Walking: technology and biology

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If all the signs are to be believed, then the twenty-first century will technologically be characterized by machine walking and its relevant products, which possess all chances to become real bulk goods in the course of the next decades. With several university institutes and with Honda and Sony from the industrial side, Japan is today and without any doubt the leading nation in research and development of walking machines. The US and Europe follow at some distance. Walking machines will influence all areas of daily and industrial life and, with the fast evolution of artificial intelligence, will become a real partner of human beings. All relevant technologies are highly interdisciplinary, they will push the future technologies of all technical fields. The special issue on this topic gives a selection of walking machine research and development including some aspects from biology.

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1. Motivation

Walking is a fascinating invention of nature. It is versatile, flexible and perfectly adapted to a natural environment. Walking in its various realizations enables biological systems to have access to all the natural structures of the Earth. Walking performance means actuating the typical walking components like legs, muscles, sensors, signal processing lines, nerves and brains. This generates motion of the complete biological system. Walking realizes motion, and motion with motion planning is the basis for intelligence, as modern biologists state. If intelligence is defined as the ability to deal with unknown and new situations, such as the possibility to find solutions for new problems, biological movement, both mental and physical, can be considered as a manifestation of intelligence. Therefore, motion and intelligence might be regarded as the prerequisites for animals and humans to conquer the Earth. All this makes walking research so extremely interesting for biologists and engineers.

Walking was studied by engineers about 20–30 years ago, although before that time numerous trials had been made to realize some mechanisms with walking capabilities. Nowadays, the computer age and a large variety of sophisticated technologies give walking machine realizations a high probability of success. To date, the technical world of artefacts has come out with a large variety of machines

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and transportation systems mainly based on the invention of the wheel, a true human artefact and as a matter of fact a really basic one. But be it cars, trains, ships or airplanes, they all need highly organized areas, at least for starting and landing, they need roads, tracks, harbours, airports, which might be seen as a price for high speed and comfort. Access to non-organized areas of the Earth is still difficult, even today. Walking machines will help to change this situation.

Most walking machines take some biological systems as templates, with two, four or six legs. This makes sense, because natural evolution has created a large variety of excellent solutions, of course under the given evolutionary constraints, historically and environmentally. For several reasons, it makes no sense to copy biology one by one. Evolution had to find its solutions within the framework of its possibilities: no wheels, muscles instead of rotating motors, nerves with synapses instead of wires and various types of sensors on a biological analogue basis. However, the number of sensors applied is sometimes extremely large. For example, one antenna of a cockroach includes 300 000 sensors! But, on the other hand, technology has to offer also some positive constructive solutions: computer and computer science, a sophisticated design methodology, excellent motor-gear combinations with a high power to weight ratio, a highly developed sensor technology and very advanced low-weight solutions. What should be done is to combine the design principles of biological evolution with the best of technological possibilities. This results in two requirements. First, biological research should be able to depict as many design principles invented by biological evolution as possible. Second, technology should make feasible the application of the most advanced software and hardware available with respect to cognition, mechanics and control with its sensors and actors. Realizing walking machines is a challenge and a technology-pushing issue by itself.

From the technological point of view, we have a large variety of aspects to develop walking robots. A decade ago, arguments started with applications in hazardous environments, in areas to which human beings have no access. In the meantime, walking robot technology made enormous progress including highly perfect mechanical systems, sensor and control concepts and astonishing advanced technologies, which at least are rather near to what might be one day artificial intelligence (see Fujita 2006; Sony). This development establishes a confidence level allowing us to say that we are able to realize a walking biped robot being able to interact with humans without boring them. Biped machines, because the infrastructure of our societies is designed for humans. Everything around us possesses human measures. Therefore, in designing humanoids with human measures spares additional investments for special walking topologies. It is a strong motivation to pursue this concept (see Hirukawa 2006).

2. Walking machines and technologies

In recent times, the first, possibly worldwide the first, to start with scientifically oriented research on walking robots, especially on bipeds, was Professor Ichiro Kato (1925–1994) in Japan, who built in 1967 his artificial biped walker WL-1 (see Lim & Takanishi 2006). Since then many activities all over the world pushed forward walking machine technology, though from the very beginning there was a clear focus in Japan owing to really significant support of the Japanese
Government and Japanese industry. This fact is underlined by the two articles of Honda and Sony within this special issue, where Honda started already in the year 1986 with its first walking robot E0 (see Hirose & Ogawa 2006). The E0 was followed by a whole series of 11 bipeds, the last one being the third version of the worldwide acknowledged ASIMO, the astonishing capabilities of which are well known. Honda, as a car manufacturer, pursues three goals with respect to its walking bipeds, namely to create new mobility, to coexist and cooperate with humans and to make general purpose robots.

Sony started its walking machine activities in the second half of the 1990s with a clear focus on entertainment robotics and as a consequence on pet-type robot configurations like AIBO or QRIO, by the way with significant commercial success. Pet-type robots need autonomy, which is achieved by modern control and cognition mechanisms. For example, AIBO includes a behaviour-based architecture with an action-selection mechanism, a stochastic state-machine realizing context-sensitive responses and to a certain extent some kind of instinct-emotion-generator. It also includes learning abilities by reinforcement learning into the architecture. Sony (see Fujita 2006) calls that intelligence dynamics with the goal of realizing an ever-developing open-ended system.

The industrial activities were and are accompanied by a broad variety of university research. We give a few characteristic examples. Kato’s Institute at Waseda University has developed a series of bipeds, the last one being WABIAN-RIV. The WABIAN family has been very successful, its last member can walk forward, backward and sideways, can dance and carry heavy goods (see Lim & Takanishi 2006). The National Institute of Advanced Industrial Science and Technology in Tsukuba, Japan, is involved in significant improvements of the HRP-robot, originally developed by Honda for maintenance tasks of industrial plants and for guard tasks of homes and offices. AIST developed new control concepts enabling HRP-2 to drive industrial vehicles, perform more sophisticated maintenance tasks, take care of patients in bed and cooperate with human workers. HRP-2P may fall down, then it can get up from the floor autonomously (see Hirukawa 2006).

One of the very advanced university robots is the H7, developed by the group of Professor Inoue at the University of Tokyo (Nishiwaki et al. 2006). The H7 was developed over several years as an experimental platform for walking, autonomy and human interaction research. With respect to the body mechanism for biped walk, lie down and stand up, support body by hand, pick itself up, a couple of features become important like the arrangement and the number of degrees of freedom, the rotation range and the maximum torques of the joints, the self-containedness, the ease of maintenance and smooth surfaces for attaching tactile sensors. Sensor availability of the H7 robot includes as a standard all joint sensors, force sensors, some foot sensors, but also tactile sensors for contacting the world and a 3D-vision system for seeing the world. This is accompanied by real-time computational and software systems in order to process from low-level software such as servo-loop and sensor-processing to high-level software such as motion planning and behaviour control. Therefore, high computational performance and most sophisticated software design are required.

The much more modest activities in Europe and especially in Germany may be characterized by the walking machines that have been developed at the Technical University in Munich and in Karlsruhe. The group at the Institute B of Mechanics

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(see Pfeiffer 2006), Technical University of Munich, started in 1989 to design and realize a six-legged walking machine MAX, which followed very closely the, at that time new, neurobiological findings by Professor Cruse in Bielefeld and Professor Bässler in Kaiserslautern with respect to the control of walking stick insects. Although this machine is already 12 years old, its control concept is still very modern and in the area of neurobiology a matter of ongoing research. Without any central surveillance, the control of MAX is completely autonomous, also in uneven terrain. The six-legged machine MAX was followed by the eight-legged machine MORITZ, which was able to walk in tubes of any position and orientation, and the control of which possesses on a lower level that of MAX supplemented by a high-level structure being able to manage the contact forces at the foot-contacts at the inner tube wall. After these research results, a large priority project of the German Research Foundation (DFG) enabled the institute to develop a biped machine with a certain degree of autonomy, which could be achieved by the combination of the two-legged machine JOHNNIE with a 3D-vision system developed by the group of Professor Günther Schmidt at the Technical University of Munich. JOHNNIE is a light-weight design with 17 joints, a height of 1.80 m and a weight of ca 40 kg. At present, a new biped is being developed by Professor Ulbrich at the same institute (successor Professor Pfeiffer).

The same idea of a close cooperation of biologists and engineers has been pursued at the University of Karlsruhe (see Dillmann et al. 2006) by Professor Dillmann and his group in developing the four-legged machine BISAM, the morphology and behaviour-based control of which follows as near as possible biological findings, especially those of Fischer in Jena (see Fischer & Witte 2006). Considering also some ideas from researchers in the US and Japan, the behaviour-based architecture forms a behaviour coordination network by connecting the inputs and the outputs of the behaviours. These connections transport control and sensor information as well as loop-back information. BISAM is driven by pneumatic joints, which on the one side show a good performance quite similar to that of biological muscles, but which on the other side generate control problems owing to their compressibility and temperature sensitivity. BISAM is walking, but improvements are still necessary.

A very successful four-legged robot was developed during the last few years by Kimura and his co-workers (see Kimura et al. 2006). The walking performance of his TEKKEN series is really impressive, owing to some good ideas concerning mechanical design, but mainly owing to a very advanced design of the control system, which is based on biological findings. Kimura applies a limit-cycle-based control for legged locomotion. It includes the adjustment of joint torques within a single-step cycle, the adjustment of initial conditions of the legs at the transition from swing to stance and an adjustment of the stance or swing phases. His ‘coupled-dynamics-based motion generation’ can interact with the environment emergingly and adaptively. The gait pattern generator deviates from that described by Cruse for the stick insect (see MAX), but is equally adaptive and autonomous.

An important contribution concerning the actuators is given by Arikawa (see Arikawa & Hirose 2006). Actuators represent the heart of walking machines, their power-to-weight ratio is the key for being able to establish many degrees of freedom (Inoue) and provide the machine with sufficiently large torques for the walking process. This problem can be neutralized at least partly by the
introduction of two ideas, the concepts of gravitationally decoupled actuation (GDA) and coupled drives. The GDA decouples the driving system against the gravitational field to suppress the generation of negative power and improve the energy efficiency. Negative power is defined as a result of braking. The coupled drive couples the driving system with the goal to distribute the load as equally as possible among all actuators, thus maximizing the utilization of the installed actuator power. Some hardware examples confirm these two ideas.

3. Biological walking

Every technological development and progress starts with examples, which in most cases are available in corresponding technical products, cars, cameras or machines. The technology of walking is a very young one without examples coming from the technical world itself. Therefore, it makes sense to look for examples in biology, where the evolution of millions of years has generated astonishing solutions. Nevertheless, by looking for such solutions one must keep in mind that nature works with completely different materials and concepts, which only in some cases might be transferred to technology. The basic ideas applied in biological systems are indeed very attractive, as far as they are known, but a one-to-one transposition makes sense only for a very few cases (see MAX and NU/DARPA/ONR). In the following, we shall give some examples from various fields of biology, where walking performance has been investigated, including a very ‘biological’ design of a walking machine.

Fischer & Witte (2006) reinforce some of these ideas stating that the evolution of legs comes late in phylogeny and that ‘biologically inspired’ technologies might be a better and a more moderate approach than bionics or biomimetics. They continue that on the one side technological structures are always designed anew, but that on the other side biological structures are always the result of a past, permanent and ongoing process, which means ‘derived from ancestors’. This antithesis is as a matter of fact only partly correct, because not only biology but also technology is carrying their special evolutionary burden, in classic technologies more than in walking technology. This results in the logical consequence that an adaptation of evolutionary ideas makes sense only if the past and the recent functional requirements are identical, which under the logically necessary prerequisite of a constant environment will even be more an exception than the rule. Therefore, applying biological concepts to technology requires a thorough investigation of goals and environments. Two-legged machines are a good solution, because they fit perfectly into the environments generated by humans through thousands of years (Hirukawa 2006; Hirose & Ogawa 2006).

The basic matter of concern of the contribution to intelligence by mechanics (Blickhan et al. 2006) consists in facilitating control by self-stability, which depends on the global system properties as well as on all major building blocks of the body. Technological design should realize as much self-stability as possible. The existing actuator systems are certainly a problem with respect to such a transposition, but the idea is convincing in spite of the fact that only simple and small mechanical configurations have been considered to date. During biological walking, potential energy is stored in the muscles, which is released during
certain phases of the walking process. Together with the mass and stiffness properties of the legs of humans or animals, the cyclic behaviour of potential and kinetic energies generate a very simple but at the same time a very robust self-stability. Experimental models composed from masses, springs and dampers are able to demonstrate astonishingly well ‘natural walking’.

The control mechanisms of human walking are not very well understood, they are a matter of ongoing intensive and worldwide research. Humans belong to the mammals, and mammals possess much more complex control behaviour than insects, which are easier to investigate and where as a consequence quite a lot about walking and walking control is known. Cruse et al. (2006), Gabriel & Büschges (2006) and their research groups are working on the problems of walking and walking control of stick insects. The control concept of these insects is widely decentralized including more or less three layers, the lowest layers for stabilization purposes, the middle layer in a similar form as a finite state machine for controlling the cycles and regarding all unexpected obstacles and the upper layer for organizing the gaits by influencing neighbouring legs shifting their phase in the right direction, inhibiting some actions or set actions going. An important property of these insect legs is the possibility to parametrize the segments of the legs. All segments move according to the coxa–femur control following some given (and environmentally adapted) laws. Cruse has developed a computer code on the basis of neural nets which gives a good mapping of the insect’s behaviour. Büschges investigates the influence of the stepping velocity on the insect’s walking control. Speed is simply generated by increasing the cycles applied to the joint connecting the first segments (coxa, femur) to the body. This is slightly in contradiction to the idea that biology applies different control structures for different speeds. Obviously, accelerating the cycles might be the simpler solution. The control structure of the stick insect has been realized in the six-legged machine MAX nearly in the sense of biomimetics.

Another example of a biomimetic robot has been developed by Ayres & Witting (2006) with their eight-legged machine NU/DARPA/ONR, the concept of which is based on the American lobster. The robot is designed to achieve the performance advantages of the animal model by adopting the biomechanical features and neurobiological control principles. Three types of controllers are considered. The first is a state machine based on the connectivity and dynamics of the lobster central pattern generator. It controls myomorphic actuators realized with shape memory alloys and responds to environmental perturbation through sensors that employ a labelled-line code. The controller supports a library of action patterns and exteroceptive reflexes to mediate tactile navigation, obstacle negotiation and adaptation to surge. The second type of control is based on synaptic networks of electronic neurons and has been adapted to control the shape memory alloy actuated leg. A rudimentary brain is being developed as a third higher order controller using layered reflexes based on discrete time map-based neurons.

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References


