing the robot to use the whole range of quadrupedal gaits (i.e. from low speed walking to fast running). A general legged locomotion controller must integrate both posture control and rhythmic motion control and have the ability to shift continuously from one control method to the other according to locomotion speed. We are developing such general quadrupedal locomotion controller by using a neural model involving a CPG utilizing ground reaction force sensory feedback for both gait generation and posture control. Especially, while using non-oscillator-typed CPGs and generating the self-excited physical oscillation as a result of local feedback, we could be able to integrate sensor-dependent posture control and sensor-driven rhythmic motion control. We used a biologically faithful musculoskeletal model[3] with a spine and hind legs, and computationally simulated stable stepping motion at various speeds combining the neural controller and the musculoskeletal model[4], [5].

IV. STEPPING REFLEX FOR POSTURE CONTROL IN BIPED

There are huge numbers of studies that measured kinematics, dynamics and the oxygen uptake and so on in human walking on the treadmill. Especially in the splitbelt[1] treadmill walking, a remarkable difference is seen between normal and cerebellar disease subjects in kinematics[6], [7]. A 2D biped robot called ‘Tetsuro’ was developed to construct the control model of human splitbelt treadmill walking and investigate how it works

A. Stepping Reflex for Speed and Posture Control

A stepping reflex is the touchdown angle control of a swing leg according to the angular velocity of the stance leg for stabilization of forward speed and posture[8]. Since this touchdown angle becomes the initial angle of the stance leg in the next step, the robot can adjust the motion of the stance leg moving mostly as an inverted pendulum while utilizing gravity. Therefore, the stepping reflex is less energy consumptive than torque adjustment at the ankle joint of the stance leg, which is used for posture control based on ZMP. Consequently, the stepping reflex enables a robot to keep forward speed and posture efficiently against disturbance such as pushing on its back.

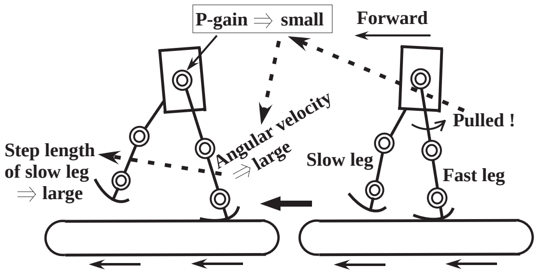
The efficient and robust 2D walking on the fixed treadmill was achieved by PD control, the cyclic motion trajectory based on the inverted pendulum, and by the forward speed and posture control depending on the stepping reflex[9].

B. Splitbelt Treadmill Walking

The course of the experiment was divided into three stages. Those are the pre-adaptation stage, the adaptation stage and the post-adaptation stage. Only in the adaptation stage, the treadmill was in the splitbelt configuration. In every step of walking, the hip joint angle of a leg at lift off: ψ_{off} was measured, and the P-gain of the hip joint of the leg in the next stance phase was updated in the adaptation and post-adaptation stages while comparing ψ_{off} to its average in the pre-adaptation stage. This P-gain adjustment was employed

---

[1] In fixed and splitbelt configurations, the speed of left and right belts is same and different, respectively.



(b) next stance phase of the fast leg

(a) stance phase of the fast leg

Fig. 1. P-gain adjustment for splitbelt treadmill walking. (a): when the speed of one belt becomes high in the adaptation period, the fast leg is pulled more backward by the belt in the stance phase and $|\psi_{off}|$ becomes larger. (b): in the next stance phase of the fast leg, as a result of the P-gain adjustment, the stiffness of the hip joint at the fast leg becomes lower, and the fast leg is pulled much more backward. In addition, since the ankle joint angular velocity of the fast leg in the stance phase becomes larger, the touchdown angle of the swing leg becomes larger by the stepping reflex. As a result, the position of the body in the world coordinate is mostly kept constant, and the robot can keep walking on the splitbelt treadmill.

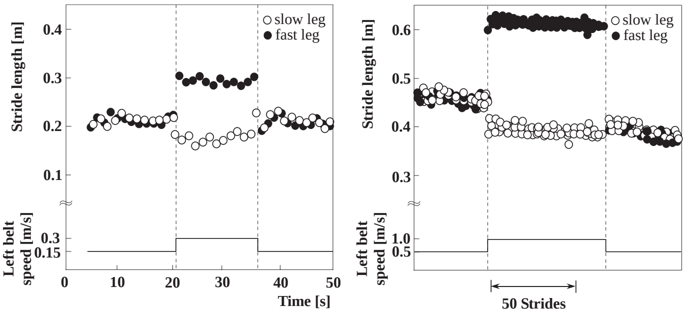
on each leg independently. The reason why such P-gain adjustment enables a robot walk on the splitbelt treadmill is shown in Fig.1.

The stride length is defined as the distance traveled by the ankle joint from the time of landing to the time of lift of another leg. The stride length measured in a robot experiment and in human (normal subject) experiments are shown in Fig.2. Each circle in those figures means the value of this index measured at the walking cycle. In Fig.2, data of a robot experiment and data of human experiments show similar patterns. We could see the same result in the duty ratio[9].

The step length is defined as the distance between positions of the ankle joints of swing and stance legs at the time of landing of the swing leg. The step length difference measured in a robot experiment and in human (normal subject) experiments are shown in Fig.3. In Fig.3, data of a robot experiment and data of human experiments show similar patterns. Here are two interesting subjects. One is that the step length difference gradually became zero in the adaptation stage in spite of the difference in speed of two belts. Another is that the step length difference quickly changed at the switch to the post-adaptation stage even though the speed of two belts became same. This is one of well known phenomena called “negative aftereffect.” We could see the same result in the difference of the ratio of the double legs stance period[9].

While seeing such results of human experiments, Reisman et al.[6] and Morton et al.[7] mentioned that there are two different types of adaptations behind human splitbelt treadmill walking, and called the first one in Fig.2 “reactive adaptations” and the second one in Fig.3 “predictive adaptations.” In contrast to such conclusions of studies on human splitbelt walking, we showed that the single reactive adaptation mechanism is enough to generate two types of indexes. We also showed that P-gain at hip joint of the stance leg is the control parameter of gait adaptations in splitbelt walking.

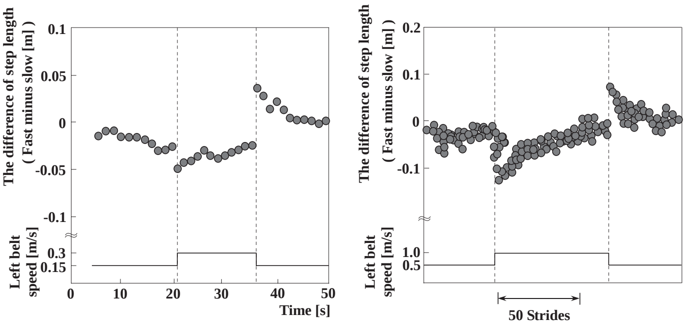
It should be noted that the stepping reflex for posture control plays an important role in the gait adaptations in splitbelt treadmill walking.



(a) a biped robot: Tetsuro

(b) human (normal subject)

Fig. 2. Results of (a) robot experiment and (b) human experiments (modified from Morton et al. 2006[7]). The stride length in splitbelt treadmill walking are shown. In the adaptation stage of robot and human experiments, speed of belts was 0.15 m/s and 0.5 m/s at the right belt and 0.30 m/s and 1.0 m/s at the left belt, respectively.



(a) a biped robot: Tetsuro

(b) human (normal subject)

Fig. 3. Results of (a) robot experiment and (b) human experiments (modified from Morton et al. 2006[7]). The step length difference (fast minus slow) in splitbelt treadmill walking are shown.

ACKNOWLEDGEMENTS

This work has been partially supported by a Grant-in-Aid for Scientific Research on Priority Areas ”Emergence of Adaptive Motor Function through Interaction among Body, Brain and Environment” from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

References

[1] Fukuoka, Y., Kimura, H. and Cohen, A.H. Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts. *Int. J. of Robotics Research* 22(3):187-202 (2003).
[2] Kimura, H., Fukuoka, Y. and Cohen, A.H. Adaptive dynamic walking of a quadruped robot on natural ground based on biological concepts. *Int. J. of Robotics Research* 26(5):475-490 (2007).
[3] Ekeberg, O. and Pearson, K. Computer simulation of stepping in the hind legs of the cat: an examination of mechanisms regulating the stance-to-swing transition. *J. of Neurophysiology* 94(6):4256-68 (2005).
[4] Maufroy, C., Kimura, H. and Takase, K. Towards a general neural controller for quadrupedal locomotion. *NEURAL NETWORKS* in press (2008).
[5] Maufroy, C., Kimura, H. and Takase, K. Towards a general neural controller for 3D quadrupedal locomotion. *Proc. of AMAM2008* (2008).
[6] Reisman, D.S., Block, H.J. and Bastian, A.J. Interlimb Coordination During Locomotion: What Can be Adapted and Stored?, *J. of Neurophysiology* 94:2403-2415 (2005).
[7] Morton, S.M. and Bastian, A.J. Cerebellar Contributions to Locomotor Adaptations during Splitbelt Treadmill Walking, *J. of Neuroscience* 26:9107-9116 (2006).
[8] H. Miura and I. Shimoyama, Dynamical walk of biped locomotion, *Int. J. of Robotics Research* 3:60-74 (1984).
[9] Otoda, Y., Kimura, H. and Takase, K. Gait adaptations of a 2D biped robot in splitbelt treadmill walking. *Advanced Robotics* submitted, (2008).

Acquiring information under mechanical constraints

Malcolm A. MacIver, Department of Mechanical Engineering, Department of Biomedical Engineering, and Department of Neurobiology and Physiology, Northwestern University, Evanston, IL

For animals that move in water or in the air, the configuration of the body has a significant impact on drag, and can have a significant impact on the information that is acquired through its sensory receptors. We explore how one animal, the weakly electric fish, handles the conflict between body configurations that increase sensory performance yet decrease mechanical performance. Using a Bayesian approach to integration of reconstructed electroreceptor stimulus levels over measured trajectories, we also show evidence that a fish-like pattern of sensor density variations on an idealized fish body results in a more rapid decrease in uncertainty about prey location than a number of other possible sensor layouts. Finally, we show that measured prey capture trajectories are similar to mechanically optimal prey capture trajectories of a simplified fish body in an ideal fluid. These results elucidate interconnections between mechanical constraints and the acquisition of information in animal behavior.

Memory-dependent modification of stepping for obstacle avoidance

Keir Pearson, Department of Physiology, University of Alberta, Canada

Walking animals rely on vision to step over or around obstacles in their path. However, visual input is not used directly to guide leg movements during walking. Instead, walking animals look three or four steps ahead of their current position and store this visual input in short-term memory for use at the appropriate time. In quadrupeds, a unique form of visual memory is used to guide the hind legs over obstacles that have already been stepped over by the forelegs. This visual memory is very long-lasting (tens of minutes) and incorporates precise information about the size and position of the obstacle relative to the hind legs. I will present data from electrophysiological and lesion studies that demonstrate that neuronal systems in the posterior parietal cortex (area 5) are necessary for establishing this memory. These results suggest that two memory systems, one lasting on the order of 1 second and one lasting much longer, are used by walking cats to guide their hind legs over obstacles while walking. I will also describe experiments demonstrating that the stepping in the hind legs can be modified for long periods of time (days) to avoid an obstacle that repeatedly contacts a hind paw during the swing phase. The modified swing movements only occur in the environmental context in which the animal received the stimuli.

Aquatic Locomotion of Miniature Mobile Robots Down to Micron Scale

Metin Sitti
NanoRobotics Laboratory, Carnegie Mellon University, http://nanolab.me.cmu.edu

Miniature robots have the unique capability of accessing to small spaces and scales directly. Due to their small size and small scale physics and dynamics, they could be agile and lightweight, and could be inexpensive and in large numbers if they are mass produced. These miniature robots could revolutionize health-care, mobile sensor networks, environmental monitoring, space, search and rescue, security, entertainment, and education applications in the near future. Different size aquatic miniature robots with various locomotion capabilities and target applications are presented in this presentation.

At the mesoscale (lizard or insect scale), two legged miniature robots walking and running on water surface inspired by water strider insects and basilisk lizards, respectively are presented to show unique amphibious robotic locomotion capabilities. Water striders can stay on water surface using surface tension based lift forces due to their very hydrophobic hairy supporting legs and can move on water up to 1.5 m/s speeds by rowing two side legs. Modeling, optimal design, and manufacturing issues of various water strider robots are presented. On the other hand, basilisk lizard uses very fast rotation of its two legs with a specific elliptic trajectory at 5-10 Hz frequencies. By slapping and stroking their feet into the water, the lizard affects a momentum transfer which provides both forward thrust and lift. The design of a basilisk lizard robot utilizing similar principles is discussed, modeled, and prototyped. Computational and experimental results are presented and reviewed with the focus being a maximization of the lift to power ratio. After optimization, two legged models can experimentally provide 12-15 g/W of lift while four legged models can provide 50 g/W of lift. Four legged robots are demonstrated to run on water with a speed of around 1 m/s.

Going down to tens or hundreds of micron scale swimming robotic bodies, significant bottlenecks are on-board micron scale actuation principles and power sources. As an alternative approach, a hybrid (biotic/abiotic) actuation principle is used to propel micron scale robotic bodies in liquid by harvesting the flagellar propulsion of attached bacteria and the chemical energy in the environment. On/off propulsion control of such stochastic hybrid micro-robots is demonstrated using chemical stimulus. Heavy metal ions hinder their propulsion while EDTA resumes their motion. To improve the speed performance of the bacteria attached beads, beads are patterned, and half coated beads show speeds in average around 33 μm/sec. Moreover, to improve the stochastic motion directionality, microcylinders are patterned and bacteria are attached to only bottom side of the cylinders.

Bio:

Metin Sitti received the BSc and MSc degrees in electrical and electronics engineering from Bogazici University, Istanbul, Turkey, in 1992 and 1994, respectively, and the PhD degree in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1999. He was a research scientist in the Department of Electrical Engineering and Computer Sciences, University of California at Berkeley during 1999-2002. He is currently an associate professor in the Department of Mechanical Engineering with joint appointments in the Robotics Institute, Electrical and Computer Engineering, and Biomedical Engineering at Carnegie Mellon. He is the director of the NanoRobotics Laboratory. His research interests include miniature mobile robots, biologically inspired micro/nanosystems, and micro/nanoscale manipulation and manufacturing systems.

He has been appointed as the Adamson Career Faculty Fellow in 2007. He received the National Science Foundation CAREER award and the CMU Struminger award in 2005. He was invited as a speaker to the National Academy of Sciences, Keck Foundation Life Engineering Symposium in 2005. He was elected as the Distinguished Lecturer of the IEEE Robotics and Automation Soceity for 2006-2008. He received the second prize in the World RoboCup Nanogram Demonstration League (2007), the best biomimetics paper award in the IEEE Robotics and Biomimetics Conference (2004), the best paper award in the IEEE/RSJ International Conference on Intelligent Robots and Systems (1998), and the best video award (2002) in the IEEE Robotics and Automation Conference. He is the Vice President of the Technical Activities in the IEEE Nanotechnology Council for 2008-2010, and he is the co-editor-in-chief of Journal of Micro/Nano-Mechatronics and an associate editor for the IEEE Trans. on Robotics.

Antennal mechanosensory control of insect flight

Sanjay P. Sane
National Center for Biological Sciences, GKVK Campus
Bellary Road, Bangalore 560 065, INDIA

In addition to olfaction, insect antennae play a key mechanosensory role in flight control. Specifically, there exist two sets of mechanosensors in the base of the antennae in Lepidoptera and certain other insect orders. One set, the Bohm's bristles, are superficial sensory bristle fields on the scape and pedicel positioned roughly orthogonal to each other. A second set, the Johnston's organs, are composed of a ring of scolopidia placed circumferentially within the pedicel-flagellum joint. The soma of each individual scolopidium resides in the pedicel and throws a process which connects the base of the flagellum to the pedicel. Thus, it encodes the motion of the flagellum with respect to the pedicel. Together, these mechanosensors provide crucial information of the insect's flight status to the brain of the insect.

Our recent investigations on the antennal control of flight in the hawk moth, *Manduca sexta*, show that the antennal mechanosensors are involved in flight control. When flying about, the hawk moths hold their antennae at a constant inter-antennal angle. This angle remains unchanged regardless of the speed with which the moth flies relative to the surrounding air. Thus, the insect actively resists bending of its antenna due to forces from aerodynamic drag. Sensory fills of the Bohm's bristles reveal that they arborize in the same area as the motor neurons, within an area of the brain called the Antennal Mechanosensory and Motor Center (AMMC). Thus, any change from the inter-antennal angle may cause the sensory bristles to activate the antennal muscles to correct this deviation. This simple negative feedback hypothesis can explain how Bohm's bristles mediate the antennal positioning response in various insects, including moths and butterflies. About a constant inter-antennal angle, the antenna undergoes rapid, small amplitude vibrations at approximately wing beat frequency. Although we do not presently know if these vibrations are active or passive, many winged insects are known to actively generate high frequency antennal vibrations. As a natural consequence of these vibrations, the antenna experiences Coriolis strain patterns when the insect turns in air during flight. The Coriolis components generate a signature signal at twice vibration frequency. Intracellular recordings from the scolopidial neurons stimulated by the antennal vibrations reveal tuning curves that peak at approximately twice vibration frequency. Thus, the Coriolis strains are transduced by the scolopidial neurons in the Johnston's organs to the AMMC to which these neurons project. If the antennal mechanosensory information is used by the insect to obtain information about flight status during aerial turns, then the insect should be unable to perform complex maneuvers when the mechanical load on these sensors is relieved by removal of the flagellum. To test this prediction, we performed behavioral experiments to test if proper mechanical loading of the antennae is necessary for flight control. When the flagellum is removed, the moths were able to take-off but they were unable to perform aerial turns leading to frequent crashes and collisions with the walls. When the flagella were reattached, the insects recovered their ability to control flight. Thus, proper mechanical loading of the antenna is essential for flight control. Based on these experiments, we propose that the antenna provides crucial sensory input required for insects to determine their own motion during flight. We propose that, like the halteres in Diptera, the antennae may detect Coriolis strain patterns arising from aerial turns during flight.

NEURAL CONTROL OF INSECT WALKING - FROM JOINT CONTROL TO ADAPTIVE LOCOMOTOR BEHAVIOR

Ansgar Büschges

Department of Animal Physiology, Zoological Institute, University of Cologne, 50923 Cologne, Germany

Animal locomotion often appears to us so ordinary and automatic that we are tempted to take the generation for granted. However, the operational basis for generating locomotor behavior is actually highly complex. Each leg movement results from a contribution of descending signals from the brain, central pattern generating networks (CPG), local feedback from sensory neurons about movements and forces generated in the legs, coordinating signals from neighboring limbs, and finally, the neuromuscular transform at the output stage of the walking system, the leg muscles.

In recent years, we have made significant advances in understanding the neural basis of walking pattern generation. My talk will present the most recent results from the stick insect walking system, which can be briefly summarized as follows: **(i)** descending signals from brain ganglia activate segmental CPGs that generate alternating activity in antagonistic leg motoneurons. These descending signals tonically depolarize all segmental leg motoneurons which increases their excitability (5,16,18). This state-dependent depolarization is mediated by muscarinic receptors and its reversal potential of -38mV suggests that it is based on a mixed cationic conductance (16,18). Activation of the segmental CPGs drives individual leg joints by providing alternating inhibition to leg motoneuron pools (9), differs between segments and depends on each others activity (6). A stepping front leg, for example, is capable of activating ipsilateral mesothoracic joint CPGs only in a forward walking animal (5). In general, the gating of phasic coordinating intersegmental influences depends on active local CPGs in the receiving segment. **(ii)** A functional stepping pattern for each leg depends on sensory feedback from movement and load/strain sensors coupling the activity of the individual joint CPGs through highly specific and non-symmetrical influences (1-4,7). The emerging picture for the sensory control of walking pattern generation has allowed us to propose a general neural controller for stepping pattern generation (8,10,17). **(iii)** We have started to investigate neural mechanisms contributing to alterations in walking speed and walking direction (4,11,12). Interestingly, single legs of a stick insect can generate proper forward, backward or turning movements without the presence of any neighboring legs (12). The change from forward to backward walking is accompanied by a reversal of the sign of influence from load feedback on the thoraco-coxal joint CPGs in the legs (4). **(iv)** Recently we have extended our work to study how the muscles transform motoneuron activity into force and movement production, and the consequences of the small size of stick insect legs on movement generation (16-18).

I will place the current knowledge and new findings from the stick insect into the broader context of locomotor behaviors in other organisms.

References:

1. Akay & Büschges, 2006, *J. Neurophysiol*. 96: 3532-3537
2. Akay et al. 2001, *J. Neurophysiol*. 85: 594-604
3. Akay et al. 2004, *J. Neurophysiol*. 92: 42-51
4. Akay et al. 2007, *J. Neuroscience* 27 (12): 3285-3294
5. Borgmann et al. 2007a, *J. Neurophysiol*. 98: 1685-1696
6. Borgmann et al. 2007b, *100.Jahrestagung DZG*, Köln, Abstr.
7. Bucher et al. 2003, *J. Neurophysiol*. 89: 1245-1255
8. Büschges, 2005, *J. Neurophysiol*. 93: 1127-1135
9. Büschges et al. 2004, *Europ. J. Neurosci*. 12: 1856-1862
10. Ekeberg et al. 2005, *Arthropod, Structure and Development* 33: 287-300
11. Gabriel & Büschges, 2007, *Phil. Trans. Roy. Soc.* B 365: 251-271
12. Gruhn et al. 2006, *J. Neurosci. Methods* 158: 195-206
13. Guschlbauer et al. 2007, *J. Exp. Biol.* 210: 1092-1108
14. Hooper et al. 2007, *J. Neurophysiol. 97*: 1428–1444
15. Hooper et al. 2007,. *J. Neurophysiol*. 98: 1718-1732
16. Ludwar et al. 2005, *J. Neurophysiol*. . 93: 1255-1265
17. Pearson et al. 2006, *TINS* 29: 625-630
18. Westmark & Schmidt, 2007, *100.Jahrestagung DZG*, Köln, Abstr.

Embodied neuronal networks for the control of a hexapod walker

Josef Schmitz & Holk Cruse
Dept. Biological Cybernetics, Bielefeld University, P.O.Box 100131,
D-33501 Bielefeld, Germany
[josef.schmitz, holk.cruse]@uni-bielefeld.de

In animals, control of walking in rugged terrain requires to incorporate different issues, as are the mechanical properties of legs and muscles, the neuronal control structures for the single leg joints, the mechanics and neuronal control structures for the coordination between legs, as well as central decisions that are based on external information and on internal states. This applies correspondingly to all similar technical applications as e.g. walking machines. Walking in predictable environments and fast running, to a large degree could rely on central pattern generators (CPG) or even solely on muscle mechanics. In contrast, slow walking in unpredictable terrain, e.g. climbing in rugged structures, has to rely on systems that monitor and intelligently react to specific properties of the environment as well as to the consequences of the interactions of the walker with its physical environment.

An arthropod model system that shows the latter abilities is the stick insect on which this seminar will be focused. An insect, when moving its six legs, has to control at least 18 joints, three per leg, and therefore has to control at least 18 degrees of freedom (DoF). As the body position in space is determined by 6 DoFs only, there are 12 DoFs open to be selected. Thus, a fundamental problem is as to how these extra DoFs are controlled. Based mainly on behavioral experiments and simulation studies, but also including neurophysiological results, the following control structures have been revealed.

Legs act as basically independent systems. The quasi-rhythmic movement of the individual leg can be described to result from a structure that exploits mechanical coupling of the legs via ground and body. The timing of step phase transitions is neither determined by the action of CPGs within the leg nor by CPGs of the leg joints. Rather, reflex chains triggered by specific sensory feedback at the appropriate phases will generate sensible switching between the step phases. Furthermore, neuronally mediated influences act locally between neighboring legs, leading to the emergence of insect-type gaits. The underlying controller can be described as a free gait controller. Cooperation of the legs being in stance mode is assumed to be based on mechanical coupling plus local positive velocity feedback controllers. These controllers, acting on individual leg joints, transform passive displacement of a joint into active movement, generating synergistic assistance reflexes in all mechanically coupled joints. A coherent action of the leg joints of each leg being in swing is assured by neuronally mediated interjoint reflexes.

This architecture of the controller is summarized in the form of the artificial neural network, WalkNet. It consists of several modules of small networks. Although the demands on the single networks are high, each of the network modules could be kept very simple because they all are embodied, i.e. situated in the physical environment of the animal. Utilisation of the external loop via the periphery (the sensory-motor system and its interaction with the physics of the habitat) allows for such simplification. For example, in the case of the SwingNet, this means that no explicit trajectory is precalculated but that a momentary change of the ongoing swing movement is generated only on the basis of the actual sensor data. This design also allows the emergence of new properties such as flexible reactions to disturbances or to failures in reaching ground. At the system level, this design gives rise to emergent behaviours. In addition to producing stable and robust gaits without a master timer, the system can stand up again by itself and resume proper walking after stumbling. Exteroceptive feedback is exploited for global decisions as are e.g. direction, curvature, and velocity of the walk. In the seminar talk we will demonstrate the usability of this controller architecture by means of dynamic simulations and hardware implementations.

Exploring the mechanisms of gait transition from swimming to walking in salamander using robots and mathematical models of CPGs

Auke Ijspeert

Animal locomotion control is in a large part based on central pattern generators (CPGs), which are neural networks capable of producing complex rhythmic patterns while being activated and modulated by relatively simple control signals. These networks are located in the spinal cord for vertebrate animals. In this talk, I will present a modeling study carried out together with Jean-Marie Cabelguen (U. of Bordeaux, France) in which we model CPGs of lower vertebrates (lamprey and salamander) using systems of coupled oscillators, and test the CPG models on board of amphibious robots, in particular a new salamander-like robot capable of swimming and walking. The goal of the project is to explore three important questions related to vertebrate locomotion: (i) the modifications undergone by the spinal locomotor circuits during the evolutionary transition from aquatic to terrestrial locomotion, (ii) the mechanisms necessary for coordination of limb and axial movements, and (iii) the mechanisms that underlie gait transitions. I will also address the possible role of sensory feedback in shaping the locomotor patterns depending on the physical interactions of the body with different media (friction with ground during walking and interaction with water during swimming).

BigDog, a Quadruped Robot for Rough-Terrain

Marc Raibert and the BigDog Team

Boston Dynamics, Waltham, MA 02451, USA

Abstract: BigDog is a dynamic robot designed to travel on rough-terrain. It uses legs for locomotion, rather than wheels or tracks, in the hopes of approaching the remarkable mobility demonstrated by legged people and animals. BigDog is powered by an internal combustion engine that drives its hydraulic actuation system. An onboard computer controls locomotion and balance, runs the sensor systems, and manages communications with the human operator. Sensors include leg position and force, inertial, a scanning LIDAR and a variety of system sensors reporting temperatures, pressures, flows and the like. So far BigDog has traveled by walking, trotting and bounding, gone over 4 mph, did a continuous endurance run of 6.2 miles, climbed a 35 degree slope, hiked a wooded trail, carried 340 lbs on the flat and jumped a distance of 3 ft. Our long-term goal is to develop a new breed of robot that captures the mobility, autonomy and speed of living creatures.

Neuromechanical redundancy and hierarchy in posture and movement

Lena H. Ting, Ph.D.
Department of Biomedical Engineering, Emory University and Georgia Institute of Technology

Standing balance control is a complex sensorimotor task that is fundamental to the performance of other motor behaviors. Neuromechancial principles for control of posture and balance are little understood, as they involve integration of multiple channels of sensory input and motor output. Descending control of postural response appears to be rather low-dimensional, as muscle activity and biomechanical outputs can be described using just a few parameters related to task-level variables. These data might suggest that the control of balance is simple, as they are aptly described by simple, conceptual, “template” models. However, there are no complex, anatomical, or “anchor” models that can actually stand up using physiological elements—including our own. Moreover, experimentally we observe a wide degree of variability in postural responses across trials and individuals, suggesting that the biological systems are quite robust to variations, whereas our musculoskeletal models are not. What are they missing?

We hypothesize that postural stability requires precise coordination among hierarchal, redundant neuromechanical elements, and that the contributions of each are flexibly adjusted by the nervous system as appropriate to a particular situation. That is, the “simple” task-level commands are only functional if appropriately subserved by neurally-modifiable spinal and peripheral mechanisms for quiet standing. Therefore, we predict that the nervous system modulates interactions between hierarchically organized neuromechanical elements that contribute to ***feedback*** neural processes required for reacting to postural perturbations and ***feedforward*** neural processes that adjust the intrinsic mechanical stability of the musculoskeletal system. We have evidence in both normal and impaired balance control, of shifts along this continuum between neural and mechanical computations for mitigating disturbances to balance. Our neuromechanical modeling efforts also demonstrate that task-level feedback, postural tone, and postural configuration cannot be independently modulated to produce stable posture. These ideas extend to all motor tasks. I propose that motor control principles adequate for allowing us to reproduce real functions will only be revealed if all levels of the neuromechanical hierarchy, and their interactions, are understood.

Insect brains and robot control

Barbara Webb

Although insects are often considered to be relatively simple animals, they exhibit many forms of adaptive movement that require the integration of information from multiple sensory modalities, learning, and simultaneous control of several interacting behaviours, enacted by a complex body morphology. We have been investigating how such competence might be achieved through a mixture of behavioural studies on insects, neural simulations, and embodied robotic models. For example, careful analysis of visually mediated turning responses in stick insects has led to a dynamic simulation of six-legged walking that produces naturalistic turns by differentiating the roles of fore-, mid- and hind-legs while maintaining coordination through distributed reflexes. We are now interested to determine how these results relate to sound orientation in crickets, to better ascertain the nature of the descending signals required to control these movements. This would impose constraints not hitherto considered in our existing robot models, which have only tried to match the high-level characteristics of the cricket's approach path. Of additional interest is how or where directional responses modulated by different modalities are co-ordinated in the insect brain. This may involve the use of internal predictive models, which could be adaptively acquired through associative learning of sensory feedback. We have implemented such learning in a robot control architecture based on the mushroom body neuropils in the insect brain.

Neuromechanics using soft materials: animal models and supple robots

Barry A. Trimmer,

Tufts University, Medford, MA 02155; Department of Biology and Biomimetic Devices Laboratory

***Abstract* – There is no general theory to guide the control of movements by structures made of soft materials. One approach is to understand the neuromechanics of locomotion by soft bodied animals and to apply these findings in engineered devices. The caterpillar is a useful model system in which the kinematics, dynamics and neural encoding can be combined with material characterization and modelling to design and build these new types of robots without stiff skeletons or joints.**

I. INTRODUCTION

A major characteristic that distinguishes man-made structures from biological ones is the preponderance of stiff materials. Most of our creations are constructed from metals, stiff plastics, stone, concrete and glass. These materials, together with naturally-occurring stiff structures such as wood, clearly have an important role in making strong and durable structures or machines. In contrast, living animals may contain stiff materials such as bone and cuticle but their fundamental building blocks are soft and elastic. Although soft materials can confer considerable advantages to the stability and versatility of moving machines relatively little is known about how to incorporate them into control systems without additional computational costs and decreased performance.

There is now growing interest in the use and control of soft materials to increase the versatility of engineered devices. A key finding from studies of animal locomotion is that material-properties are themselves part of any natural motor system and that complex materials can be exploited to produce new robotic capabilities. For example, through the use of soft materials it will be possible to build robots that are continuously deformable and capable of collapsing and crumpling into small volumes. These robots will have numerous applications including biomedical instrumentation, search and rescue in emergency situations and hazardous environments, space instrument repair and as mine detectors.

The development of these soft machines requires new actuators, sensors and electronic circuitry that can be built from, or interfaced with, soft materials. This presents significant challenges in materials fabrication and there is relatively little theoretical basis to help engineer such materials into practical applications. The work described here will use the "biology as default" approach in which questions about design and production of new technologies will be guided by the mechanisms found in biological systems [1]. A key detail is that, by concentrating on soft materials in the design of devices, there will be a closer relationship between encountered engineering problems and their biological solutions.

II. MANDUCA LOCOMOTION AS A MODEL SYSTEM

A three-dimensional kinematic study of straight line crawling shows that caterpillars (*Manduca*) do not move by worm-like peristalsis [2]. Instead, waves of movement pass from the terminal segment towards the head and there is a transition in the kinematics and ground reaction forces between posterior segments and those in the mid body. Each segment compresses in the first part of the swing phase and re-extends before entering stance again [2]. The dorsal and ventral parts of each segment change length in phase with one another, implying that lifting and bending across the length of the caterpillar occurs by folding of the intersegmental membranes. Unexpectedly, the length and radius of each body segment co-vary, hence, unlike the leech, segment volume in *Manduca* is not necessarily conserved during a crawl, so tissue, fluid, or air (in the tracheal system) can be transported from one part of the body to another and back again. Remarkably, the essential kinematics of crawling are not different on curved or flat, surfaces nor in different orientations.

A. Body shape and structure

Manduca is essentially a pair of non-compartmentalized concentric elastic cylinders (the body wall and gut) separated by a fluid-covered layer of actuators (muscles). The body wall is contoured and this appears to be very important for normal movements. The ventral surface has passive gripping devices (prolegs).

The Softbot platform consists of a contoured cylinder surrounding a central cavity that will be used for the control system and for payload. Actuators are bonded to the body wall and arranged to mimic the major muscles of *Manduca*.

B. Body wall materials

The primary components of *Manduca* cuticle are fibrous chitin chains arranged in complex layers within a protein matrix. *Manduca* establishes a baseline body pressure and the material properties of the body wall are expected to be important in distributing forces and directing movements. Uniaxial mechanical testing of endocuticle *in vitro* show that circumferential strains yield a modulus at least twice that measured in the longitudinal direction and consistent with the pressurized cylinder model.

Softbot is being constructed from a matrix of silicone elastomer with embedded woven polymer fibres. The fibres can be oriented using textile fabrication methods to provide the appropriate anisotropy.

---

* This work is partially supported by NSF grants IBN 0117135 and IOS 0718537 to BAT and by the Keck Foundation.

C. Muscles and actuators

Manduca muscles are slow to contract and they have a large tetanus-to-twitch force ratio (8.5; [3]). They have a wide working strain range and display pseudoelasticity, loading hysteresis, viscoelasticity, low resilience and dynamic changes in stiffness. Many of these properties have been modeled using large deformation theory [4, 5]. During strain cycling that resembles normal crawling, trains of neural commands produce work loops that cycle between actuation and work dissipation. Changes in the timing and duration of these commands have marked effects upon the work performance suggesting that individual muscles can be "tuned" for diverse functions [3].

Actuators for the Softbot are constructed from shape memory alloy wires that are coiled to allow working strains of 100% and 0.3N of repeatable working force. These SMA springs are bonded to the body wall whose elasticity serves as a bias (recoil) spring. Using duty cycle modulation of current pulses these actuators can be driven to produce changes in length or stiffness that closely resemble *Manduca* muscles. Stimulating the actuators at different frequencies changes the work loops and can be used to transition between operating regions of stress and strain.

D. Proprioception and sensors

Manduca has 3 primary classes of mechanosensors: the internal scolopodial stretch receptor organs (SROs), the epidermal multidendritic sensory plexus and external filiform (hair) mechanoreceptors. Only the SROs appear adapted for proprioception, the other receptors are more concerned with touch and noiciception. The SROs do not signal force but are very sensitive to strain and they contribute to an increase in muscular force exerted by caterpillars when extra loads are applied to their forward movement (the "resistance reflex"). Although the dorsal SRO is thought to signal displacement at low frequencies (0.25Hz) and velocity at high frequencies (3-4Hz) our experiments using realistic strain cycling reveal marked non-linearity in these responses including adaptation and other history-dependent effects.

Sensors for the soft robots will include micro-machined arrays of touch sensitive posts, and stretch sensitive polymeric composites. As for the caterpillar, mechanical information will be available from locations on the body wall but absolute position or shape will not be encoded.

E. Neural commands and control

In contrast with the widely accepted model of caterpillar locomotion [6], both dorsal and ventral muscles in each body segment co-contract. Single muscles (e.g. VIL) in different segments are phase-delayed, but even muscles that are 4 segments apart are co-active for 70% of their duty cycle. Some muscles (e.g., the dorsal internal muscle, DIM) continue to be activated as they re-extend, suggesting that they play an important role in resisting stretch, perhaps stiffening the body wall to transmit forces.

The robot central command is based on coupled oscillators that generate segmental phase delayed activity. Each actuator is controlled using a pulsed current source driven by a master oscillator to maintain the overall cadence of a crawl. Movement produced by these patterns can be optimized using genetic algorithm approaches both in a virtual (simulation) environment and using the robot prototype.

III CONCLUDING REMARKS

The realization of autonomous, soft-bodied robots requires the development of new concepts in motor control, novel actuators and sensors, and the development of flexible conductive layers and carriers for neuromorphic integrated circuits. Together these technologies will find application in a wide range of devices including more conventional robots, medical diagnostic equipment (endoscopes, surgical tools) and space vehicles. The materials and methods of integrating them with controllers will be of particular importance at the interface of biological tissues and electronic devices. They will therefore have applications in prosthetics and in the development of mind-machine technologies.

ACKNOWLEDGMENT

B.A.T. thanks Dr. Dorfmann, Dr. William Woods, Michael Simon, Huai-ti Lin and Linnea van Griethuijsen for helpful discussions.

REFERENCES

[1] R. D. Beer, H. J. Chiel, R. D. Quinn, and R. E. Ritzmann, "Biorobotic approaches to the study of motor systems," *Curr Opin Neurobiol*, vol. 8, pp. 777-82, 1998.

[2] B. A. Trimmer and J. I. Issberner, "Kinematics of soft-bodied, legged locomotion in *Manduca sexta* larvae.," *Biological Bulletin*, vol. 212, pp. 130-142, 2007.

[3] W. A. Woods, Jn., S. Fusillo, and B. A. Trimmer, "Dynamic properties of a locomotory muscle of the tobacco hornworm *Manduca sexta* during strain cycling and simulated crawling," *Journal of Experimental Biology*, vol. in press, 2008.

[4] A. Dorfmann, B. A. Trimmer, and W. A. Woods, Jr., "A constitutive model for muscle properties in a soft bodied arthropod.," *J. R. Soc. Interface*, vol. 4, pp. 257-269, 2007.

[5] A. Dorfmann, W. A. Woods Jn, and B. A. Trimmer, "Muscle performance in a soft-bodied terrestrial crawler: constitutive modelling of strain-rate dependency," *J. R. Soc. Interface*, vol. 5, pp. 349-362, 2008.

[6] R. Barth, "Muskulatur und Bewegungsart der Raupen," *Zool. Jb. Physiol.*, vol. 62, pp. 507-566, 1937.

Towards the Self Deploying Microglider, a biomimetic jumping and gliding robot

Mirko Kovač, Jean-Christophe Zufferey, Dario Floreano
Laboratory of Intelligent Systems,
Ecole Polytechnique Fédérale de Lausanne,
Lausanne, Switzerland
{mirko.kovac,jean-christophe.zufferey,dario.floreano}@epfl.ch

Abstract

Robotics can learn, at the least, one thing from nature; How to successfully move in unstructured and rough terrain. In this sense, gliding flight is a very powerful mean to overcome ground obstacles and to travel from one point to another. We claim that it has high potential and can be applied in miniature robotics as an easy to use and energy efficient mode of locomotion.

In the animal kingdom, many small animals are able to get into the air by jumping, fast running or dropping down from trees. Once airborne, they recover, stabilize (passively and/or actively) and perform goal directed aerial descent (e.g. gliding frogs, flying geckos, gliding lizards, locusts, crickets, flying squirrels, gliding snakes, gliding fish, gliding squid, gliding ants, birds, etc.). These animals do not use steady state gliding [1,2], but change their velocity and angle of attack dynamically during flight to increase the gliding ratio or to precisely land on a spot. The same locomotion principles may be advantageous for small aerial robots as well.

In the project of the Self Deploying Microglider, we thus aim at developing a palm sized robot that possesses the ability to autonomously self-deploy from ground or walls, to then open its wings, recover from any position in mid-air and subsequently perform goal directed gliding and attachment to walls.

As a first step in our exploration of gliding as an alternative and complementary locomotion method in the domain of miniature robotics, we developed a 22cm long Shape Memory Alloy actuated microglider [3] (figure 1) weighing a mere 1.5g and flying at about 1.5m/s. It is equipped with sensors and electronics to achieve phototaxis, which can be seen as a minimal level of control autonomy.

Figure 1. 1.5g Shape Memory Alloy-actuated microglider capable of autonomous phototaxis.

As a next step, in order to decrease aerodynamical friction during self-deployment, we developed a

bioinspired bat-like wing folding mechanism. It allows contracting the wings and unfolding them very quickly (50ms) on demand in midair using a SMA based locking mechanism [4]. This wing folding mechanism is an important milestone to ensure an efficient transition from the self deployment to the subsequent gliding phase.

As the propulsion unit for the Self Deploying Microglider, we developed a 5cm 7g jumping robot [5] (figure 2) that is capable to overcome obstacles of up to 1.4m (corresponds to more than 27 times its own size). It applies an elastic storage mechanism and a cam to charge and release the mechanical energy using a small pager motor in less than 3.5s. In order to be able to optimize the jumping performance, we employ a four bar linkage leg system that is fully adjustable in jumping force, take off angle and force profile during the acceleration phase.

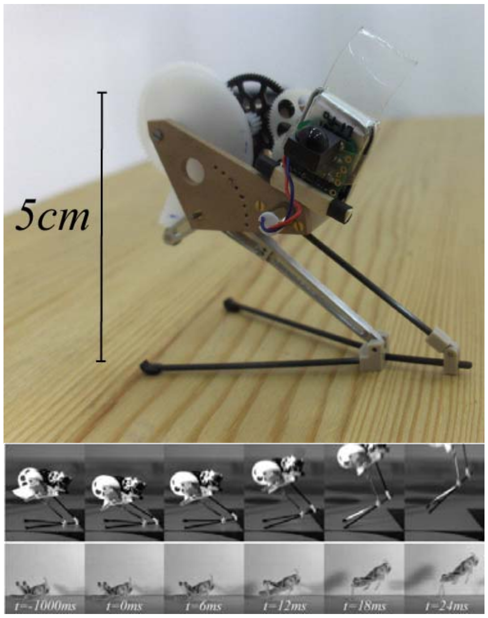


Figure 2. Novel locust inspired 7g jumping robot

Work in progress addresses the perfection and integration of the different mechanisms developed so far and the study if the dynamics and control of the entire system.

References

[1] Dudley, R., Byrnes, G., Yanoviak, S.P., Borrell, B., Brown, R.M., McGuire, J.A. (2007) Gliding and the Functional Origins of Flight: Biomechanical Novelty or Necessity? Annual Review of Ecology, Evolution, and Systematics 38(1): 179-201

[2] Maynard Smith, J. (1952) The importance of the nervous system in the evolution of animal flight, *Evolution*, 6(1): 127–129

[3] Kovač, M., Guignard, A., Nicoud, J.-D., Zufferey, J.-C., Floreano, D. (2007) A 1.5g microglider looking for the Light, *Proceedings of the 2007 IEEE International. Conference on Robots and Systems,* Roma, Italy.

[4] Kovač, M., Fuchs, M., Savioz, G., Guignard, A., Nicoud, J.-D., Zufferey, J.-C., Floreano, D. (2007) Self Deploying Microglider. *Proceedings of the 2007 Flying Insects and Robots Symposium,* Monte Verita, Ascona, Switzerland

[5] Kovač, M., Fuchs, M., Guignard, A., Zufferey, J.-C. and Floreano, D. (2008) A miniature 7g jumping robot, *Proceedings of the 2008 IEEE International. Conference on Robots and Systems,* Pasadena, USA.

Tapping into the brain for control of assistive devices

Dawn Taylor
Case Western Reserve University

Brain activity associated with attempted movements can now be 'decoded' in real time. Those movement commands can then be applied to the control of a variety of assistive devices. Decoding movement intent from brain signals in real time has the potential to enable severely paralyzed individuals to control assistive devices just by thinking about doing so. Understanding how to transform recorded neural activity into movement commands for the control of devices that may or may not resemble the natural biology can provide insights into the flexibility of our motor control system.

Principles of Active Sensing: Insights from the Rat Vibrissal System

Mitra Hartmann
Northwestern University

Rats are nocturnal, burrowing animals that use their vibrissae (whiskers) to tactually explore the environment. Using only its whiskers, a rat can determine object size, shape, orientation, and texture. This makes the rat vibrissal system an excellent model to explore the structure of movements that subserve sensing. I will describe recent experiments in our laboratory that have aimed to understand neural processing in the vibrissal system from the outside-in. I will walk through our laboratory's suggested answers to the following questions:

1. What are the primary mechanical variables sufficient for three-dimensional feature extraction by the whiskers? We suggest that these variables are angular position, angular velocity, and rate of change of moment (torque) at the whisker base. I will show results from a hardware model to demonstrate that these variables are sufficient for feature extraction.

2. How are these variables encoded by the electrical activity of neurons in the first stage of neural processing? In a re-analysis of data from Jones et al. [1] we have found evidence that neurons of the trigeminal ganglion use a state encoding scheme to represent pair-wise combinations of the mechanical variables identified above.

3. How are the variables transformed in the second stage of neural processing, and why might they be transformed in this way? We hypothesize that neurons with multi-whisker receptive fields in the trigeminal nuclei help to compute the relationship between spatial and temporal gradients generated as the animal moves its sensory surfaces through the environment. These gradients, expressed as the complete derivative, are computed based on the animal's own velocity, and provide an inviolate mathematical description of information flow over moving sensory surfaces. Computing the complete derivative at multiple spatial and temporal scales would allow the animal to predict the stimulus that it will measure in the next sensory instant, conferring tremendous survival advantage.

Jones LM, Depireux DA, Simons DJ, Keller A (2004) Robust temporal coding in the trigeminal system. Sc*ience* 304:1986 – 1989.

Neuromechanics of elastic energy storage and recovery during ballistic movements.

Jenna Monroy, Leslie Gilmore, Theodore Uyeno, A. Kristopher Lappin, and Kiisa Nishikawa
Department of Biological Sciences, Northern Arizona University

Muscle physiologists typically study the behavior of muscle under a limited set of conditions, such as isometric tetanus or isotonic shortening, which rarely apply to movements of freely behaving animals. While investigating ballistic prey capture behavior in toads, we re-discovered the usefulness of an old technique, the load-clamp, for quantifying contractile and elastic properties of muscles and their connective tissues under physiologically relevant conditions. This technique allows muscle properties to be studied under a wide range of conditions, particularly those in which muscles develop force against a resisting force, and shorten when the resisting force is reduced. Using this technique, we developed an elastic recoil model of muscles and connective tissues during ballistic movements. The model accurately predicts the observed amplitude and velocity of movements given only the duration of muscle activation prior to unloading and the external load. It predicts elastic behavior during active shortening for several muscles (depressor mandibulae, sartorius, extensor digitorum longus, soleus) in different species (frog, mouse). In addition, it predicts the elastic behavior of muscle under isometric and isotonic conditions. At the level of the whole organism, the model predicts that appendages of smaller animals will operate at higher stiffness, and hence at greater frequencies, than those of larger animals. The model demonstrates that actively shortening muscles exhibit dynamic stabilization to perturbations in load without requiring neural input. It also suggests that control of rapid movements may require specification of relatively few variables.