Robo-Salamander – an approach for the benefit of both robotics and biology

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ABSTRACT

Even if the character of robotics is primarily technological, it was always closely connected with biology right from the beginning. However, most of the time this was only a one-way relationship, for biological insights were often used as a pool of approved ideas and methods to find solutions for rudimentary problems in robotics (walking machines in particular) with little in return. In contrast to this general habit, our project “Robo-Salamander” started with the attempt to gather evidence for the answer to an old query in biology from a technical point of view – the first step in the evolution of vertebrate walking. We found a simple principle which indeed helps to understand the locomotion of the first tetrapodes (that can still be observed today by watching salamanders and certain lizards), and its continuous development into more existing walking schemes. By transferring this quite simple idea to a first prototype robot, we could also find its interesting technological advantages referring to movability, efficiency, flexibility, robustness and redundancy of walking machines and their capability to cope with rough and demanding environments. These characteristics were very useful for testing our latest learning algorithms based on a combination of reinforcement learning and neural networks with very promising results. Furthermore they turned out to be the ideal tool for our research on evolving neural networks as controllers for complex walking machines by using incremental evolution. For the Robo-Salamander combines at least two independent, different complex methods of locomotion, it allows to evolve controlling networks stepwise beginning by few actuators and sensors with simple movements and rising up to the final complex robot with many degrees of freedom. Although the idea of using incremental evolution for handling high complexities is not new, it is still not completely known how previously gained functionalities of a network can be preserved while adding new actuators, sensors or even neurons in the next steps. This paper firstly discusses the properties of the Robo-Salamander that make it the ideal platform for our research on solving these problems and secondly shows the first results.

1 INTRODUCTION

The search for the origin of vertebrate walking in order to understand its basic principles and evolutionary development leads to a missing link in the early history of evolution [Fig.1a]. About 370 million years ago, one of the most important conquests in the evolution of life on earth happened - the first step by vertebrates from water to land. Although this demanded many substantial adaptations to master a completely different habitat, the evolution from fish to the first tetrapodes on land appears to have occurred in a relatively short amount of time for biologists still have not found any fossils that would fill the gap. Mainly two opposed hypotheses are in discussion (more details in [1, 2]). Some state that rudimentary limbs together with supporting hips and shoulders must have been developed in the water before a reasonable movement on land was possible [Fig.1b]. However, the question is why these changes that are specific for carrying the bodyweight on land should have taken place in the water? Others assume that species of lobe-finned fish were very well capable of leaving the water on their fins – good enough to flee from predators and tap new food resources [Fig.1c].

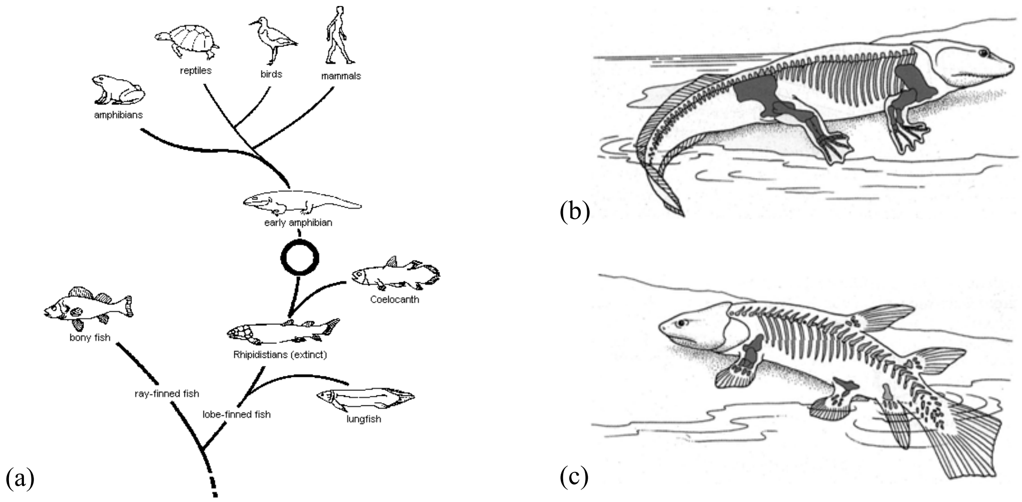


Fig. 1: There still is a missing link between fish and the first amphibians (a). The two mainly discussed scenarios are shown in (b) and (c) [3].

Conquering the land on fins would have made a very fast evolution to amphibian tetrapodes quite imaginable, which would explain the difficulties in finding the missing link. But is this really possible? How can a swimming movement be turned into rudimentary walking? There is some evidence for both theories but no reliable proof.

While biologists find more and more clues by studying the conditions of the Devonian world looking for possible reasons for adaptations in both theories [4], a technical survey can indicate the mechanical aspects that are necessary for such a big step in respect to a further continuous progression. That is where robotics has another opportunity to come to the aid of biology instead of just using its insights to solve own problems concerning walking machines most of the time. So the questions now are: "What are the mechanical constraints for a fish that tries to move on land?" "What are the basic technical principles of tetrapode movements – how can they be continuously extrapolated out of swimming and what muscular strengths are needed to perform them?" Answering these questions would add strong evidence to the existing speculations and could hopefully increase the understanding of all the different types of walking to the benefit of both biology and robotics. In the following we will discuss the details of tetrapode locomotion and its technical implementation as a basis for our research.

2 LOCOMOTION OF EARLY TETRAPODES

2.1 The Morphological Background

The first step in understanding locomotion is analysing the very system that makes it happen – the musculature. From what is known of the earliest amphibians their general body structure persists almost unchanged in the family of salamanders [2, 4]. One look on the musculature of salamanders (in Fig.2a) makes the important point become quite obvious.

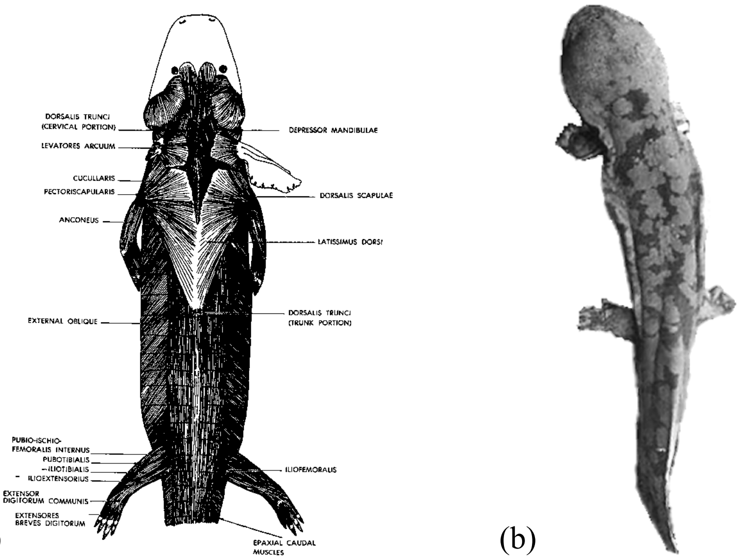


Fig.2 Muscle configuration of a typical salamander [5]. The giant salamander (b) (Andrias) is considered to be most similar to the first amphibians.

Even though the legs of a salamander are supported by bones, hips and shoulders, they still are too weak, too small and too far apart from each other to play the dominant role in its locomotion [4]. Similar to a fish, most of the muscles are still concentrated along the spinal chord allowing powerful bending movements. The best living example for this concept is the giant salamander [Fig.2b], a “living fossil” that is considered to be the closest and most similar existing relative to the first tetrapodes. Despite its very low leg/body-ratio, a length of more than 1 meter and 25-30+ kg of weight it is still able to flee quite fast and even climb vertical walls higher than itself.

2.2 The Basic Principle

So it is obvious that the lateral bending of the whole body appearing in walking patterns of many amphibians and reptiles is not just an aquatic heritage to retain swimming abilities but a very effective way to walk and climb on relatively weak limbs.

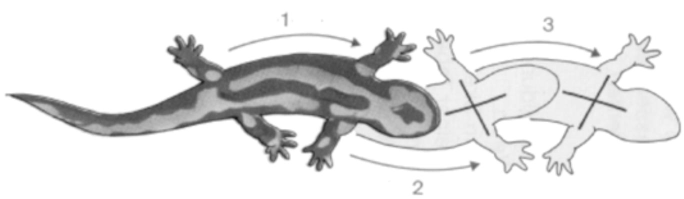


Fig.3 Walking pattern of a salamander [6].

By bending the back to one side, two diagonally opposite lifted limbs are pushed forward at the same time without moving them individually. The outstretched limbs, instead of lifting and pushing the body, only have to be flexible enough to find a good grip on uneven grounds and strong enough to allow the powerful muscles in the back can pulling the body forward and pushing the two other limbs to the front during the next bend to the other side [Fig.3]. So the step width of this fast 2-cycle locomotion is primarily defined by the length and the width of the body between the limbs. These are the reasons why digits are much more important than strong limbs. Interestingly, there is evidence that digit-like fin-extensions were developed prior to the first legs (probably to stand against strong currents) [2].

3 LATERAL BENDING IN ROBOTICS

3.1 Transferring the Principle

By realising this quite simple bending principle with robots it is not only possible to build primitive but robust and easy controllable 4-legged crawlers with just two motors: one for the lateral bending, the other for a longitudinal rotation, guaranteeing that only two opposing legs (fixed extensions) are on the ground at the same time [Fig.4] (for satisfying maneuverability a second lateral motor is recommended).

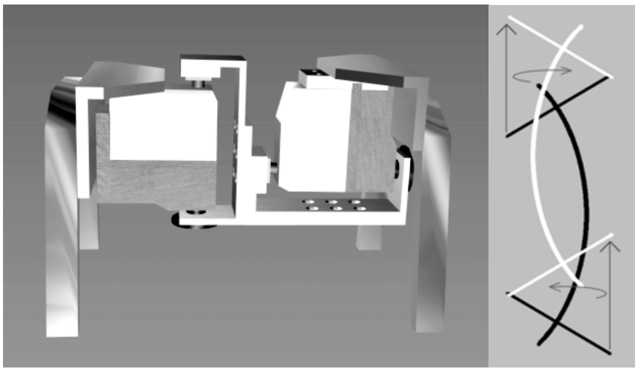
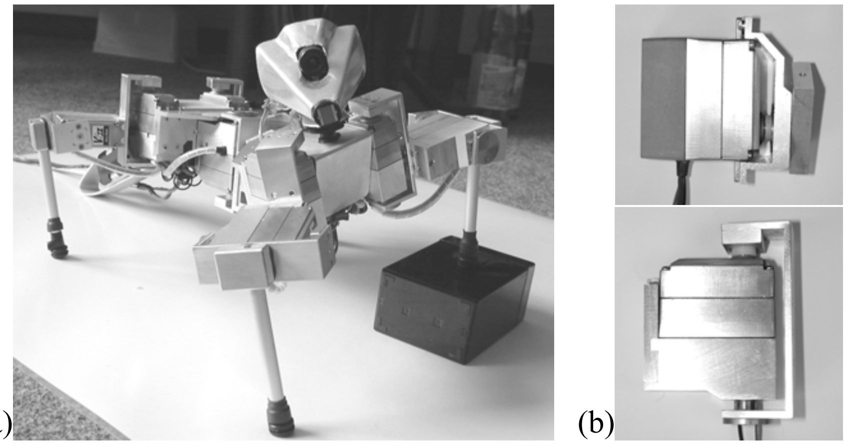


Fig.4 The simplest realisation of the bending principle.

These two motors rather are an ideal core element that can gradually be extended to far more complex walking machines for serious research in many different ways.
The first prototype of the Robo-Salamander project was built on such a core with two strong middle motors and two additional motors for each leg [Fig5a].



(a) (b)

Fig.5 The first prototype of the Robo-Salamander robot (a), constructed with the joint-modules of the AIS-Walking-Robot-Kit (b)

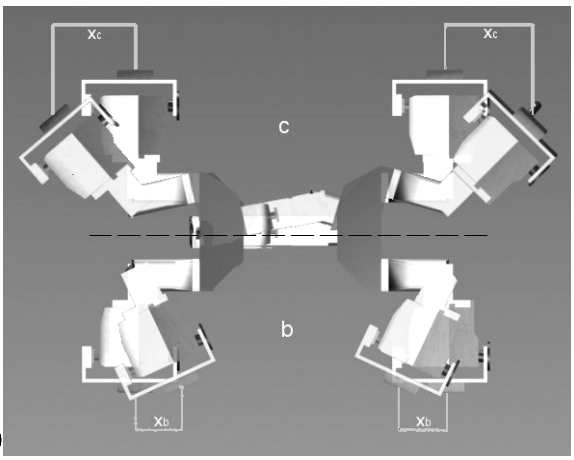
It was constructed using the AIS-Walking-Robot-Kit [W1]- a set of easy combinable joint-modules, based on servo motors of various strengths [Fig5b], as well as different electronic and sensory components developed to support a quick and reliable realisation of many walking robot designs for education and research.

3.2 Advantages
The first experiments with the Robo-Salamander fully verified our expectations concerning the advantages of the combination of common concepts with the salamander movement:

1. *redundancy & flexibility:*
   The implementation of the bending and rotation movement provides two generally independent locomotion styles. Dependent on the situation, it is now possible to use either the salamander style or a common leg-style separately, or it is possible to combine them freely. Thus the robot is able to adapt and optimise its movements to different environments and energy consumption constraints and has the ability to compensate weaknesses or even complete failures of motors.

2. *distribution of strength:*
   When it comes to serious climbing and walking the weight/payload-ratio of each leg becomes quite important. It is always a problem to find a good compromise between the speed, the strength and a preferably low weight of the legs so that high obstacles and difficult terrains are still manageable. The salamander approach offers to use very strong motors in the centre of the robot to let the legs be weaker and lighter, for the centre can support the lifting and pushing efforts of each leg in charge in every move. So the legs can be cheaper, faster and longer as long as they are able to hold their position. In our experiments, the motors are able to hold over 2 times more than they can lift. Soon we will offer motors with special self-locking gears that are blocking automatically each time external forces are too high or the energy is cut off. So they will hold much more without damaging the motors while consuming less energy.

3. *increase of range:*
   Very useful is the increase of the operating range of each leg. Bending the centre adds a considerable amount to the individual movements of the legs. Hence the total step width of the robot as well as its speed is increased [Fig.6a: scen.c with -, scen.b without bending].

(a) 

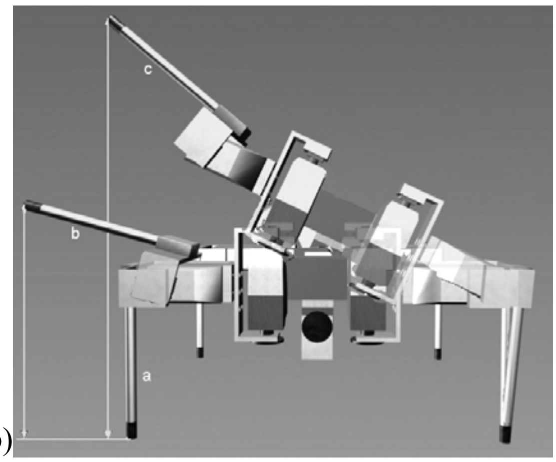
(b) 

Fig.6 The range enhancements of lateral bending (a) and longitudinal rotation (b)

So the motor gears can be optimised with respect more to strength than to speed and range. The same advantages apply for the longitudinal rotation [Fig.6b: scen.c with -, scen.b without rotation]. Additionally, the legs can reach much higher to cope with obstacles while at the same time the centre cares about actually getting over it. The effects of these abilities are of course dependent on the actual design.

4. dynamic stability:
This kind of walking is highly dynamic, as only two legs are on the ground at the same time. Even so it is not at all unstable. The worst that could happen is that it falls on a lifted leg before the normal walking cycle is completed, shortening the step width respectively. Due to the heavy centre this was never a problem with our machine and the adding of a tail reduced this possibility even further to a barely recognizable minimum.

4 A PLATFORM FOR RESEARCH

This machine surely combines many different aspects which are quite interesting for various kinds of research. Its variable degrees of freedom, redundancy and stability makes it an ideal platform for our development of general learning algorithms for autonomous robots, which are able to generate models of their environment as well as of themselves just by actor-sensor-correlation to be independent from the actual robot morphology in order to cope with high complexities and compensate actuator/sensor failures without cancelling their tasks [7].
On the other hand the evolutionary and biological background of the Robo-Salamander offers a perfect opportunity for a different discipline of Artificial Intelligence. Evolutionary algorithms have proven to be very powerful in developing neural controllers for robots, but their ability to find solutions in reasonable time descents quite rapidly with the complexity of the problem. The common answer to deal with it is the idea of “incremental evolution” where a controlling network is evolved beginning with a simple machine going stepwise up to the final more complex one. While this sounds like a promising and biologically well supported idea, it is still not completely clear how to preserve the functionality of such a network after step wise adding new actuators, new sensors and, of course, new neurons to the system. How should the new elements be connected to the network? How can it improve its complexity based on its already gained abilities? The Robo-Salamander, with its at least two different locomotion styles that are in general independent but are much more effective when they are combined, is the perfect platform to find answers to these questions.
In our previous work we already used the ENS^3-algorithm [8, 9] to evolve neurocontrollers and introduced methods to develop the modular structure of controllers adapting to higher complexities [W2].
Some of the interesting aspects of evolving controlling networks for salamander-like locomotion in one shot were introduced by A.J. Ijspeert and his group at USC. He presented controlling networks that allowed a simulated salamander to perform the transition from land into water by continuously adapting the motion patterns to the new habitat, though without using the lateral bending principle on the land [10]. Achieving comparable results with incrementally evolved, hierarchical structured modules will be the next goal of our research.
However, the first step to start our investigations was to evolve controllers for the basic core of the Robo-Salamander. The simple movements of the two centre motors demand a controller that is just able to generate two sinusoidal motor signals with a convenient phase shift to move straight forward. Applying a phototropic task giving the robot a limited amount of time to reach a single light source, we were looking for the minimal neural controller

solving it. We used an implementation of the ENS[3]-algorithm [8] applying no-biased, additive sigmoidal neurons. As basic fitness function we used the remaining distance to the light source at the end of a period.

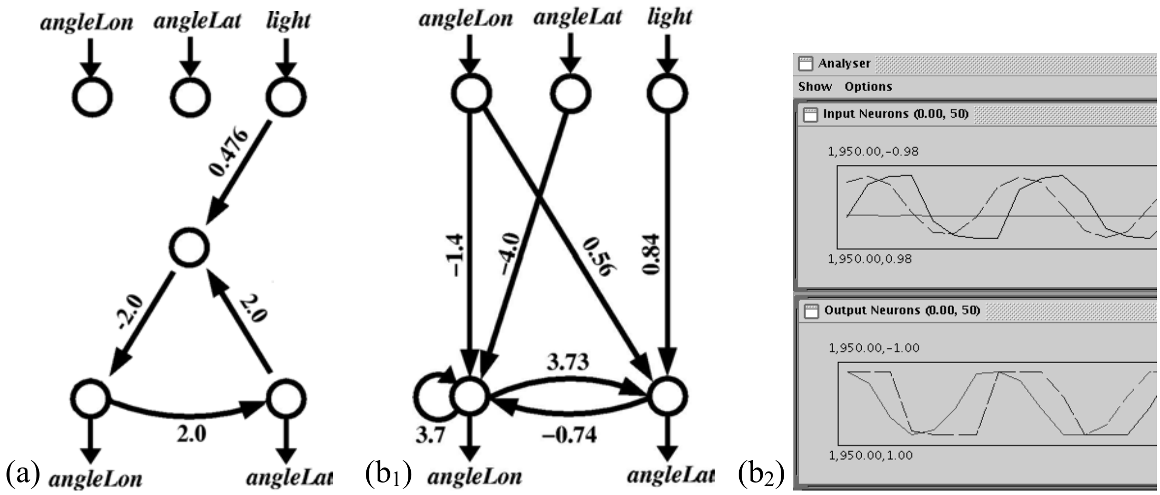


Fig.7 Evolved networks for the centre motors of the salamander (phototropic task): a simple oscillator module (a) with the proper phase shift to move forward and a more advanced one (b_1) with a smoother, more adaptive walking pattern (b_2).

We found a simple network [Fig.7a] that offered the minimal structure with one oscillator to produce proper signals, yet without the ability to stop and too unsteady signals which stressed the machine very hard. By punishing hard ground contacts in the fitness function, we obtained more complex networks like the one shown in [Fig.7b_{12}] which were able to consider the real motor latencies and transition times to generate much smoother movements.
In the next phase we will enable the control of the remaining 8 motors hoping to evolve additional modules which are able to control the legs properly in both possible walking patterns triggered by the centre module and environmental demands.

5 CONCLUSION & OUTLOOK

In this paper we introduced the biological and technical background as well as the promising advantages of the idea to use the salamander like locomotion in robots for actual research on Artificial Intelligence. On the other hand we now have the platform that will also allow us to start our biological research in respect to mechanical constraints, energy consumption, neuronal locomotion pattern generation and the transition between different walking schemes to gain a better understanding of the process behind the evolution of walking. In our further work we will concentrate on increasing the complexity of the Robo-Salamander and exploring proper incremental evolution methods respectively. We will also add learning capabilities to these modules in order to gain more flexibility and adaptivenes and, by comparing them to real salamanders, hopefully get a better understanding of the dynamics and structure of biological systems.
The next step of increasing the complexity of the robot will be the adding of shoulder-joints to each leg allowing it to reconfigure its legs in such ways that studying and using locomotion styles similar to those of dogs and horses become possible.

Last but not least there is the hope that due to its not compromised basic movement the Robo-Salamander will still be able to swim. Developing learning algorithms and controlling neural networks of a real amphibian robot is a highly interesting perspective especially when it is possible to understand real biological systems at the same time.

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[W1] Walking-Robot-Kit: http://ais.gmd.de/~breitha/projects/RoboKit/RoboKit.html

[W2] Evolution of Neurocontrollers: http://www.ais.fraunhofer.de/INDY/research.html