

Using Biological Inspiration to Develop Versatile, Adaptive, and Autonomous Walking Machines

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Living creatures like walking animals and humans have found fascinating solutions for the problem of legged locomotion in the way that their movements give the impression of elegance and smoothness. They are able to move around not only on flat terrains but also on rough terrains and even to perform a variety of walking behaviors. Furthermore, they can adapt themselves to environmental changes in order to survive. Neurophysiological and ethological studies have revealed that solving such tasks basically results from coupling appropriate *biomechanics* [1] with *neural control* [2]. For instance, walking animals (e.g., insects, cats) can walk forward, backward, and in lateral directions and perform self-stabilization to minor disturbances (stumbling) because of their appropriate biomechanical design. Neural control, on the other hand, plays a role in generating different walking behaviors as well as adaptivity. Therefore, during the last few decades several roboticists have begun actively to look to the biological sciences for the constructions (biomechanics) and the controller (neural control) design of robotic systems in particular walking machines to approach the living creatures in their levels of performance.

The diverse researches in the domain of biologically inspired walking machines have been ongoing for over 20 years [3, 4]. Most of them have focused on the mechanical design to have animal-like properties and perform efficient locomotion [5]. Others have concentrated on the generation of locomotion based on engineering technologies [6] as well as biological principles [7]. While impressive in their own right, the versatility (behavioral repertoire) of these systems is much smaller. Typically they are not adaptive (learning capabilities) and most of them still fail to be autonomous (function without continuous human guidance). From this point of view, during last years we have developed two different types of walking machines (an insect-like robot [8, 9] and a biped robot [10]) where they now combine the three key aspects (versatility, adaptivity, and autonomy) under neural sensor-motor control. The description of the development of each walking machine system and its performance is presented in the following.

AMOS: Insect-like hexapod

AMOS is an advanced mobility sensor-driven walking device (see Fig. 1a). It consists of a two-part body connected by one backbone joint (BJ), at which six identical legs and one tail are attached. Each leg has three joints (three degrees of freedom) controlled by analog servo motors: the thoraco-coxal (TC-) joint enables forward (+) and backward (−) movements, the coxa-trochanteral (CTr-) joint enables elevation (+) and depression (−) of the leg, and the femur-tibia (FTi-) joint enables extension (+) and flexion (−) of the tibia [9]. The morphology of these multi-jointed legs is modeled on the basis of a cockroach leg [8]. Each tibia contains a spring compliant element to absorb impact force as well as to measure ground contact during walking. The body of AMOS consists of two segments: a front segment where two forelegs are installed and a central body segment where the two middle and the two hind legs are attached. They are connected by one active backbone joint inspired by the invertebrate morphology of the American cockroach's trunk. This backbone joint driven by a digital servo motor is for up- and downward bending, which allows the walking machine to climb over obstacles. Moreover, a tail with two degrees of freedom, rotating around a horizontal and a vertical axis, is implemented in the center on the back of the trunk. On this actively moveable tail, which can be manually controlled, a mini wireless camera is installed for monitoring the environment while the machine is walking. This walking machine has a multitude of sensors: six foot contact sensors (FC), six reflexive optical sensors (RO), eight infra-red sensors (IR), two light dependent resistor sensors (LDR), one upside-down detector sensor (UD), one gyro sensor (GR), one inclinometer sensor (IM), and one auditory-wind detector (AW) sensor. The hexapod receives 26 sensory inputs, and controls 19 motors to achieve a broad behavioral repertoire including foothold searching, elevator reflex (swinging a leg over obstacles), self-protective reflex (standing in an upside-down position), obstacle avoidance,

auditory- and wind-evoked escape responses, phototaxis (turn towards a light source), climbing over obstacles, and five different gaits.

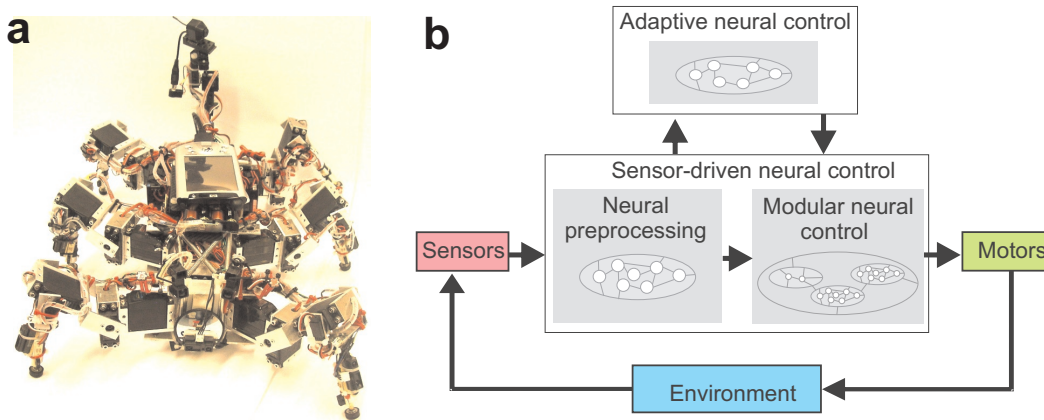


Figure 1: **a**, The physical insect-like hexapod AMOS (see [9] for the details of the location of the sensors on AMOS). **b**, The diagram of the neural controller of AMOS. The controller acts as an artificial perception-action system; i.e., the sensor signals are passed through the neural preprocessing unit into the modular neural control unit which directly drives the actuators. In addition, the adaptive neural control functions as high level control. It is used for learning capability. As a result, the hexapod's behavior is generated by the interaction with its physical environment in a sensorimotor loop.

These complex autonomous behaviors are generated through a so-called sensor-driven neural controller consisting of a neural preprocessing unit and a modular neural control unit (Fig. 1b). The neural preprocessing unit filters sensory noise, combines, and shapes sensory data to drive corresponding behaviors. On the other hand, the modular neural control unit based on a central pattern generator (CPG) is used for locomotive generation. It coordinates leg movements, regulates walking speed, and produce a variety of walking patterns. Furthermore, adaptive neural control using a correlation based differential Hebbian learning rule [11] has been implemented. It allows the hexapod to learn to respond to a conditioned stimulus, e.g., predator-recognition learning. As a result, all reactive and adaptive behaviors of the hexapod are generated by interacting with a physical environment through a sensorimotor loop (see [8, 9] for more details). The results of the real robot walking experiments can be seen as video clips at <http://www.nld.ds.mpg.de/~poramate/AMOSWD06.html>.

RunBot: Planar Dynamic Biped

RunBot is a planar dynamic biped robot (see Fig. 2a). It consists of four actuated joints: left hip, right hip, left knee and right knee. Each joint is driven by a modified servo motor where the built-in pulse width modulation (PWM) control circuit is disconnected, while its built-in potentiometer is used to measure the joint angles. RunBot has no actuated ankle joints, resulting in very light feet and efficiency for fast walking. Its feet were designed having a small circular form (4.5 cm long). Each foot is equipped with a switch sensor to detect ground contact events. A mechanical stopper is implemented on each knee joint to prevent it from going into hyperextension. Approximately seventy percent of the robot's weight is concentrated on its trunk and the parts of the trunk are assembled in a way that its center of mass is located forward of the hip axis. In addition, it has an upper body component (UBC), which can be actively moved to shift the center of mass backward or forward for walking on different terrains, e.g., level floor versus up or down a ramp. It leans backward during walking on a level floor (see Fig. 2a) and this position is also suitable for walking down a ramp while it will lean forward (reflex action) when RunBot falls backwards or after it successfully learned to walk up a ramp. The corresponding reflex is controlled by an accelerometer sensor (AS). The AS is installed on top of the right hip joint. Additionally, one infrared (IR) sensor is implemented at the front part of RunBot pointing downwards to detect a ramp. These IR and AS sensory signals are used for adaptive control (see [10] for details). As described here, the biomechanical design of RunBot has the following special features that distinguish it from other powered biped robots and that facilitate high-speed walking and exploitation of natural dynamics [10]: (a) small, curved feet allowing for rolling action; (b) unactuated, hence light, ankles; (c) lightweight structure; (d)

light and fast motors; (e) proper mass distribution of the limbs; and (f) properly positioned mass center of the trunk. Utilizing all these properties, RunBot can perform self-stabilization of gaits [10] and it also exhibits passive walking characteristics [10] reflected by the fact that during one quarter of its step cycle all motor voltages remain zero.

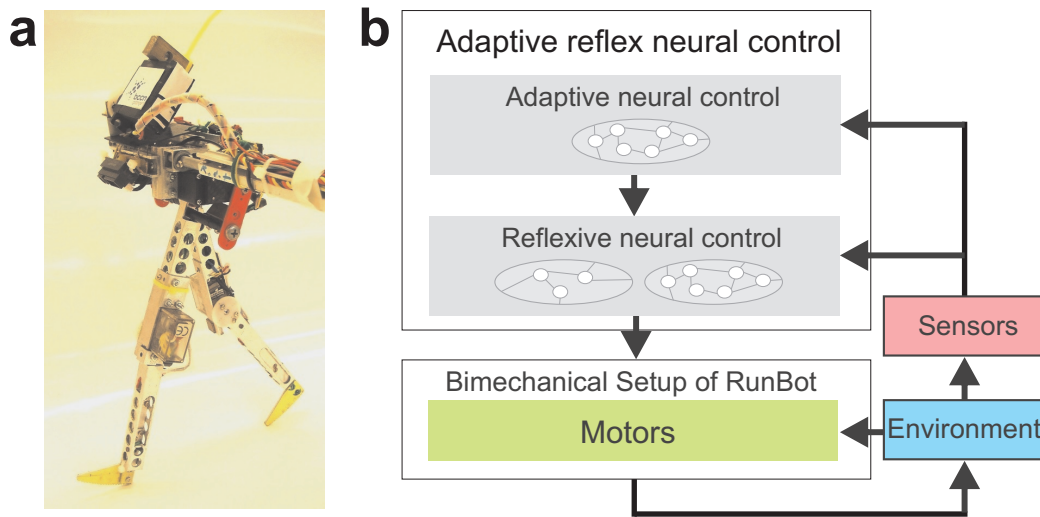


Figure 2: **a**, The planar dynamic biped robot RunBot (see [10] for the details of the location of the sensors on RunBot). **b**, The diagram of the neural controller of RunBot where the adaptive network is implemented on top as high level control to modulate the reflexive networks (lower level) through learner neurons (not shown but see [10] for details). Accordingly, the adaptive dynamic walking behavior of RunBot is achieved by the interaction with its physical environment in a sensorimotor loop.

RunBot's locomotion is driven by adaptive reflex neural control (see Fig. 2b) which doesn't employ any trajectory control. It consists of two main circuits: adaptive neural control and reflexive neural control circuits including signal preprocessing. The reflexive neural control based on reflex mechanisms uses proprioceptor signals (sensory feed-back) coming from ground contact sensors, stretch receptors, and joint angle sensors to generate dynamic stable gaits while its AS sensor is used to trigger the body reflex. In the adaptive neural control where the correlation based differential Hebbian learning rule [11] is applied, it serves for gait and posture adaptation during walking up a ramp. As a consequence, through the tight coupling of biomechanics with neural control, RunBot can autonomously walk with a high speed (> 3.0 leg length/s), self-adapting to minor disturbances, and reacting in a robust way to abruptly induced gait changes [10]. At the same time, it can learn walking on different terrains, requiring only few learning experiences [10]. The results of the real robot walking experiments can be seen as video clips at <http://www.nld.ds.mpg.de/~poramate/Runbot.html>.

Taken together, this study shows that the biologically-inspired walking machines are fascinating technology to study with respect to their biomechanical design including sensor and actuator systems as well as the realizations of control concepts. They can serve as hardware platforms for better understanding and solving the sensorimotor coordination problems of many degrees of freedom, for performing experiments with neural controllers, and for the development for versatile artificial perception-action systems. In particular the biped walking robot, it can serve as an experimental device in order to understand human walking which is a formidable challenge and which has been addressed through physiological studies as well as robotics research. Moreover, this walking machine technology is shown to be a highly interdisciplinary technology, uniting contributions from several areas as diverse as biology, biomechanics, material science, neuroscience, engineering, and computer science.

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