Synchronization within Independent Neural Modules Controlling a Simulated Hexapod Robot

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Abstract

In this paper we illustrate a system consisting of a collection of identical neural modules, that communicate by exchanging signals, that control a simulated hexapod robot with twelve DOF. The evolved neural controllers display an ability to generalize their ability to different environmental and body conditions. Synchronization and phase differentiation between joints and legs is achieved through simple acceleration/deceleration mechanisms based on local interactions.

1. Introduction

Synchronization, i.e. coordination with respect to time, is a phenomenon of interest to disciplines ranging from astrophysics (e.g. celestial mechanics) to laser physics, and from biology and neuroscience to communication (Strogatz, 2003). In most of the cases, syncronization can be characterized as a self-organizing process, i.e. as a property at the global level of the system that results from local interactions among lower-level components (Camazine et al. 2001, Strogatz, 2003).

In living beings, syncronization processes occur both at the level of the individual (as a result of the interaction between elements that constitute the individual) and at the level of group of individuals (as a result of the interaction between individuals). Examples of the former category include the syncronization between the pacemaker heart cells, and that between the nerve cells generating locomotion (Glass, 2001). Examples of the latter category include syncronized flashing in fireflys and syncronized foraging activities in ants (Camazine et al, 2001).

In this paper we investigate how syncronization processes might be exploited in design of artificial agents (robots). More specifically, we investigated how six independent neural modules that control the six corresponding legs of an hexapod robot with twelve degrees of freedom can coordinate in time so to allow the robot to walk effectively.

Rather than following a bio-mimetic approach (i.e. observing a specific natural organism exhibiting the target behaviour, identifying the crucial elements and the rules that govern their interactions, and reproduce the elements and the interaction rules in an artificial system as accurately as possible - Cruse et al, 2002; Calvitti & Beer, 2000) we used on an automatic process based on artificial evolution (Nolfi and Floreano, 2000). The number of characteristics of the system that are hand-crafted is reduced as much as possible, and the rules that govern the behaviour of the six independent neural modules and their interaction are left free to self-organized during the evolutionary process (for related approaches, see Gallagher et al., 1996; Ijspeert and Cabelguen, 2003).

2. The experimental setup

In this section we describe the simulated hexapod robot used in the experiments, its control system, and the evolutionary algorithm used to set the free parameters of the robot's control system

2.1 The hexapod robot

The simulated robot (Figure 1) consists of a main body (with a length of 20 cm, a width of 4 cm, and a height of 1.5 cm) and 6 legs.

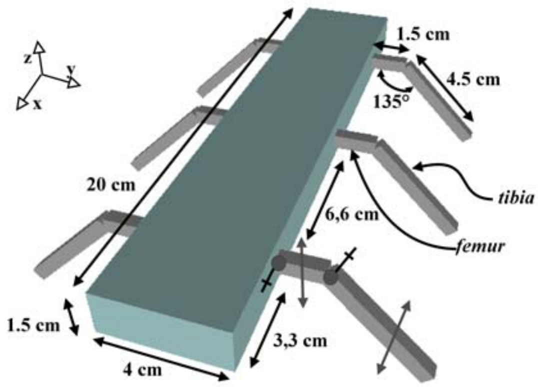

Figure 1. The simulated hexapod robot. The grey circles on the leg shown on the bottom-right side of the picture indicate the position of the joints. The two grey arrows indicate the rotational axis of the corresponding joints.

Each leg consists of two segments (a "femur" and a "tibia" with a length of 1.5 and 4 cm respectively) and has two motors controlling two corresponding joints (the body-femur and the femur-tibia joints). The femur and the body-femur joint allow the robot to raise its central body from the ground and to move the tibia up and down. The body-femur joint is a motorized hinge joint with rotational axis parallel to the x-axis that can rotate from - $\pi/16$ to + $\pi/16$ rad. The femur-tibia joint allows it to move the tibia forward or backward. It is a motorized hinge joint that rotates from - π/8 to + π/8 rad with respect to its own axis (i.e. an axis rotated of π/4 rad with respect to yz-plane). The motors controlling the joints can apply a maximum torque of 0.03*Nm* at maximum speed of 3100 rpm in both directions. For each leg, two simulated position sensors detect the current angular position of the corresponding joint. The total weight of the simulated robot is 387g. Gravity force is –9.8 m/sec^2. The environment consists of a flat surface. The robot and the robot/environment interaction was simulated by using the VortexTM toolkit (Critical Mass Labs, Canada), that allows to realistically simulate the dynamics and collisions of rigid bodies in 3D.

2.2 The control system

To robot is controlled by a distributed control system consisting of six independent neural modules, located at the junction between the main body and the legs, that control the six corresponding legs (see Figure 2). The six neural modules are identical (i.e. have the same architecture and the same free parameters) have access to local sensory information only. More specifically, each neural module has access to the current angular position and controls the frequency of oscillation of the two joints of the corresponding leg. Neural modules communicate between themselves by producing signals and by detecting the signals produced by other neural controllers located within a given Euclidean distance. Signals thus are analogous to gaseous neurotransmitters such us nitric oxide that are released by neurons and affect other neurons located nearby in a diffuse manner (see Elphick et al., 1995, 1996; Husbands *et al.* 2001).

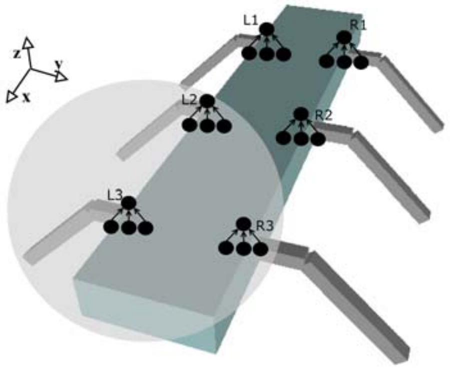

Figure 2. The robot and its control system consisting of 6 neural modules. L1, L2, and L3 indicate the front, middle, and rear leg located on the left side of the robot. R1, R2, and R3 indicate the front, middle, and rear leg located on the right side of the robot. The grey circle represent the range of diffusion of the signal produced by one neural module (i.e. the neural module controlling the L3 leg).

Each of the twelve motors neurons produces a sinusoidal oscillatory movement with a variable frequency of the corresponding joint, within the joint's limits. More specifically, the current desired position of a corresponding joint is computed according to the following equation:

$$pos(t) = \sin(V(t) \cdot t + \varphi) \qquad (1)$$

where pos(t) indicates the desired angular position of the joint at time t, V(t) (that ranges between 7 and 14 Hz) indicates the current frequency of the oscillator, and φ indicates the starting position of the joint. The desired position is normalized within the range of movement of the corresponding joint. Motors are activated so as to reach a speed proportional to the difference between the current and the desired position of the corresponding joint.

Each neural module has four input neurons directly connected to four output neurons (Figure 3).

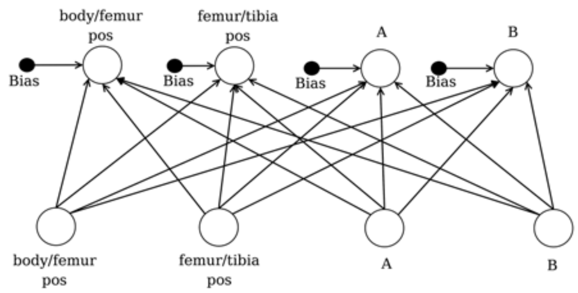

Figure 3. The topology of each neural module. The four input neurons indicated in the bottom part of the picture encode the current angular position of the two joints of a leg and signal A and B (see text). The four output neurons are indicated in the top part of the picture. The first two modulate the frequency of oscillation of the two corresponding motorized joints and the others two determine whether or not the signal A and B are produced.

The input neurons encode the current angular positions of the two joints of the corresponding leg (normalized in the range [0.0, 1.0]) and whether signals A and B, produced by other neural modules, are detected. Each neural module can produce two different signals (A and B) that diffuse and can be detected up to a certain distance (D_a and D_b, in the case of signal A and B, respectively). The intensity of the signal detected is linearly proportional to the number of neural modules that are currently producing the corresponding signal located within the corresponding maximum diffusion distance.

The activation of output neurons is computed by using a standard logistic function. The first two output neurons determine how the frequency of oscillation of the two corresponding joints varies. More specifically, each time step (i.e. each 1.5ms), the frequency of oscillation of a joint can vary within [-1.4Hz, +1.4Hz] according to the following equation:

$$V(0) = Val \qquad 7 \le Val \le 14$$

$$V(t) = V(t-1) + \begin{cases} (Out - 0.75) \cdot 1.4 & Out \ge 0.75 \\ 0 & 0.25 < Out < 0.75 \\ (Out - 0.25) \cdot 1.4 & Out \le 0.25 \end{cases} \qquad (2)$$

Where Val indicates the initial value of frequency of a joint that is randomly set within the range, Out indicates the output of the corresponding motor neuron, and V(t) indicates the current frequency, V(t-1) indicates the frequency at the previous time step. Frequency is bounded in the range [7Hz, 14Hz], i.e. variations that exceed the limits are discarded.

The other two output neurons determine whether or not signal A and B are produced. More specifically, signal A and B are produced when the output of the corresponding output neuron exceeds the corresponding threshold (T_a and T_b, in the case of signal A and B, respectively).

2.3 The evolutionary algorithm

The free parameters of the neural modules are evolved through an evolutionary algorithm. Robots were selected for the ability to walk along a straight direction as fast as possible. Each robot was allowed to "live" for 2 trials, each lasting 3000 ms (i.e. 2000 time steps of 1.5 ms). The state of the sensor and motor neurons, the torque applied to the motors, and the dynamics of robot/environment interaction are updated each time step (i.e. each 1.5 ms). At the beginning of each trial: the main body of the robot is placed at a height of 4.18 cm with respect to the ground plane. The initial position of the twelve joints and the initial desired velocity of each corresponding motor is set randomly within the corresponding range. The fitness of each robot is computed by measuring the Euclidean distance between the initial and final position of the centre of mass of the robot during each trial. The total fitness is computed by averaging the distance travelled during each trial.

The initial population consisted of 100 randomly generated genotypes that encoded the connection weights and the biases of a neural module, the maximum distance of diffusion of the two signals (D_a and D_b), and the thresholds that determine when signals are produced (T_a and T_b). Each parameter is encoded as real number. Connection weights and biases, diffusion distances of signals, and thresholds that determine signal emission are normalized within the following ranges: [-15.0, +15.0], [0.0, 10.0], [0, 1.0], respectively. Each genotype is translated into 6 identical neural modules that are embodied in the robot and evaluated as described above. The 20 best genotypes of each generation were allowed to reproduce by generating five copies each, with 3% of their genotype value replaced with a new randomly selected value (within the corresponding range). The evolutionary process lasted 300 generations (i.e. the process of testing, selecting and reproducing robots is iterated 300 times). The experiment was replicated 15 times starting from different, randomly generated, genotypes.

3. Results

By analysing the results of the evolutionary experiments we observed that evolved robots display an ability to walk effectively, in all replications of the experiment. Figure 4 shows fitness through out generations.

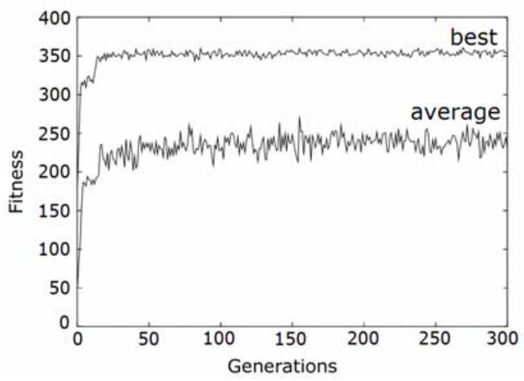

Figure 4. Fitness (i.e. average distance in cm travelled during two trials) of evolving individuals through out generations in a typical replication of the experiment. The curves indicate the fitness of the best individual of each generation and the average performance of the population through out generations.

By visually inspecting the evolved walking strategy we observed how, in all replications, evolved robots display an ability to quickly coordinate the phases and the frequency of oscillation of their twelve motorized joints by converging toward a tripod gait, a type of gait used by all fast moving insects, independently from the initial position of the joints (see Figure 5, 6, and 7).

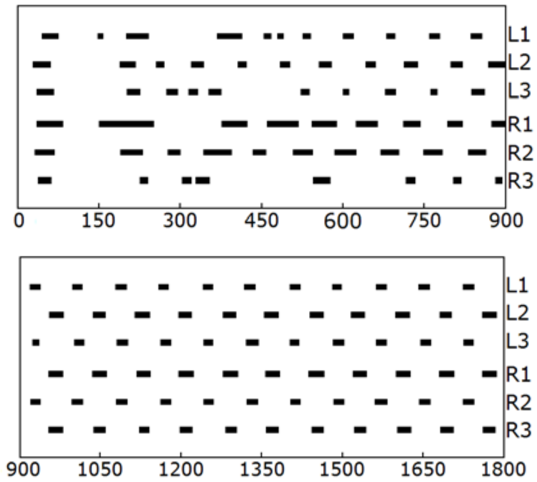

Figure 5. A typical behaviour exhibited by an evolved robot during a trial. At the beginning of the trial the position of the joints and frequency of oscillation are randomly initialised within limits. The black lines indicate the phases in which the tibia of the corresponding leg touch the ground. Legs are labelled with L for left and R for right and numbered from 1 to 3 starting from the front of the insect. The horizontal axis indicates time in millisecond.

The analysis of the evolved robots indicates that after an initial coordination phase (that last about 1000 ms, on the average):

- the 12 joints converge on the same average frequency,
- the body-femur and femur-tibia joints of each leg coordinate so that the tibia touches the ground during retraction movements (in which the tibia moves to-

ward the rear of the body) and do not touch the ground during protraction movement (in which the tibia move toward the front of the body), see Figure 6 and 7.
- the two groups of legs (L1, L3 and R2) and (L2, R1, R3) are in phase within the group and in anti-phase between groups, see Figure 5, 6 and 7.

Once the twelve joints coordinate, they tend to keep the same frequency of oscillation (on the average, over a time span of 100 ms) but also slightly accelerate or decelerate, with respect to each other, to compensate for misalignments arising during motion.

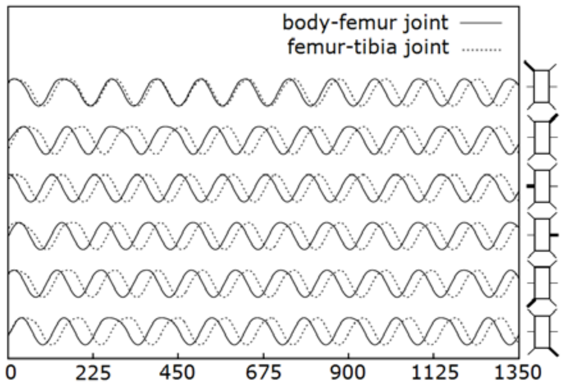

Figure 6. Desired angular position of the twelve joints during the same trial shown in Figure 5. Each line indicates the position of the joints of the leg indicated with a dark line in the right part of the Figure. Full lines and dotted lines indicate the position of the body-femur and femur-tibia joints, respectively. High values indicate positions in which the femur is elevated with respect to the main body and positions in which the tibia is oriented toward the front of the robot.

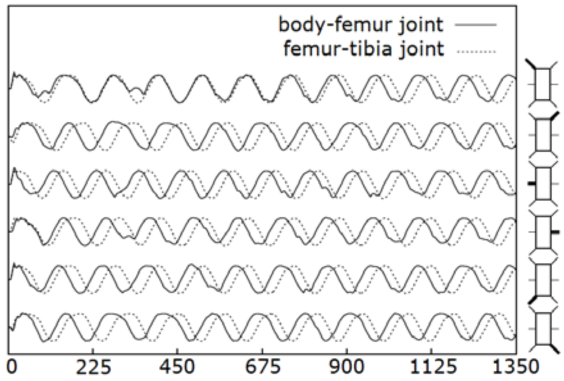

Figure 7. Current angular position of the twelve joints during the same trial shown in Figure 5 and 6. Each line indicates the position of the joints of the leg indicated with a dark line in the right part of the Figure. Full lines and dotted lines indicate the position of the body-femur and femur-tibia joints, respectively. High values indicate positions in which the femur is elevated with respect to the main body and positions in which the tibia is oriented toward the front of the robot.

The dynamical behaviour produced by the walking robots does not only result from the interaction between the six neural modules that control the six corresponding leg but also from the dynamics originating from the interaction between the robot body and the environment. Indeed, the way in which the actual position of the joints vary in time (Figure 7) is influenced not only from the variation of the desired joint position (Figure 6) but also from the forces arising from the collision between the legs and the ground. These forces are influenced by several factors such us the actual orientation of the robot with respect to the ground, the current velocity of the robot, the characteristics of the ground, etc. As shown in the figures, the effects of the robot/environment physical interaction are much more significant during the initial phase in which the legs are not yet coordinated.

4. Analysis of the mechanisms that lead to legs' coordination

To understand the mechanisms that lead to the synchronization of the twelve joints, we analysed the interaction occurring within each neural module and between different neural modules (i.e. the conditions in which signals are produced and the effects of signals detected). Here we report the analysis conducted in the case of the evolved individuals already described in Figure 5-7.

As could be expected, the synchronization between the two joints of each leg is achieved within each single neural controller. More specifically: (a) the body-femur joint decelerates when it is elevated and the tibia is oriented toward the rear (Figure 8, top-left picture), and (b) the femur-tibia joint decelerate when the body-femur joint is elevated and the tibia is oriented toward the front of the robot (Figure 8, bottom-left picture). The combination of these two mechanisms leads to a stable state, that correspond to the synchronized phase, in which the protraction movement of the tibia is performed when the body-femur joint is elevated the retraction movement is performed when the body-femur joint is lowered.

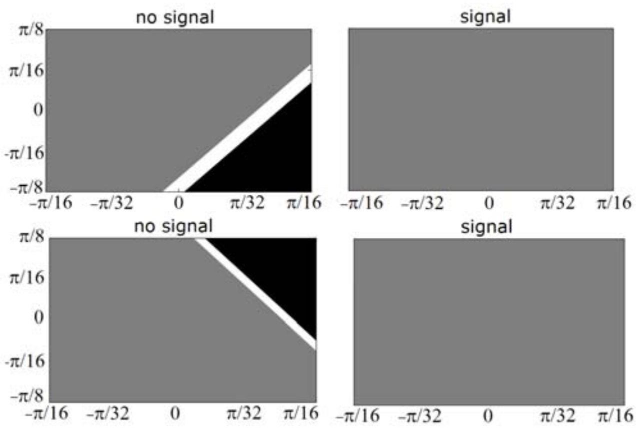

Figure 8. Conditions in which joints accelerate (grey area), decelerate (black area) or maintain the the same frequencey (white area), as a function of the current joint positions and of whether the neural module detects signal A or not. The vertical and horizontal axes indicate the femur-tibia and body-femur joints, respectively. Top: acceleration/deceleration effects on the body-femur joint. Bottom: acceleration/deceleration effects on

the femur-tibia joint. Left: effects when signals are not detected. Right: effect when 1,2, or 3 signals are detected.

Although neural modules can produce and detect up to two different signals (i.e. signal A and B), this individual only produces one of the two signal: signal A. By analysing the signals used during the course of the evolutionary process we observed that, in all replications of the experiment, evolving robots use both signals during the first evolutionary phases. However, after 150 generations, robots use one signal only. Since the maximum distance of diffusion of signals A is 7.12 cm (in the case of the individual shown in Figure 5-7), the signal produced by each leg affects the contra-lateral leg of the same segment and the previous and succeeding leg of the same segment (when present). This means that the signal produced by a leg of one group ([L1,L3,R2] or [R1,R3,L2]) affects only the legs of the other group that should be in anti-phase in a tripod gait. The legs that are affected by a signal are 2 out of 3 legs in the case of legs [L1,L3,R1,R3] and 3 out of 3 legs in the case of legs [L2,R2].

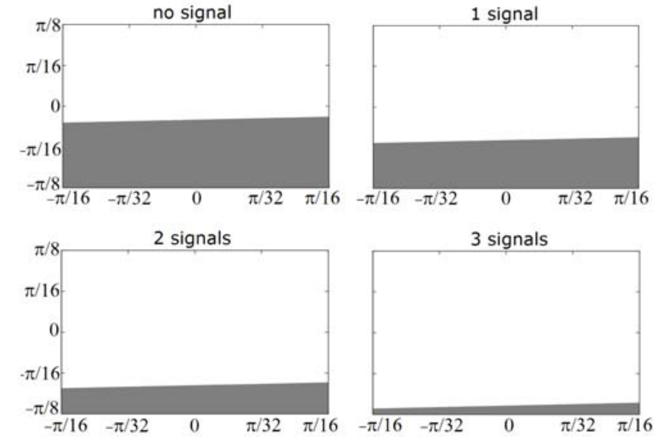

Figure 9. Conditions in which the signal A is produced (grey areas) as a function of the current current joint position and of the number of detected signals. The vertical and horizontal axes indicate the femur-tibia and body-femur joints, respectively. The four pictures indicate whether the neural module detects 0, 1, 2, or 3 signals produced by other neural modules.

To explain how the six legs coordinate we should explain why uncoordinated states are unstable and lead to coordinated phases (through relative acceleration/deceleration of the joints) and why coordinated state are stable.

The latter aspect can be explained by considering that when legs belonging to the two groups are in phase within the group and in anti-phase between groups. The effect of the signals produced by the leg of the two groups does not produce a relative acceleration/deceleration of the legs of the two groups.

A leg produces a signal when its tibia is oriented toward the rear (Figure 9). This implies that, when the legs of the two groups are in anti-phase, signals are produced in an alternate way from the two groups. This signal produce by the leg of the first group accelerate the joints of the legs of the second group (i.e. it prevents the deceleration that occurs when the signal is not detected, see Figure 8). However, the legs of the second group later produce a signal that accelerate the legs of the first group, so that the original relative frequency is restored.

To explain the former aspect (i.e. why uncoordinated phases are instable) let us consider the case in which, when the leg of the first group completed their retraction movement, the legs of the second group did not completed their protraction movement yet. Since signals are produced by the leg that have their tibia oriented toward the rear (see Figure 9) and produce an acceleration only on legs that have their tibia oriented toward the front (see Figure 8) the acceleration effect produced by the legs of the first group on the legs of the second group is lower than in synchronised conditions. This lack of deceleration of the legs of the second group increase their delay with respect to the leg of the first group. This implies that, the signals produced by the legs of the second group later on produce a larger lack of deceleration on the legs of the first group. This asymmetrical effect reduces the amount of de-synchronization between the two groups, until a synchronized state is reached.

Finally, the instability of the cases in which, the legs of the two groups are erroneously in phase or almost in phase can be explained by considering the effects of the signal produced by one group of legs on the body-femur joints of the other group of legs (see Figure 8).

The way in which the legs of one group tend to synchronize and phase within the group is an indirect effect of the processes that lead to synchronization and anti-phase between groups, described above.

5. Generalization

By testing the evolved neural controllers in new conditions we observed how they generalize their ability to produce an effective walking behaviour to new environmental and body conditions.

Evolved robots display an ability to coordinate by exhibiting a tripod gait and to effectively walk also when tested on uneven terrains (see Figure 10) or on inclined surfaces. The average speed of the robot after the initial coordination phase in these test conditions decreases of about 35% and 15%, in the case of the rough terrain and in the case of an inclined surface with a slope of +15°, and increases of about 15%, in the case of an inclined surface with a slope of -15°.

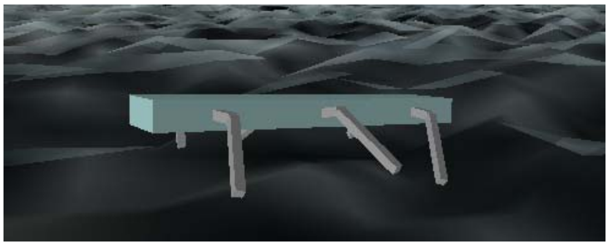

Figure 10. A robot evolved on a flat terrain tested on a rough terrain (i.e. an uneven terrain with variation in height up to 5 cm).

Evolving robots also show an ability to carry additional weight. Indeed, in test conditions in which the weight of the robot is duplicated we observed that the robots are still able to coordinate and to walk. In this test condition, speed decreases of about 25%, with respect to the normal condition.

Finally, by embedding the neural controllers evolved in robots with six legs in robots with a different number of legs, we observed that robots keep an ability to coordinate on a tripod gait. Robots with a larger number of legs are able to walk at higher speed and to coordinate faster than hexapod robots. For example, a robot with 20 legs provided with 20 identical copies of the neural modules described in the previous section (see Figure 11) is able to walk with a speed that is about 10% higher and to coordinate in a time that is about 25% shorter than hexapod robots.

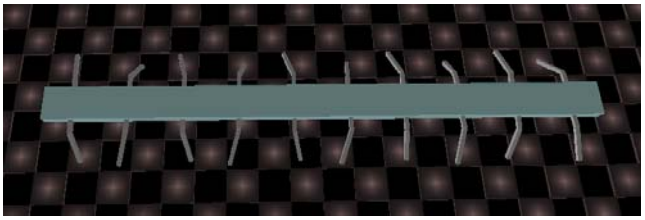

Figure 11. A robot with 20 legs and a body length of 67 cm controlled by 20 neural modules identical to that evolved in robots with 6 legs.

In future research, we plan to evolve robots in varying environmental conditions to verify whether, by being selected for their ability to cope with environmental variations, they can develop even more effective strategies.

6. Discussion

Syncronizazion is a widespread phenomena in the universe and occur in a large variety of animate and inanimate entities at different space and time scales. This generality can be explained by considering the inevitability of syncronization (Strogatz, 2003) providing that two simple conditions are met: syncronizing elements spontaneously exhibit an oscillatory behaviour with a given intrinsic frequency, and each oscillatory element appropriately increases or decreases its frequency of oscillation on the basis of the output of the other elements (that provide an indication of their actual phase) and of its own phase. When the differences between the intrinsic frequency of oscillation of the elements do not overcome a given threshold, sincronization will always occur, independently from the initial condition of the system and of the number of interacting elements (Strogatz, 2003).

In this paper we demonstrated how an automatic process based on artificial evolution can develop the rules that determine: (a) the output of oscillatory elements, and (b) how frequency of oscillation of a given element is affected by the output of other elements.

Moreover, we demonstrated how, by leaving the system free to determine the range of interaction and whether the interaction is local or global, the system converges towards a local interaction modality. This local interaction form combined with the fact that oscillatory elements are located in space with a given spatial configuration, allow the system to produce both a syncronization of the oscillatory elements and a differentiation of the phases of oscillation of the different elements. This phase differentiation, in turn, allows the system to produce a tripod gait, i.e. a coordinated movement in which contra-lateral legs of the same segment alternate in phase.

Further research might investigate whether this surprising result can be generalized to other problems and domains and whether distributed system consisting of collection of homogeneous elements located in space and interacting locally can produce complex coordinated behaviour in which individual elements or group of elements play different complementary roles.

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