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MODELLING AND SIMULATION OF ROBOT MANIPULATORS

A PARALLEL PROCESSING APPROACH

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To my Mother .... for Everything

We are still ahead of them,...
man is still the most
extraordinary computer of all.
J. F. Kennedy

Foreword

In his 1940 play entitled *Rossum's Universal Robots*, Karel Capek introduced Humanoid Robots which could think and behave like humans. Though superior to humans in many ways such as strength and accuracy, in the play they proved to be weak in one area, that being that they did not have a heart. As a work of fiction, albeit visionary, many other differences of a more technical nature, which still exist more than fifty years on, were not put forward, examples being self-portable power supplies and coordinated control mechanisms, as well as the principle present day difference of intelligent behaviour. Many other technical differences are however manifest and can be seen clearly even with simpler, commonplace, robot mechanisms such as industrial robot manipulators.

Industrial type robot manipulators have been with us now for over twenty years and yet we still do not have a straightforward understanding of the principles behind their operation. A detailed mathematical analysis of such manipulators in terms of kinematics and dynamics results in a set of complex nonlinear identities which are certainly not well suited to elementary computations, even when approximations are made, noise is discounted and smaller, less effective terms are neglected. The problems are further enhanced if sensory systems such as vision and taction are also analyzed along with the higher level requirements of path-following, adaptive behaviour or task planning. Overall, therefore, the problem of robot control, particularly in terms of on-line algorithmic control, is fraught with high computational load difficulties if even a set of reasonably approximate identities is used. Unfortunately giving in to a plethora of approximations not only reduces a robot's repeatability and accuracy, but also introduces further problems in terms of lack of control in certain regions due to the nonlinearities present.

On the positive side, computing power, availability and usefulness have increased at an explosive rate, particularly in the last ten years. At one extreme this has meant that new computing procedures could be introduced and investigated, such as novel computer graphics packages, which are now realising new avenues of research, such as virtual reality. On the other hand, the result is that computational procedures previously known, but requiring a very high computational load, can now be attacked in a way which makes them useful in the real world on real problems and possibly even in real-time. The field of robotics and robot control is assuredly in this latter category, which means that a significant step in both the control of, and our understanding of, robot manipulators can be, and indeed is being, taken due to the improvements in computer technology.

Of the new computer technology introduced, parallel processing and reduced instruction set computers are having a significant impact, and it is interesting to note that this book specifically concentrates on those two forms of computing power. It would be foolish simply to apply any available higher powered computational ability without relating it to a more in-depth study of the field of application. The two aspects must go hand-in-hand in order to ensure that full benefit is being obtained, previously unknown advantages are gained, trade-offs are understood and costs involved are minimized. In this book such an approach is taken and a cohesive picture is given of the use of highly efficient computational techniques in the field of robot manipulator modelling and simulation. This naturally means that the text crosses the traditional boundaries of mechanics and computing, as well as related Engineering disciplines. For those interested in a deeper understanding of robot manipulators, in terms of their analysis and control, the text is an extremely useful aid and reference. However it also provides a vital link to the next generation of robots in which a much greater degree of intelligence and self-control will be present.

Kevin Warwick
University of Reading
October 1992

Preface

Parallel and distributed computer architectures can provide the computing power required by robots to achieve high degrees of autonomy. It is a compelling notion that one might build a system that computes a wide range of robotic algorithms in a fraction of a second. Whether and to what extent this challenge can be met is still an open question. This book examines the use of parallel and multiple processor architectures for the computation of robot kinematics and dynamics. The book originated from research that was conducted at the Department of Automatic Control and Systems Engineering at Sheffield University (United Kingdom), during the years 1987-1990, for my doctoral dissertation. However, since then most of the work has been revised and a significant amount of expository and explanatory material has been added. Hence, there are more case studies and more informal intuition behind the formal mathematical results.

Computational robotics can be defined broadly as the analysis and study of fast and efficient techniques (algorithms and architectures) to alleviate the computational load associated with most robotics algorithms. These algorithms cover a wide area ranging from mechanical manipulation to computer vision and artificial intelligence, however, in this book we will address the areas of robot kinematics and dynamics. The efficient computation of kinematics and dynamics influences the development of algorithms in other areas of robotics, such as task-planning, path-finding, control, and vision, to name a few. In general, the field of robotics is still undergoing many changes and there are many outstanding problems that need to be resolved. Nevertheless, we hope that the book will serve a purpose. Since knowledge about computational robot kinematics and dynamics is widely scattered in the literature, it is difficult for a newcomer to get a good grasp of the field. Hence, in this book we have tried to survey a reasonable amount of suitable source material on the topic that hopefully will provide further assistance. The material in the book is structured in a modular fashion, with each chapter reasonably independent of every other chapter.

The development of parallel algorithms can be realised through several levels. One level, which is adopted in this work, is to focus on the details of implementation on a particular machine or architecture. This approach allows for a better understanding of the computational and communication complexities of a given implementation. The core of the book is the presentation of implementation results and benchmarks. Most of the algorithms presented in the book are evaluated on two different computer architectures: a SUN-SPARC station and a network of Transputers running the C and OCCAM programming languages, respectively.

Computer architectures are driven by technology. Everyday new devices are introduced adding to the existing capabilities. The key issue is to learn about computer architectures in the context of today's technology. It is important to look at both cost and performance when evaluating an architecture and not only performance. This book aims to look at providing solutions to certain problems with cost and performance trade-offs.

The material in the book is interdisciplinary in nature. It combines topics from certain aspects of computer science, vectorial mechanics, control theory, and linear algebra. The book can be used by senior undergraduates, postgraduates, and researchers in Electrical and Computer Engineering, Mechanical Engineering, Manufacturing Engineering, and Computer Science. It assumes that any potential reader has had a basic course in statics and dynamics, a course in linear algebra, and some programming experience in a high level language.

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Albert Y. Zomaya
Perth, Western Australia
February, 1992.

Contents

CHAPTER 1

Introduction

Current-day robot manipulators are the descendants of the earlier *numerically-controlled* (*NC*) machines and master-slave *teleoperators*. However, the computer plays a major role in controlling today's robots (Engelberger 1980). This *artificial brain* makes the robot far superior to other machines that usually appear on the factory floor. Extensive use of industrial robots and manipulators is predicted for the next decade in response to increased demand for *flexible* automation. In view of this, the forms, designs and technology of these robots will improve as time progresses. However, due to the multi-disciplinary nature of robotics, new problems are emerging and solutions need to be provided. This requires a multitude of expertise from diverse areas of endeavour (Dorf 1983; Hunt 1983; Fu *et al.* 1987; Spong and Vidyasagar 1989; Schilling 1990).

The field of Robotics is not a here-today gone-tomorrow phenomenon. Robots are here to stay, and the different research directions are motivated by severe limitations in the performance of today's robots. For example, robots cannot participate in the planning of their activities. They must be programmed in detail or led through specific sequences of motions which they then repeat in a very dumb way. Moreover, they cannot respond to unexpected shortcomings in an intelligent way, that is, their environment must be highly structured (as in today's automated factories). In the more complex dynamic situations, robots do not quickly recognise and assess the condition of objects either by vision or by touch, and they do not learn on the basis of visual and tactile experience.

Some researchers consider the present robotics age as a part of the larger computer revolution. Undoubtedly, any advances in computer technology will have a prominent effect in introducing new areas of research and revolutionising old ones.

Advanced and high-performance computer architectures, especially those applying parallel and multiprocessing techniques, allow for the application of sophisticated algorithms and solution methodologies. These algorithms are necessary for the development of the next generation of robotic systems. The potentials of such systems cover a wide range of applications; under-sea and space exploration (Defigueiredo and Jenkins 1987), medical applications (Kwoh *et al.* 1987), computer-aided manufacturing (Sassani 1987), and agriculture (Harrell *et al.* 1987), to name a few.

The development and implementation of parallel and multi processor algorithms for robotics applications are the themes of this book. Immediately following is a brief description of some of the background material and the motivating factors of this work. This will be followed by a précis of the work and its organisation. Finally, a brief explanation of the notations employed throughout the book is presented.

1.1 Overview

The widespread use of robot manipulators in industry was foreseen early in the twentieth century (Sassani 1987). However, justifiable development and construction of a useful robot did not take place until the 1950's. After World War II, man found a need to build machinery that would take his place in the increasingly hostile environments that he had to confront.

As noted earlier, today's robots are the result of the marriage of two technologies; the (NC) machines and tele-manipulators. The former are relatively simple machines that provide linear motion along two or three axes. The latter have progressed from purely mechanical devices to complex systems in which the computer is a major and indispensable part (Thring 1983). The first tele-manipulator was designed and built at Argonne National Laboratory in (1947), to handle radioactive materials (Groome 1972). This earlier form of manipulators worked by using a master-slave mode of operation depending on the operator's visual feedback.

In (1954) *George Devol* designed the first programmable robot manipulator and in (1956) *Joseph Engelberger* bought the rights to Devol's robot. This led to the first industrial application of a robot in a General Motors plant in (1961) at New Jersey in the USA. Since then, robots have gradually progressed to their current state, but they are still deficient in their interaction with the environment. This is because essential sensory perceptions are not available in a universal form.