UNIVERSIDAD AUTÓNOMA DE MADRID

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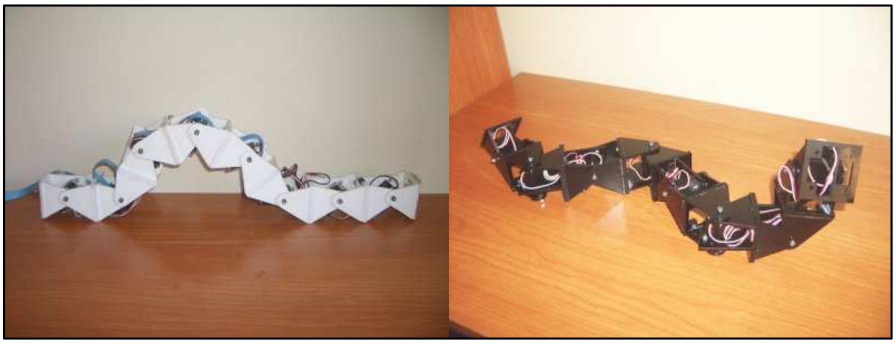
Ph.D. Thesis

MODULAR ROBOTICS AND LOCOMOTION: APPLICATION TO LIMBLESS ROBOTS



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Juan,
Madrid, September 2008

Preface

Snakes aren’t the kind of cuisine most people look for when ordering, but the speciality of the house was Juan González-Gómez’s amazing servo-driven snakebot. All snake robots I’ve ever seen –even Gavin Miller’s amazing bots- cheat. They replicate a snake’s motion, be it sinusoidal, caterpillar, or side-winding, but always with wheels on the bottom to eliminate friction and help the bot along. Gonzalez, however, perfected a system that most closely replicates how snakes really move. There are no wheels on his robots. Just his own servo housings. Watching a snake robot skitter across the floor is always cool. But when you pick up Juan’s bot and realize that it’s got no wheels and can still move the same way any snake can, you’re truly awed. Even more inspiring is the fact that his bots are totally modular. You can have as few as two modules or as many as 256 – good for both garter snakes and anacondas.

Dave Calkins,
President of the Robotics Society of America,
Lecturer of the Computer Engineering Program at San Francisco State University
Founder of ROBOlympics/RoboGames - the International all-events robot competition

Abstract

This thesis deals with the locomotion of modular robots concentrating specifically on the study of configurations with one dimensional topology, that we call apodal robots. The problem we face is how to co-ordinate the movement of the articulations of these robots so that they can move as easily in one as in two dimensions.

One of the biggest challenges is to develop a robot that is as versatile as possible and is able to move from one place to another over various types of terrain, even the roughest and most broken. This is of special importance where the environment is unknown, such as the exploration of the surface of other planets, navigation in hostile environments or in search and rescue operations.

To increase versatility of movement, modular robotics proposes the creation of robots based on basic modules. Each configuration would have different locomotive characteristics that must be studied. If also the modules were self configuring, the robots could constantly be selecting the optimum configuration for each environment.

One type of controller used is bio-inspired, based on CPG (Central Pattern Generators), these are specialised neurones that produce rhythms that control muscle activity in living beings. In the stationary state they act like fixed frequency oscillators which permits them to be substituted by a simplified model formed by sinusoidal generators. The advantage is that they are extremely simple to implement and require very few resources for their production. What is more they can be produced employing different technologies: software, digital circuits or even electro-analogical.

In this thesis a classification of the modular robots is established, according to their topology and type of connection and the hypothesis is presented to use sinusoidal generators as locomotion controllers for the apodal modular robots with one dimensional topology, of the groups pitch-pitch and pitch-yaw. The results show that this simplified model is viable and the movements obtained are very gentle and natural. The robots can move using at least five gaits. Some of them, such as rotation, are original, and as far as we know, have not been studied before nor implemented by other investigators.

Another problem that presents itself is that of the minimum configurations. To find the robots with the least number of modules possible that can move in one or two dimensions. Two minimum configurations capable of this and the relationship between their parameters have been found.

It has been shown that the answers found to the problem of co-ordination are valid for their use in real robots. They have been tested in four prototypes of apodal robots constructed on the basis of the union of Y1 modules, designed specifically for this thesis. The verifying of robots with a different number of modules has been carried out using the simulator developed for this purpose.

Finally the knowledge about the locomotion of apodal robots of the study groups has been resumed in 27 fundamental principals.

Contents

Chapter 1

Introduction

"My work is a game, but a serious game."

– M.C. Escher.

In this introductory chapter the application environment for this thesis is presented, its aims and how the memory content has been organised. In the following chapter the context is described in more detail and the bibliography is given.

1.1 Presentation

This thesis deals with the locomotion of modular robots concentrating specifically on the study of configurations with one dimensional topology, what are called apodal robots. The problem faced is how to co-ordinate the movement of the articulations of these robots so that they can move as easily in one as in two dimensions.

Locomotion is the capability that permits living beings belonging to the animal kingdom to move from one place to another at will. There are two important aspects to have in mind: control and voluntariness. If the movement is to be considered locomotion the individual has to want to complete it and what is more be able to control it. In this way, the water lilies that rest on the surface of the water move driven by the currents or other animals, but it is not considered locomotion because it is neither voluntary or controlled. The robots that possess locomotive capacity are called mobile robots. The field of robotics that studies and designs robots capable of functioning for themselves in unknown environments is known as mobile robotics.

The study of locomotion is divided into two levels, called superior and inferior. The inferior level is in charge of the control and co-ordination of the actuators so that the robot can move from place to place. It includes the different gaits that can be obtained (turns, moving in a straight line, sideways movements, etc.). The questions to be resolved at this level are: How do I move? How do I co-ordinate the actuators to take a step? It is easy to resolve them if the robot has wheels or caterpillar tracts and the terrain is appropriate. It is sufficient to turn the motors to obtain the movement required. Nevertheless, when the robot has articulated feet or has to complete the manoeuvre using body motions, as is the case of apodal robots, resolving the difficulty is complicated. In these cases it is necessary to co-ordinate correctly all the articulations. The superior level is in charge of planning the routes, navigation and other higher level tasks. It is concerned with voluntariness. The questions that define this level are: Where do I want to go? How do I get there?

> *This thesis concentrates on the lower level of locomotion addressing the problem of the co-ordination to obtain different ways of movement for apodal robots.*

One of the biggest challenges is to develop a robot that is as versatile as possible and is able to move from one place to another over various types of terrain, even the steepest and most broken. This is of special importance where the environment is unknown, such as the exploration of the surface of other planets, navigation in hostile environments or in search and rescue operations. Up to now the robots that have been made have less locomotive capacity than a mammal. Even when they are operated by remote control, where the superior level is carried out by a human, mobility is limited by the robot's design. To improve it raises the questions: What kind of elements are best: feet, wheels, caterpillar tracks, etc.? What configuration of feet must be used?

The traditional approach is to study *a priori* the characteristics of the terrain and design the most adequate structure of robot: whether it uses feet, wheels, or caterpillar tracks. This has the disadvantage that a wrong choice at this level will imply redesigning the robot. Also applications exist where the environment is changeable or unknown.

In 1994, Mark Yim, in his doctoral thesis, proposed a new approach. He proposed constructing robots employing simple modules, joined one to another to make up different configurations. Maximum versatility would be obtained if these modular robots were able to configure themselves. In this way the robots could change their form to enable them to move in the most efficient way, according to the terrain. To illustrate this idea, Yim proposed a setting in which a robot had to go from his laboratory in Stanford to a neighbouring building. To do this it had to cross the porch, pass underneath the railings, go down a step and cross broken ground. None of the robots known up to then could do it, even the remote controlled ones failed, Nevertheless a self configuring modular robot could adapt its form to cross the porch, following that it would become a worm to go underneath the railing and down the step. Finally it would transform itself into a quadruped to move across the broken ground. It is a robot that has used three different forms of locomotion. It has adapted to the terrain to move across it in the most efficient way possible.

A new area of investigation was born: modular robotics. In this the basic modules are designed, and then based on them different configurations of robots are created. Each one will have different locomotive characteristics. If also the modules are self configuring, the robots will be able to select at each moment the configuration best suited for each environment. In this way a new line of investigation arises: the locomotion of modular robots, where the aim is to study the locomotive properties of all possible configurations. This is a titanic task, given that the quantity of potential configurations grows exponentially with the number of modules.

As a first step the modular robots can be classified according to their topological dimensions, of one, two or three dimensions. Each one of these groups has different characteristics and within each family sub-families appear with other properties.

This thesis studies modular robots with one dimensional topology. Within this family the way that the modules are connected between themselves defines three distinct groups. The groups that we will concentrated on are those with connection pitch-pitch and pitch-yaw.

> *This thesis studies the problem of the co-ordination needed so that apodal modular robots with one dimensional topology, of the groups pitch-pitch and pitch-yaw, can move in one or two dimensions respectively.*

Another important aspect in the locomotion of the modular robots is the controller that is employed. Its mission is to calculate the positions of the articulations at each moment, in function of established parameters. The classical solution is to employ specific controllers that obtain the angles of the articulations by means of inverse kinematics. As an entrance the curves of the trajectory are used (either from the centre of the masses or from the extremes of the feet, if they have them) and the positions of the servos are obtained. This approach presents two problems when applied to modular robots. On one hand these controllers are too specific, which makes it difficult to re-use them in other configurations. Each configuration has its own kinematics and consequently its own equations, therefore each controller will be different. On the other hand, the calculating power necessary is high. Inverse kinematics demands many calculations that must be done quickly, which restricts the choice of microprocessor and its operational speed.

Another, different approach, is to use bio-inspired controllers. Millions of years ago nature resolved the problem of locomotion of living beings. Why not study how it has resolved it and find inspiration there. In the 60's biologists discovered that living beings possessed specialised neurones, called central pattern generators (CPGs). These centres produce rhythms that control muscular activity to carry out vital functions, such as breathing, bowel movements, chewing, locomotion, etc. The problem of co-ordination is resolved employing controllers that implement the mathematical models of these CPGs and finding the adequate values for their parameters. In contrast to the classic approach, the bio-inspired controllers are not based on the knowledge of where certain points are situated in space, but act directly on the articulations. They are, therefore, faster, generating movements that are more natural and, generally, demand less computing power.

Nevertheless, there exist a certain complexity in biological mechanisms, as well as a lot of redundancy. Perhaps these solutions are very specialised, being 'rich', supplying too much information that may not be necessary for robotics locomotion. For this reason, the other approach for the control of movement, followed in this thesis, is to employ simplified models of CPGs. If the study of locomotion is made in permanent regime, a possible simplification is to substitute the CPGs for sinusoidal generators that directly control the position of the articulations of the robot. This is possible because CPGs act as fixed frequency oscillators once they have reached the stationary regime. What is more, the observation of animal locomotion shows that the frequencies of the rhythmic movements are equal and there is no evidence that oscillators of the dorsal spine use different frequencies.

The advantage of these controllers is that the are extremely simply to implement and require very few resources to realise. Also they can be formed using different technologies: software, digital circuits or even electronic analogue. By means of the use of FPGAs specific circuits can be designed that allow the robot to move "by hardware" in the same way that the tails of lizards move when they are severed. The problem of co-ordination is resolved by finding the amplitude values and the different phases of the generators that make the robot move.

> *The hypothesis of this thesis is the employment of sinusoidal generators as controllers for the locomotion of the modular apodal robots with one dimension topology, of the groups pitch-pitch and pitch-yaw.*

1.2 Aims of the thesis

The main aim of this thesis is **to study the problem of locomotion of the modular apodal robots with one dimensional topology of the groups pitch-pitch and pitch-yaw; of any length, in one or two dimensions**. We want to know what gaits are possible and how to co-ordinate the robot's articulations to obtain it.

The problem dealt with is very wide ranging and can be addressed from different viewpoints. The hypothesis examined is the use of a controller based on sinusoidal generators. Below the concrete **aims** are formulated, each one linked to a question:

1. To study the viability of the locomotion of the apodal robots of the mentioned groups of any length employing sinusoidal generators. (*Is robot movement achieved?*)
2. Discover different gaits. (*What types of movement can be performed?*)
3. Characterise the gaits using the minimum number of parameters. (*What is the minimum number of parameters needed to perform the movements?*)

4. Establish the lower limits of the number of modules that enables the robot to move. (*Which are the robots with the lowest number of modules capable of movement?*)
5. Discover the relationship between the parameters of the sinusoidal generators, the kinematics parameters of the robot and its shape. (*How does each parameter affect the movement controller and shape of the robot?*)
6. Sum up the results in a series of principals of locomotion that permit application engineers and other investigators to put into operation the apodal robots. (*What do I have to do so that this apodal robot of M modules moves in a certain way?*)

To address these questions this study presents the following **secondary aims**:

- Revise the state of the art in modular robots and apodal robots. Study the evolution of the robots created in the leading research centres, classify and identify the original contribution of this thesis.
- Creation of the mathematical models for robot groups: pitch-pitch and pitch-yaw.
- Develop a simulation software environment to evaluate the proposed solutions.
- Design a module for the construction of modular robots of the study groups.
- Construction of prototypes of modular robots to carry out the experiments and the verification of the solutions in real robots.

Finally, as a **personal aim** of the author of this thesis, the experimental platform created for the verification of the results, made up of hardware, software and mechanics, **has to be open and free**, and also designed, as far as possible, using **free development tools** that run in a free operating system. This aim will allow any investigator to reproduce the platform, verify the results of this thesis on it, and carry out improvements and continue with the investigation.

LIMITS

To make the study of the locomotion of apodal robots accessible, the following limits have been applied.

- The various movements of the apodal robots are studied in a permanent regime. This restriction permits the substitution of the CPGs for sinusoidal generators.
- The surface is homogeneous, without obstacles. The first step is to search for solutions to the problem of co-ordination for this kind of surface.

- Control in open loop. The articulations are positioned in open loop. The controller sends the desired positions, supposing that the servo[1] reaches them in a certain time. It does not wait to receive any type of notification. This supposition is reasonable given that the surface is homogeneous and without obstacles. There is no impediment to the movement of the servos.
- Modules without sensors. It is assumed that each module possesses only one actuator, and no sensor. On one hand they do not need sensors to read the position of the servos as the control is in open loop. On the other hand it is not necessary to obtain information of the environment at this level of locomotion. It will be necessary to add sensors to operate at the superior level.

Aims that DO NOT form part of the thesis

The realisation of a simulation software and the construction of prototypes of modular robots are planned to demonstrate the viability of the ideas proposed in the thesis. The aims that objectively do not form part of this thesis are the following:

- The construction of autonomous apodal robots. To verify the ideas proposed it is not necessary to construct prototypes that are autonomous. The controllers will be programmed in the computer and sent the positions of the servos to the robot by cable, by means of a serial connection. The power source will be external, situated outside the robot. Once the viability of the solutions is found, to make a robot that does not need any type of cable is purely a technological problem, and easily viable
- Superior levels of locomotion. It is not the aim of this thesis to programme behaviour in the robots or address other aspects related to the superior levels of locomotion, such as perceiving the environment, planning of routes, etc.

1.3 Structure of the Document

In the first chapter the context of the thesis has been introduced, without going into details and the aims have been presented. In the second chapter the progress in modular robotics and apodal robots will be described in greater detail and it will be shown more exactly where this thesis relates to it. In the third chapter the models used for the modules, apodal robots, the controller, the kinematics and the mathematical models will be presented.

The following three chapters form the major part of the thesis, each one is dedicated to a different problem. The study of locomotion has been divided into three parts. The first (chapter 4) the problem

[1] Internally the servo closes the loop, using a potentiometer to confirm that it has reached the position, but this information is not supplied to the superior controller.

of one dimensional locomotion (in a straight line) of the apodal robots belonging to the pitch-pitch group is addressed. In the second (chapter 5) two dimensional locomotion of the pitch-yaw group is studied. In the third (chapter 6) the problem of the minimum configurations is dealt with and the answers found are given.

In the seventh chapter the developed robotic platform is described and the most relevant experiments are documented, both in simulations and real robots.

Finally, in the eighth chapter, the conclusions are expounded, with the future lines of investigation. At the end of each chapter the specific conclusions are given, in such a way that with reading the introduction and the conclusions of each chapter the reader will have a synthesis of the work done.

Bibliography