Towards Robotic Self-repair by means of Neuronal Remodelling

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Abstract

Adaptivity in mobile robotic systems is recognized as a difficult issue. In the invertebrate world several species are known to have remarkable adaptive behaviour triggered by environmental changes. The adaptivity is the result of remodelling their brain according to environmental needs. In this conceptual paper we propose a methodology to obtain true adaptivity in robotic systems based on neuronal remodelling in insects. Contrasting other AI related research in the field of robotics, we will use complex neuronal structures instead of standard artificial neurons. We propose three research tracks and our results from the first track are presented and discussed.

1 Introduction

Adaptivity is acknowledged to be a core problem in mobile robotics by the AI research community (Matarić, 1998). Adaptivity in this domain is the ability of a robot to adapt itself to changes in the environment. These changes are either caused by factors in the environment itself, by external factors or by a sudden malfunctioning of the robot which causes it to have a noisy perception. In this paper we solely focus on the adaptation of the robot to environmental changes induced by malfunctioning which is generally referred to as *self-repair*. An example clarifies what is meant. Suppose that a sensor breaks down or fails. Sensor failure results in perception of corrupted information and from the point of view of the robot the environment is now changed. Evidentially, not only sensing failures affect the robot's behaviour but also other kinds of failure such as a partially blocked locomotion system. Since all mobile robots possess a certain level of autonomy self-repair is an important and challenging research area.

In the past decade several solutions have been proposed for the problem of self-repair. Roughly speaking, the proposed solutions are either hardware-repair (*hard-repair*) or software repair (*soft-repair*). Soft-repair is an instance of robotic self-repair in which the control system (e.g., neural network) has the task to repair the behaviour of the robot. An example of hard-repair (also called self-reconfiguration) is the HYDRA project (Østergaard et al., 2005). In this paper we only focus on soft-repair. An exhaustive listing of proposed solutions for soft-repair is beyond the scope of this paper, however, we wish to present some ideas from the community. A popular methodology is evolutionary computation (EC) (Koza, 1992) in combination with artificial neural networks (ANN) (Nolfi and Parisi, 1997; Nolfi, 2002). In this approach parameters of a neural robot controller are tuned in a way similar to Darwinian evolution. The *artificial evolution* of robot controller is performed in real-time on real robots (Mondada et al., 1994; Nolfi and Parisi, 1997) or in simulation as in Floreano and Urzelai (2001); Torben-Nielsen et al. (2005a). Plastic Neural Network (PNN) are often proposed as solution; they no fixed weights in the neural network but rather update the weights on-line during task execution (Floreano and Urzelai, 2001). PNNs proved to be highly adaptive within evolved strategies (Torben-Nielsen et al., 2005a).

It is worth noting that most of the aforementioned techniques of soft-repair are inspired in some way by biology. Recently, a new research field, *biorobotics*, has arisen in between engineering (e.g., robotics) and biology (Webb and Consi, 2001). The goal of biorobotics is twofold, it aims at being beneficial for both engineering and biology. For engineering, biology has proven to be an almost inexhaustible source of inspiration. For biology, synthesised models of biological systems can be used to test, falsify, or generate hypotheses (Webb, 2002). However, in most biorobotic projects the aim is either engineering or biology. In the domain of soft-repair several biorobotic projects were conducted. For example GasNets by Husbands et al. (1998) who used a recently discovered model of gas emission as extra inter-neuronal communication leading to faster evolution of desired controllers (Smith et al., 2002). Another example directly aimed at damage recovery in mobile robots is the application of a neuronal activity-dependent model on a robot platform (Elliott and Shadbolt, 2001).

The results show that these solutions work quite well in a highly specific environment while performing a predefined task. Although some remarkable techniques are proposed to tackle the problem of self-repair, self-repair in highly dynamic and noisy environments has not been achieved yet. With respect to the earlier listed results, we can post a general requirement that needs to be satisfied in order to achieve reasonable capabilities of soft-repair: *on-line generation of new behaviours.* This requirement can be divided into two parts. The first part *on-line* refers to the fact that a robot must be able to repair itself during job execution. It is not feasible to return the robot to the lab, repair or re-train the robot and put it back into the environment. The second part *generation of new behaviours* refers to the fact that adaptation within a single behaviour is not sufficient; a completely different behaviour can be required. As an example, think of a robot that has to move towards a light source with damaged light sensors. In this case, using a temperature sensor might result in successful performance which is achieved by a completely different behaviour or strategy. However, note that the term *new* does not imply that the new behaviour is developed from scratch but rather that it is new and different with respect to the failing behaviour.

In this paper we propose a new methodology to tackle the problem of self-repair. We propose a method based on the mechanism exhibited by specific invertebrates that remodel their central nervous system to meet new environmental requirements. Our proposed methodology consists of three research tracks: (i) constructing a neuronal model that allows information processing similar to certain computations in real neurons, (ii) automated remodelling of the generated neuronal morphologies, and, (iii) embedding the results from track (i) and (ii) on a robot platform. Our proposed method is original in the future employment of a new artificial neuronal model. The model will be based on realistic neuronal morphologies and plausible information processing in the neurites.

The next section explains the biological inspiration of our work as well as the biological background required to understand posted assumptions and decisions. Section 3 presents our new approach to tackle the problem of self-repair. Three research tracks are formulated and results from the first track are presented. We present a conclusion in Section 4.

2 Biological inspirations

In the invertebrate world, several species are known to change their central nervous system (CNS) upon changing environmental needs. The remainder of this section elaborates on the phenomenon of *neuronal remodelling* (e.g., Duch and Levine (2000)). Two specific cases are presented as they are relevant for the conceptual application of neuronal remodelling in the robotics domain.

First, the tobacco hornworm (*Manduca sexta*). The Manduca belongs to the class of metabolous animals that change shape during their lifetime. Moreover, holometabolous animals (like the Manduca) change the shape of their body completely in different life phases (Consoulas et al., 2000; Tossit and Stocker, 2000). The animals go from a larva phase where they are caterpillars, to a pupal phase in which they do not move and prepare for the metamorphosis to finally end as a moth. It is not hard to see that the different life phases require different behaviours, e.g., a slow crawling movement as caterpillar and flight behaviour as a moth (Duch and Levine, 2000; Libersat and Duch, 2002). Several studies investigated the neural mechanism that allowed the Manduca to change its behaviour so drastically.

It was found that both the anatomy and physiology of the involved neurons changed (Consoulas et al., 2000). An interplay between anatomical changes (i.e., changes in morphology) and physiological changes was observed. Nevertheless, “there is little known about how the physiological changes accompany structural remodeling” (Duch and Levine, 2000). Yet, as pointed out in Consoulas et al. (2000) “dendritic remodeling might also be important for modifications of the intrinsic properties of motorneurons”, implying that morphological changes affect the passive information processing due to changing cable properties of a dendrite (e.g., Mainen and Sejnowski (1996); Libersat and Duch (2002)) (for a review of the *cable theory*, see for example Mel (1994)). For this reason, we concentrate on the morphological changes and assume that electro physiological change accordingly[1].

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[1] In the remainder of the manuscript, remodelling of the CNS is used as synonym for anatomical remodelling.

It was found that the CNS is remodelled by (i) cell death, (ii) cell growth, and (iii) reshaping of persistent neurons (Libersat and Duch, 2002). The latter is of importance for our study: how does the morphology of neurons affect the individual and ensemble behaviour? In case of the Manduca, it was found that the dendritic morphology of the persistent motor neurons undergoes complete transformation to go from slow firing neurons (as larva) to oscillatory neurons for flight behaviour.

Second, crickets (i.e., the *gryllus bimaculatus*) show strong behavioural adaptation during phonotactic behaviour. Cricket phonotaxis is the behaviour a cricket exhibits when tracking a specific sound coming from other crickets (e.g., Popov and Shuvalov (1977)). Two tasks are required for successful phonotaxis: (i) recognition, and (ii) localisation of the sound. Different studies from both biology (Simmons, 1988; Michelsen, 1998) and biorobotics (Webb and Scutt, 2000; Torben-Nielsen et al., 2005b) show that the cricket has a highly tuned auditory apparatus and dedicated auditory neurons (Schmitz et al., 1982; Thorson et al., 1982) to perform the two tasks successfully[2]. The highly tuned auditory apparatus has two main eardrums and transfers directional information (required for localisation) to the brain (Michelsen, 1998). The exceptional adaptivity manifests in the fact that even with one ear drum amputated or occluded the cricket still performs phonotactic behaviour with a reasonable performance (Schmitz et al., 1983; Huber et al., 1984; Schildberger et al., 1988). Experimental studies showed that after loss of (relevant) sensory input from one of the ear drums, specific auditory neurons change their morphology (Huber and Thorson, 1985; Schildberger et al., 1986; Schmitz et al., 1988). By this alteration in neuronal morphology, the cricket is enabled to perform phonotaxis reasonably well[3]. For our study, the cricket serves as an example of a living organism that remodels its CNS after injury, thus repairing itself.

Both examples show the power of changing neuronal morphologies with respect to behavioural change and damage recovery. It can be observed that the triggers for remodelling the CNS are different in both examples: the *Manduca* brain undergoes modelling as a result of a hormonal *trigger*, whilst the *Gryllus* brain remodels after a sensory trigger. For application in the robot domain, only the second trigger is of interest. However, regardless the trigger, the mechanism underlying changing neuronal morphology to achieve new behaviour is crucial. We aim at establishing a mapping between morphology and function.

3 Our approach

This section presents how the biological inspirations contribute to our approach to tackle the problem of self-repair. Our approach consists of three main research tracks. This paper presents the first track. For completeness, we start this section with an overview of the three tracks.

3.1 Three research tracks

We propose a methodology to tackle the problem of self-repair in mobile robotics which is inspired by the ability of insects to remodel their CNS to cope with changing environmental requirements. The long-term goal of our study is to port main principles underlying remodelling of the CNS in invertebrates to a robotic system with the ability to repair itself. The rationale here is that the neurons in the neuronal robot controller will alter their morphology to meet new environmental demands. With a brain as flexible as (some functions of) the invertebrate brain, a robot should overcome injuries to a certain extend. Generally, three research tracks need to be pursued to reach our goal: (i) constructing a neuronal model, (ii) automated remodelling, and (iii) embedding the results of the two previous tracks in a robot system.

First, a more realistic neuronal model is required. As elaborated in Section 2, the morphology plays a key role in information processing capabilities of neurons. However, current neuronal models as employed in Artificial Intelligence (AI) are considered shapeless computational units (e.g., McCulloch and Pitts (1943); Yao (1999)). Therefore, we need to construct artificial neurons that have analogous morphological features as neurons found in nature. In this track we investigate how to develop a suitable neuronal model.

Second, the artificial neuron as generated by the model from track one needs to be changeable in terms of its morphology. The process of remodelling has to be executed on-line and automatically. In this track we want to investigate how principles of neuronal plasticity (e.g., homeostasis or Hebb (Turrigiano and Nelson, 2000)) can regulate the remodelling process.

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[2] For sake of completeness we have to say that the two tasks, recognition and localisation cannot be seen apart from each other. For a detailed explanation see Webb and Scutt (2000); Torben-Nielsen et al. (2005b).

[3] Changing morphology gives an explanation for long-term recovery of ear-injuries; instantaneous recovery is also observed but cannot be explained by changing neuronal morphology.

Finally, the mechanism underpinning neuronal information processing and neuronal plasticity investigated in the two other research tracks needs to be embedded in a robotic system. This track is the most tentative track. Nevertheless, we believe that the sensory trigger initiating remodelling in the cricket brain might give insights into the embedding of abstract methodologies into a body (e.g., robot) and how the interactions between control structure and body function.

3.2 Track one: neuronal model

First, we summarize two biological findings to present the rationale of the first track. Then, we present a technique we developed to generate artificial neurons with complex morphological properties and finally, we present results from the first research track.

Rationale

The rationale is based on two biological observations. First, neuronal morphology plays a crucial role in information processing. Second, the change in neuronal morphology plays a key role in the generation of new behaviours in some invertebrates. Indeed, a plausible morphology in combination with a passive processing model will allow us to mimic specific computations performed in biological neurons. I.e., delay lines as results of dendritic filtering (London and Häusser, 2005).

However, as pointed out before, neurons in AI are considered shapeless computational units. According to the abstract concept of artificial neurons, the computational power of a neuron results solely from the integrative capabilities of the cell body (Segev and London, 2000). In the more biologically accurate view, a neuron consists of a cell body, a dendritic field and an axon. consequently, the information processing capabilities also result from integrative properties of dendrites and axons. The integrative power of dendrites is explicitly shown in the compartmental models (Segev and London, 2000), and the cable theory concerning signal propagation (London and Häusser, 2005). We can conclude that *standard* AI neurons are not sufficient for work in our methodology. In order to be able to remodel neuronal morphologies and exploit the morphology-function mapping, we need biologically more realistic neurons. More realistic neuron models can be obtained from *virtual neurons*, digitised biological neurons that are used in neuroscience for subsequent modelling. In turn, virtual neurons are obtained by tracing, reconstruction or generation from scratch (Ascoli et al., 2001). We have developed a new technique for generating virtual neurons from scratch. We point out a major difference with virtual neurons as used in neuroscience. Our goal is to generate neurons possessing specific biological properties (i.e., morphology) without attention for biological accuracy.

Morphology generation

We use a mathematical formalism of rule rewriting, L-Systems named after its inventor Aristid Lindenmayer (Prusinkiewicz and Lindenmayer, 1990). L-Systems are used to algorithmically describe branched structures like plants or in our case, neurons. The idea is powerful yet simple. A set of axioms and a set of production rules is defined over a certain alphabet. Then, cyclic rewriting of the axioms takes place: each rule symbol in an axiom or rule is substituted by the contents of the according production rule. In this way, complex strings can be generated. Below an example of an L-System.

axiom:	F[X]
rules:	F → YF
	X → BX
1^{st} cycle	YF[BX]
2^{nd} cycle	YYF[BBX]

In this example, the L-System consists of the alphabet $\{B, F, X, Y\}$, one axiom and two rules. During the initialization phase, the L-System stores a string containing but the axiom. After the first cycle the string contains the substitution of the axiom symbols by the content of the evoked rules. In each cycle all symbols corresponding to a rule are now substituted by the content of each rule.

An L-System is nothing more than a way of generating large strings from an alphabet, i.e., a syntax. Without semantics L-Systems have no meaning. The semantics are defined by a geometric interpretation which translates the rewritten string to a graphical structure. We use the Rotation-Elevation interpretation to convert a string to a 3D structure. This scheme is analogous to polar coordinates and uses two parameters to define positions in three dimensions. A rotation angle defines the rotation on a plane, the elevation angle denotes the rotation on a second plane orthogonally intersecting the other plane (illustrated in Figure 1).

Results

We implemented the neuron generation technique. Figure 2 illustrates a 2D virtual neuron as generated

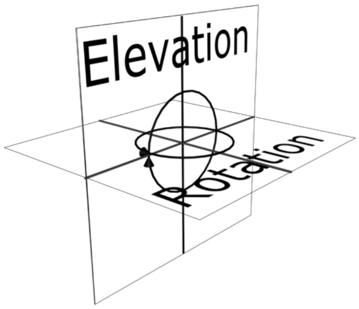

Figure 1: Rotation-Elevation interpretation of an L-System. A point in 3D space is defined by the rotation and the elevation on the plane orthogonally intersecting with the rotation plane. When generating 2D structures only the rotation angle is required.

by our system. The illustrated virtual neurons are all generated by the same L-System: usage of random parameters mimics the intrinsic uniqueness of real neurons. The different neuronal elements like axons and dendrites are clearly observable in the illustration.

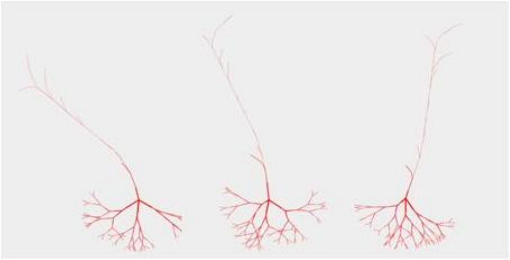

Figure 2: Two dimensional neuronal structure as generated by our system. Explanation in the text.

Furthermore, our system is able to generate neuronal structures in three dimensions as illustrated in Figure 3. The shape is stored in a Cartesian format as adopted by other neuronal morphology modellers (Cannon et al., 1998). The Cartesian storage allows the shape to be used in further experiments. We have to note that the neuronal structures illustrated in both figures are not biologically accurate structures (i.e., their parameters do not match with *fundamental parameters* of neuronal shape as defined by Hillman (1979)). For this work the biological accuracy is not crucial as long as we create complex neuron-like structures that in combination with passive cable properties allow complex non-linear computations.

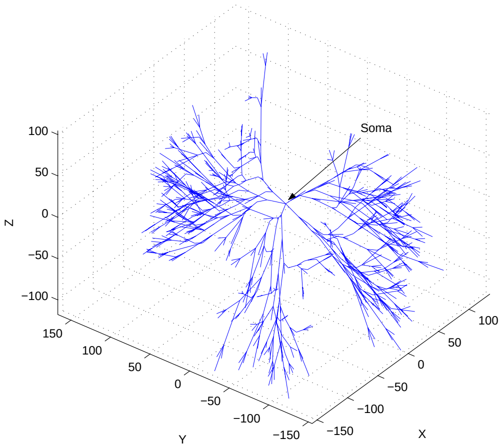

Figure 3: Three dimensional neuronal structure as generated by our system. Explanation in the text.

4 Conclusion

In this paper we have proposed a new three-fold methodology to tackle the problem of self-repair in mobile robotics, of which the first step has been completed. We introduced a methodology based on principles of neuronal remodelling in invertebrates. The approach is original in the fact that we are the first to propose to exploit morphological properties of neurons to achieve nature-like complex non-linear computations. For this reason we introduce non-standard artificial neurons. We introduced a technique using L-Systems to generate artificial neuronal structures. We showed empirically that we are able to generate both two and three dimensional neuronal structures. Currently, we only have morphometric descriptions of neurons. Functionality is not yet built in but dedicated neurophysiological simulators (e.g., Genesis (Bower and Beeman, 1998)) can simulate information processing for virtual neurons described in the SWC format that we use.

Current topic of research is the generation of biologically realistic and accurate virtual neurons. In general, virtual neurons are considered biologically accurate when there is no significant difference in the *fundamental parameters* of a specific biological neuron and the virtual counterpart. The fundamental parameters are a set of parameters describing neuronal shape defined by Hillman (1979); these parameters are still used as a reference for proving biological accuracy (Ascoli et al., 2001).

For future research, and keeping the next proposed research track in mind, it is useful to construct a virtual neuron generation method that interacts with the *substrate* in which the neuron is grown. We already built this functionality in in our system, but this function is currently limited to two dimensional neuronal structures (unpublished results). The interactions are based on principles of chemical attracting and repulsion (Feng et al., 2005).

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