Overview of Bio-Inspired Control Mechanisms for Hexapod Robot

Marek Zak
Faculty of Information Technology
Brno University of Technology
Brno 612 66, Czech Republic
Email: izakmarek@fit.vutbr.cz

Jaroslav Rozman
Faculty of Information Technology
Brno University of Technology
Brno 612 66, Czech Republic
Email: rozmanj@fit.vutbr.cz

Frantisek V. Zboril
Faculty of Information Technology
Brno University of Technology
Brno 612 66, Czech Republic
Email: zboril@fit.vutbr.cz

***Abstract*—This paper deals with overview of possible control mechanisms for hexapod robot. Basic characteristics of legged robots, a few existing robots and their pros and cons are described in the introduction of this paper. Main part of the paper is focused on the previous work done in the field of hexapod robot control, especially the usage of evolution techniques like neural networks and genetic algorithms. The last part of this paper is about a hexapod robot of our design.**

***Keywords*-Hexapod Robot; Hexapod Control; Evolution Techniques For Hexapod Control**

I. Introduction

Walking robots have been the subject of many researches and studies for long time. Although they are not commonly used, their use is not negligible. Walking robots are suitable for rough terrains. They are capable to cross large holes and can operate even after losing a leg [1]. But their control is quite difficult, because walking robots have a lot of degrees of freedom.

When we design a controller for legged robots, we want to achieve rhythmic and fluent movement, which we can observe in animals. Insects, for example, can walk very fast over rough terrain, while changing gaits and adapting to changes in load or leg damage. But we encounter some issues. The first is, that we do not have enough knowledge about animal's neural system. The second one is, that muscles of animals are much more stronger and lighter than any motor or system that humans invented.

There is still intensive research on the field of neurobiology and engineering, so we can build robots, which will move like animals.

II. Examples of Legged Robots

Even today, we can find several examples, which are used in extreme conditions. An example might be ATHLETE [2], a robot by NASA (Figure 1). This six-legged robot was designed for exploration of planets, especially of Mars. His legs are equipped with wheels and it is able to walk and ride. In the field, where driving on the wheels is not possible, come the legs. The robot is also able to grab a tool and drill into the ground or carry burdens.

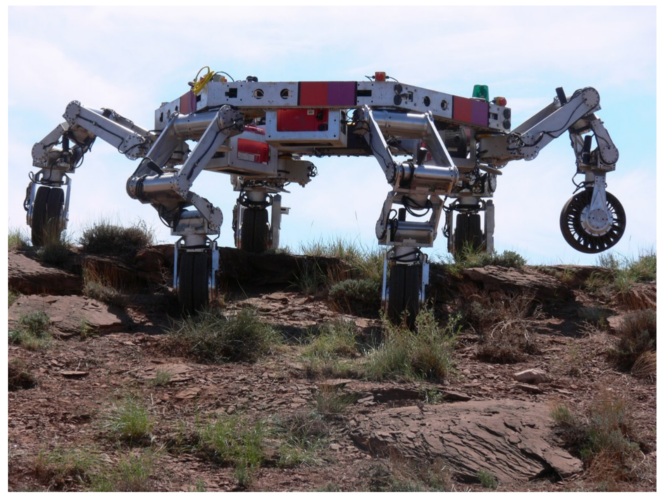


Figure 1. ATHLETE. This six-legged robot was designed by NASA for exploration of planets, especially of Mars [2].

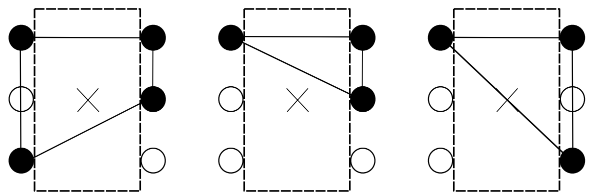
Another example may be LS3 [3], a robot manufactured by Boston Dynamics. It is a four-legged robot that is capable of reaching speeds of up 10 km/h and will serve the military for carrying material and equipment. This robot, unlike the ATHLETE, moves dynamically. That means he can stay in balance even when he has lifted two or more legs.

The ATHLETE and LS3 are examples of working prototypes, which are designed for some specific tasks. There are also a lot of smaller robots, which were developed for research and experiments. Many of them are described in [4]. There are also described issues of designing a hexapod robot such as body types, actuators or robot proportions.

III. Characteristics of Legged Robots

This part of the paper focuses on several characteristics of walking robots. Some classifications of walking robots and most common walking gaits are described.

There are many ways how to classify walking robots - by a body shape [5], number of legs, number of degrees of freedom per leg or locomotion technique. Various options can be combined to achieve many different configurations. At least two degrees of freedom are needed to construct a walking robot - the first for lifting the leg, second for



(a) Statically stable (b) Statically unstable (c) Critical stable

Figure 2. Possible positions of the chassis during its movement. This figure is taken from [7].

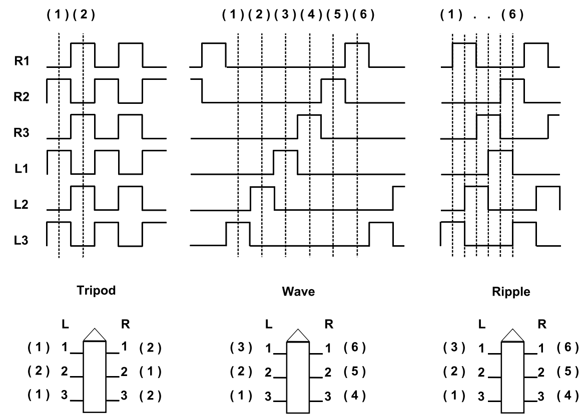


Figure 3. Walking gaits. The chart shows the movement of each leg in time. A high value represents leg movement, low values means no movement. Tripod, wave and ripple gaits are shown in this figure. Tripod has two group of legs, all the legs in the same group move at once. In the wave gait only one leg is moving forward at any time. After all legs are set up to their new positions, step is completed. In the ripple gait all legs move the same way, but their moves are shifted. Inspired by http://www.oricomtech.com/projects/cynthia2.gif, 30. 9. 2015.

rotating it. Nevertheless there should be three degrees of freedom for a good functioning chassis, because the legs move along a circle and the forward movement of the body causes slipping between the foot and the terrain, which can be compensated by the third joint [6], [7].

Walking chassis can get into three basic states during its movement based on the number of legs and gait (Figure 2) [7]. The first state is statically stable, when the chassis rests on at least three legs and is in balance. This is usual for the chassis with more legs (e.g., hexapod), which is characterized by statically stable walking (the chassis at each moment occurs in a stable position). It can also be in statically unstable state when the chassis is not balanced, which leads to collapse. This instability can be compensated with dynamic move. Then we talk about dynamically stable walking, which is a typical example of bipedal chassis. The last state is between the previous two. This is a critically stable state when the chassis balances on the edge of its center of gravity. These features should be also considered when designing a control system.

A. Walking Gaits

Management of a legged chassis is significantly more difficult than managing wheeled or tracked chassis. Just because of the fact that the wheeled or tracked chassis is able to stand on the spot due to its construction, while legged chassis need control, even when they are not moving. Also forward movement is significantly more complicated. It is not enough to activate the engine and let it run. The legged chassis needs putting legs in appropriate order.

A gait refers to the locomotion achieved through the movement of robot legs. Compared to humans, the legged chassis usually has more than two legs. Therefore, the locomotion of a robot is much more complicated. There are several basic gaits, such as tripod, wave or ripple (Figure 3).

Tripod gait is based on two groups of legs. During each step the first group of the legs is lifted and is rotated forward and is laid on the ground. Then the other group is lifted. Now both groups are moving, the first group backward, the second group forward and finally the second group is laid on the ground. It is obvious that both groups perform the same movement, but they are shifted by half a period. Tripod gait is very fast, but also very unstable. That is because at one moment half of the whole weight of the robot is only on one leg, which can lead to slip or even to fall.

Another gait is wave, which is the most stable gait, but also the slowest. Wave gait consists of a sequential adjustment of the robot legs forward. Once all the legs are set to the new positions, the step is completed. Maximally one leg is lifted up in each phase of a step. This leads to high stability of this gait.

Ripple gait is inspired by insects. Each leg performs the same move – up, forward, down, backward. Leg moves partially overlap. In other words, the time when the first foot is lifted and begins to move forward, the second leg begins to lift up. In this way the robot cycles through all legs.

There are other common gaits such as tetrapod or rotation. The number of possible combinations can be expressed according to the number of legs of the chassis as:

$$N = (2K - 1)!$$

where K is the number of legs [8]. It is obvious that the number of different algorithms grows rapidly with the number of legs (for robot with six legs there are 11! = 39,916,800 possible sequences of movement). However most of them cannot be used in practice, because they do not lead to efficient movement or cause instability and crashes of the robot. Still, the number of all possible gaits is quite high and you cannot check them all.

IV. Hexapod Controllers

Because of the huge number of all gaits, researchers are trying to develop some methods, which would generate the best gait according to given situation. Wide range of evolution techniques, such as neural networks or genetic algorithms, can be used to generate control pulses.

A. Controllers Based on Neural Networks

Beer [9] developed a recurrent neural network based on studies of the American Cockroach, but the neural network was tuned by hand to produce the desired results. Although results of his work are great success, it still has too much human interaction. Beer et al. proposed several papers on the field of walking robots. They created distributed neural network based on insect neurology. Beer et al. [10] have presented a fully distributed neural network architecture designed to hexapod robot control. The design of the network is based on work on the neuroethology of insect locomotion. The controller was tested in simulation in previous work. They report in this paper, that they successfully applied the controller on a real hexapod robot. The results were quite similar to the results observed in simulation. The robot is capable of movement using different gaits. The controller is in the Figure 4. Each leg had its own controller, which operates in following manner: Normally, the foot motor neuron is active (supporting the robot body). When the command neuron excites the foot motor neuron, the leg is moved backward (stance phase). Periodically, the pacemaker neuron interrupts the stance phase and excites the forward swing motor neuron (swing phase). The frequency of pacemaker bursts and the velocity output of the backward swing motor neuron depend on the level of excitation provided by command neuron. Additionally, sensors can reset the pacemaker neuron. Adjacent pacemakers mutualy inhibit one another to ensure, that adjacent legs will not swing at the same time.

Chiel et al. [11] discuss the robustness of the controller based on the used gait. The robot was capable of stable movement at slow, medium and fast gaits with disconnected forward or backward angle sensor of any leg. Also removing the connections between pacemaker neurons did not prevent the robot from walking stably at any speed. Finally, after disabling the lift motor of the middle leg and retracting the leg so it does not supported anu load, the robot was capable of stable walk at the slower gaits, but the robot was unable to walk using the fastest gait, because the tripod gait requires the middle leg. If the leg was disabled, but it was allowed to contact with the ground, the robot turned toward the side with the disabled leg.

Suitable inspiration for the design of the controller is the movement of animals. Beer et al. [12] discuss bio-inspired robots and controllers. They point out, that distributed controllers are more suitable for locomotion generation than controllers with one centralized system. This is similar to the insect approach. Espenschied and Quinn [13] describe a bio-inspired hexapod robot. Its controller was firstly developed in simulated environment and then applied to real hexapod

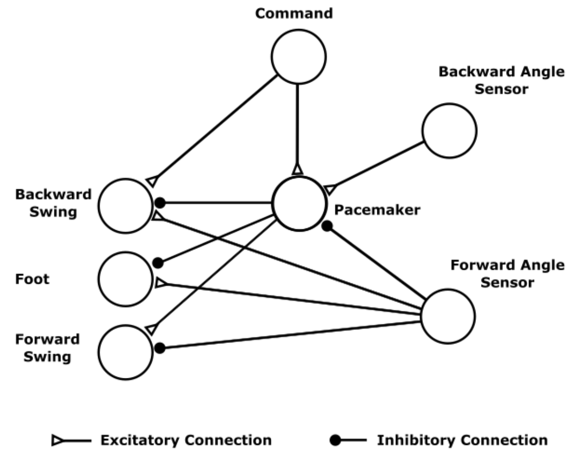


Figure 4. The leg controller. Each leg is controlled by three motor neurons, which are driven by the pacemaker neuron whose output rhythmically oscillates. A single command neuron makes the same two connections on every leg controller. The forward angle sensor can inhibit the pacemaker neuron and the backward angle sensor can excite pacemaker neuron and change its rhythm. This figure is taken from [10].

robot. This robot is more insect-like than its predecessor in the terms of leg configuration and degrees of freedom. The robot is capable of turning, walking on a rough terrain and walking quickly.

Studies of animal nervous system show that the pattern of locomotion is controlled by neural centers known as central pattern generators (CPGs), whose output is an oscillating signal with a certain frequency. These CPGs are also widely used to generate control signals for walking chassis. Ijspeert et al. [14] present a spinal cord model. They address three fundamental issues related to vertebrate locomotion: the modifications of the spinal locomotor circuits during the evolutionary transition from aquatic to terrestrial locomotion, the mechanisms necessary for coordination of legs, and the mechanisms of gait transitions. They create a CPG model, which is composed of a body CPG and a leg CPG implemented as a system of coupled nonlinear oscillators. The CPG model produces walking and swimming patterns, which are similar to the real salamander patterns. It was observed in stimulation experiments of mesencephalic locomotor region, that the model produces transition between gaits by changing the drive. The swimming and the walking movement of the robot is similar to real salamander.

Yu et al. [15] propose a novel CPG-based control architecture for hexapod walking robot. They divided the motion control into the gaits generation level and joints coordination level. The first level is implemented using CPG network in ring based on modified Van der Pol oscillator. The second level they address the problem of multi-DoF coordination of a single leg through phase order modulation and amplitude adjustment of the neural oscillators. Each leg has its own controller, which provides rhythmic signal. Six of these controller are connected and produce periodic signals with identical amplitude and frequency, but the phase difference of each controller is precisely shifted, so they produce desired gait. The gait transition can be understood as the controller has the ability to recover from the initial condition "out of phase". The authors also present the results of testing the controller on real robot.

Barron-Zambrano et al. [16] present a CPG-based controller for quadruped and hexapod walking robots, which can generate several gaits. The proposed implementation of the controller is modular and configurable so it can control legged robots with different number of degrees of freedom. The controller is implemented on an embedded Field Programmable Gate Array. A method based on genetic algorithm was used to find the parameters of CPG.

Chung et al. [17] proposed a CPG-based control strategy for hexapod walking robot. The CPG controller uses the Matsuoka's neural oscillator. Each oscillator is consisted of two neurons mutually inhibiting each other. The controller uses a inertial measurement unit to get the attitude of the body and to generate the control signals accordingly. The controller was successfully tested on real robot in irregular terrain.

The problem with CPGs is wiring the data from sensors to it. It is possible, however, it is quite complicated, because the signal from the sensor may come at any state of the step and it may not be possible to handle it. The solution is to wire the output of CPGs to another neural network, which controls and modulates the output of CPGs based on the data from the sensors. Barron-Zambrano et al. [18] modulate the output of CPG using fuzzy logic approach, which manages gait speed modulation and direction control, and finite state machine, which selects gait and manages transitions among them.

Parker and Lee [19] suggest to learn individual legs separately and then connect the individual neural networks together. At first, a small network is formed, which is able to control the movement of one leg. This network has no connection to the other legs and is able to generate pulses independently from the others legs. These individual networks are then connected in one large network, which controls whole gait generation.

B. Neural Networks Training Approaches

Standard methods, such as backpropagation, can be used to find appropriate weights of individual neurons in the network. But there are also other possibilities. Parker and Lee used genetic algorithms for learning neural networks. The network structure is created (individual neurons and their connections), and then genetic algorithms are used to create descendants, who represent the weight vectors of the individual neurons.

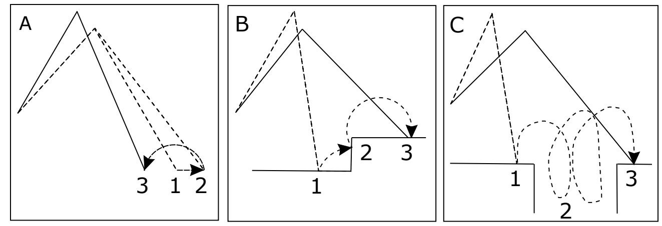


Figure 5. A) Stepping reflex. The leg can step from the position (2) to the position (3) to better support the body. B) Elevator reflex. If the leg encounters an obstacle (2), it tries to lift the leg higher to step over the obstacle. C) Searching behaviour. If the leg cannot reach ground at expected location (2), it tries to find another foothold (3). This figure is taken from [23].

Neural network prepared this way is started and it generates hundreds of control pulses for the motors. The generated pulses are then evaluated by the fitness function, which has three basic parameters. The first parameter is the forward motion, which corresponds to the movement when the leg is placed on the ground. The second parameter is the number of leg lifts. It is a penalty, because lifting leg does not move forward and needlessly consumes energy. The third parameter is the resistance, which is a penalty which occurs when a leg is set in the rearmost position and is placed on the ground. Such limb merely slows forward movement.

Also other researchers use genetic algorithms. Lewis, Fagg and Bekey in [20] describe staged evolution of a complex motor pattern generator (CPG) for movements control of a hexapod robot. The CPG is designed as a neural network. But insted of using a learning algorithm to train the neural network they used genetic algorithm to alter the interconnection weights of the neural network. The same controller is described in [21]. Parker and Rawlins [22] introduced cyclic genetic algorithms, which can be used to gait generation.

C. Inspiration in the Nature

Almost all approaches used in design and control of walking robots are inspired by the nature. It is not a coincidence, that all walking robots with four and more legs looks like some animals. The construction of their body is well formed and verified through a long evolution. But we can find inspiration not only when building a walking robot, but also when controlling it. Except of evolution methods, which are also inspired by nature, we can study, how animals solve difficult situation during their movement.

Espenschied, Quinn, Beer and Chiel [23] proposed using reflexes, which were observed in insect. When the leg moves forward, stepping, elevator and searching reflexes are used to find suitable position for the leg. See Figure 5.

The stepping reflex ensures, that the robot keeps the legs in the best positions to spare energy or to better support the body. If it is possible, the leg is moved closer to the body.

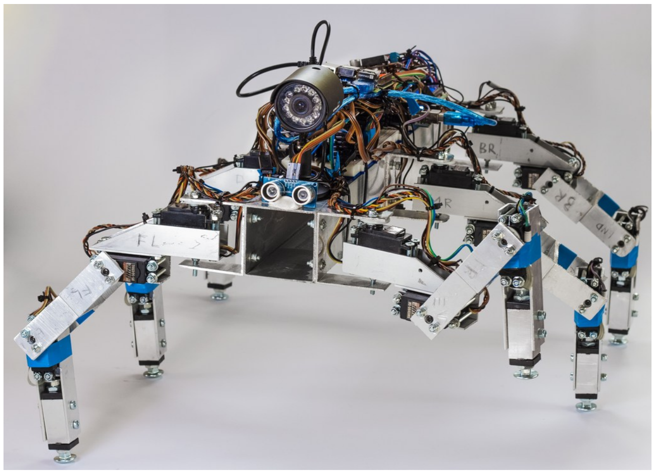


Figure 6. Hexapod robot of our design. This robot was designed and constructed during the project. It is equipped with sonars, camera, LCD display, force-sensitive resistors, encoders and more accessories. The robot is capable of movement using many gaits including tripod, wave and ripple. The robot is constructed of aluminium profiles, is powered by one Li-Po accumulator and can operate in rough terrain. Each leg is equipped with three degrees of freedom. Servomotors HS-5485HB and HS-5645MG are used to move robot legs.

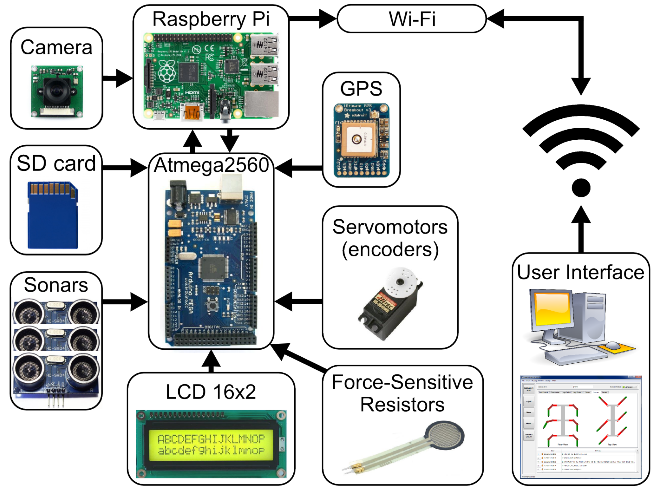


Figure 7. The electronic system of our robot. In the center is a MCU Atmega2560 integrated on a Arduino Mega 2560. Most of the sensors like sonars, LCD display, memory card, GPS module or force-sensitive resistors are connected to it. There are also 18 servomotors connected to digital pins and driven by MCU's timers. Arduino board is connected to the Raspberry Pi via USB cable. Raspberry Pi is connected to the computer via wi-fi and provides data from the sensors to the computer and commands from the computer to the Arduino. Data from the sensors are visualized in the user interface on the computer.

The elevator reflex is used when the leg is moving to new position. If the leg encounters an obstacle and cannot finish its move, it tries to lift the leg higher and step over the obstacle.

Searching reflex is used when the leg cannot reach the ground at expected location. It then tries to find another foothold to support the body and finish the step.

Ferrell [24] compares three different insect-inspired locomotion controllers – reflexive, hybrid and patterned. Each controller was tested while unloaded (walking while suspended above ground), loaded (walking on flat terrain), with lesion (loss of a leg) and with external leg perturbations.

V. Our Robot

In our future work we want to continue in the research of controlling hexapod robot using evolution techniques. Therefore we build our hexapod robot so we can test our solutions (Figure 6). Our robot is build of aluminum profiles and has 18 servomotors (each leg has 3 degrees of freedom). The servomotors are equipped with encoders and each leg has a ground sensor, which can detect obstacles or ground under the leg during step. To detect the ground we use force-sensitive resistors, which are better than tactile sensors, because the value from force-sensitive resistor can be used to distribute the weight of the robot to all legs equally.

The robot is controlled by microcontroller Atmega2560 [25] and Raspberry Pi board, model B+ [26], which provides enough computing power to run more complicated calculations. The robot is also equipped with ultrasonic sonars to detect obstacles, LCD display, which displays basic information about the robot, SD card, GPS module and camera. The scheme is in Figure 7.

We also developed a user interface program (UI), which allows to control the robot and visualizes actual positions of the legs and data from sensors. Up to ten robots can connect to the UI and user can switch among them to see data from sensors and to control the selected robot. The UI has a tool to generate custom gaits, which can be simulated within the UI or directly on the robot. The UI includes a console which can be used to send commands directly to the robot MCU.

The robot is capable of movement in rough terrain and can use common gaits. Unlike commercial versions of walking robots, which can be purchased, this robot has more sensors and can be easily extended. More information about our robot and some videos can be found at http://hexapod.marekzak.cz.

VI. Conclusion

This paper dealt with overview of several controllers for hexapod robots designed using evolution techniques, such as neural network or genetic algorithms. New researches show, that central pattern generators are very suitable to generate control signals for legged robots. We have placed several characteristics of legged robot and their most common gaits. We also mentioned several existing walking robots and we introduced a hexapod robot of our design.

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