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International Centre for Mechanical Sciences

Dynamical Systems, Wave-Based Computation and Neuro-Inspired Robots

CISM Courses and Lectures, vol. 500

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CISM COURSES AND LECTURES

The series presents lecture notes, monographs, edited works and proceedings in the field of Mechanics, Engineering, Computer Science and Applied Mathematics.
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INTERNATIONAL CENTRE FOR MECHANICAL SCIENCES

COURSES AND LECTURES - No. 500

DYNAMICAL SYSTEMS, WAVE-BASED COMPUTATION AND NEURO-INSPIRED ROBOTS

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SpringerWien NewYork

This volume contains 126 illustrations

Printed in Italy
SPIN 12244348

All contributions have been typeset by the authors.

ISBN 978-3-211-78774-8 SpringerWienNewYork

PREFACE

This volume is a special Issue on "Dynamical Systems, Wave-based computation and neuro-inspired robots", *based on a Course carried out at the CISM in Udine (Italy), the last week of September, 2003. From the topics treated within that Course, several new ideas were formulated, which led to a new kind of approach to locomotion and perception, grounded both on biologically inspired issues and on nonlinear dynamics. The Course was characterised by a high degree of multi-disciplinarity. In fact, in order to conceive, design and build neuro-inspired machines, it is necessary to deeply scan into different disciplines, including neuroscience, Artificial Intelligence, Biorobotics, Dynamical Systems theory and Electronics. New types of moving machines should be more closely related to the biological rules, not discarding the real implementation issues. The recipe has to include neurobiological paradigms as well as behavioral aspects from the one hand, new circuit paradigms, able of real time control of multi joint robots on the other hand. These new circuit paradigms are based on the theory of complex nonlinear dynamical systems, where aggregates of simple non linear units into ensembles of lattices, have the property that the solution set is much richer than that one shown by the single units. As a consequence, new solutions "emerge", which are often characterized by order and harmony. Locomotion in livings is a clear example of this concept: ordered motion is the solution of a great amount of concurrently co-operating neurons; neural "computation" is also rather "wave based", than "bit based". In this direction, continuous time spatial temporal dynamical circuits and systems are the paradigmatic mirror of neural computation.*
The volume mainly reflects the structure of the Course, but is directed toward showing how the arguments treated in that CISM Course were seminal for the subsequent research activity on action-oriented perception. The volume is therefore constituted of three main parts: the first two parts are mainly theoretical, while the third one is practical. The theoretical aspects, reported in the first part of the volume, discuss new programmable processing paradigms, the Cellular Nonlinear Networks (CNNs). These architectures constitute wave based computers processing spatial-temporal flows. Another important theoretical topic regards neurobiological and neurophysiological basis of in-

formation processing in moving animals, with the introduction of the paradigm of the Central Pattern Generator. Then a unifying view will be presented, where CNN approach, the neurobiological aspects and the robotic issues will be organically fused together, referring to a number of bio-inspired robotic prototypes already developed and really working. Finally, very interesting issues regarding how bio-robots can be used to model biological behavior are given, together with examples of neural controllers based on spiking neurons, applied to model optomotor reflex and phonotaxis.

The second part of the volume includes the use of sensory feedback in locomotion controlled by the CPG. Then a looming detector for collision avoidance, inspired by the locust visual system, is modelled and shown. Sound localization and recognition is also addressed by using a network of resonate and fire neurons and finally a chapter introduces the main aspects of robot perception.

School attendees were also allowed to implement and realise some applications of what theoretically learned, helped by a series of practical tutorials introduced by Tutors. The results of the practical work done by the students have been also added at the end of the volume to demonstrate the interest shown by attendees and the implementation of the new ideas conceived by them.

A special thank goes to Prof. M. G. Velarde, for supporting the organization of the Course. The Coordinator particularly thanks Prof. Leon O. Chua for transmitting the CNNs basics, starting point of a large research wave. The invited speakers Prof. B. Webb and Prof. T. Deliagina are acknowledged for their contribution through interesting and attracting lessons and for collaborating in the production of the present volume. A warm thank is also addressed to Dr. M. Frasca and Dr. A. Basile, who actively worked as Tutors for the students during the practical part of the Course. The Coordinator would like to thank Prof. L. Fortuna for transmitting the view of nonlinear complex dynamics within multidisciplinary research, giving rise to a large part of the contents of the volume and to the following research activity on robot perception.

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CONTENTS

Part I

Foundations of Neurodynamics and wave based computation for locomotion modeling

Overview of Motor Systems. Types of Movements: Reflexes, Rhythmical and Voluntary Movements

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Abstract One of the principal characteristics of the animal kingdom is the ability to move actively in space. Our movements are controlled by a set of motor systems that allow us to maintain posture, to move our body, head, limbs and eyes, to communicate through speech. Motor control is one of the most complex functions of the nervous system. During movement, dozens and even hundreds of muscles are contracting in a coordinated fashion. This coordination is a basis for a remarkable degree of motor skill demonstrated by dancers, tennis players and even by ordinary people when walking or writing a letter.

1 Types of movements

Most movements performed by animals and humans can be divided into three broad classes: reflex responses, rhythmical movements and voluntary movements.

Reflexes are relatively rapid, stereotype, involuntary responses that are usually controlled in a graded way by a specific eliciting stimulus. For example, protective skin reflexes lead to withdrawal of the stimulated part of the body from a stimulus that may cause pain or tissue damage. Coughing and sneezing reflexes remove an irritant from the nasal or tracheal mucosa by inducing a brief and strong pulse of air. This is caused by synchronized activation of abdominal and respiratory muscles triggered by afferents activated by irritant. Swallowing reflexes are activated when food is brought in contact with mucosal receptors near the pharynx. This leads to a coordinated motor act with sequential activation of different muscles that propel the food bolus through the pharynx down the esophagus to the stomach. Postural reflexes are responsible for maintenance of the body and its parts in a stationary position.

Rhythmical movements are characterized by sequence of relatively stereotyped, repetitive cycles generated automatically. For example, we are continuously breathing from the instant of birth, without thinking about each inspiration . expiration movement. In contrast to breathing, the majority of rhythmical movements are not generated continuously but should be initiated either voluntary (like locomotion in higher vertebrates) or by specific sensory stimuli (like scratching in cats or dogs or locomotion in invertebrates).

Voluntary movements. Examples of this wide class of movements are the skilled movements of fingers and hands, like manipulating an object, playing the piano, reaching, as well as the movements that we perform in speech. Voluntary movements are characterized by several features. They are purposeful, goal directed, initiated in response to specific external stimuli or by will. The performance of voluntary movements improves with practice. As these movements are mastered with practice, they require less or no conscious participation. Thus, once you have learned to drive a car you do not think through the actions of shifting gears or stepping on the brake before performing them. It is necessary to note, however, that this classification of movements is not perfect because it is difficult to draw a clear-cut dividing line between the different classes. Voluntary movements with practice become more and more automatic like reflexes. By contrast, rhythmical movements and reflexes can also be modified by will. For example, we can voluntary terminate our rhythmical breathing movements when diving, we can also modify the duration of the inspiration and expiration when singing. If necessary, we can keep a hot object in our hand despite it can damage the skin. This is possible because of voluntary inhibition of protective withdrawal reflexes. If, however, the object is touched without knowing that it is hot, the hand will be withdrawn automatically with the shortest possible latency. Despite we define reflexes as stereotyped movements, some reflexes can underlay plastic changes. A good example is the vestibulo-ocular reflex. This reflex is responsible for stabilization of the visual image on retina during head movements. For instance, movement of the head to the left evokes movement of the eyes to the right with such a speed and amplitude that the visual image on retina does not move. The movement of eyes is initiated by the signal from vestibular afferents activated by head movement. When the animal observes the world through minifying or magnifying glasses (that alter the size of visual image on the retina) the compensatory eye movements, that would normally have maintained a stable image of an object, are now either too large or too small. Over time, however, the vestibulo-ocular reflex recalibrates and the amplitude of eyes movement changes in accordance with the artificially altered size of the visual field. Finally, different rhythmical movements, from the point of view of their initiation, do not represent a homogeneous group, since some of them are initiated as reflexes (like scratching, paw shaking), but others, like locomotion in higher vertebrates, are initiated voluntary.

2 Basic components of motor system

2.1 Motoneuron

A movement is performed due to a contraction of muscles which, in their turn, are controlled by motoneurons. Each motoneuron sends its axon to one muscle and innervates limited number of muscle fibers. A motoneuron with its muscle fibers is referred to as a motor unit, since a single action potential generated by the motoneuron evokes contraction of all muscle fibers that it innervates. All motor commands eventually converge on motoneurons, whose axons exit the CNS to innervate skeletal muscles. Thus in Sherriningtons words, the motoneurons form a "final common pathway" for all motor actions.

2.2 Neuronal networks generate motor patterns; Central pattern generators

Each type of motor behavior can be characterized by its own motor pattern, which can be defined as the sequence and degree of activation of particular muscles. For example, the locomotor pattern consists of alternating activity of flexor and extensor muscles around different joints of the limb, with specific phase shifts between different limbs. Each of the numerous motor patterns is generated by a group of neurons. the neuronal network. The network contains the necessary elements and information to coordinate a specific motor pattern such as swallowing, walking, breathing. When a given neuronal network is activated, the particular motor pattern is expressed. A typical network consists of a group of interneurons that activate a specific group of motoneurons in a certain sequence. The interneurons also inhibit other motoneurons that may counteract the intended movement. For normal functioning of the network, sensory information signaling about execution of a movement is usually very important. In many cases, however, the network can generate the basic motor pattern without sensory feedback, though the pattern more or less differs from the normal one and is not adapted to the enviroment. Such networks are often referred to as central pattern generators (CPGs). There are CPGs for locomotion, scratching, swallowing, breathing, etc., which can be activated in in vitro, immobilized, or deafferented preparations in which sensory feedback