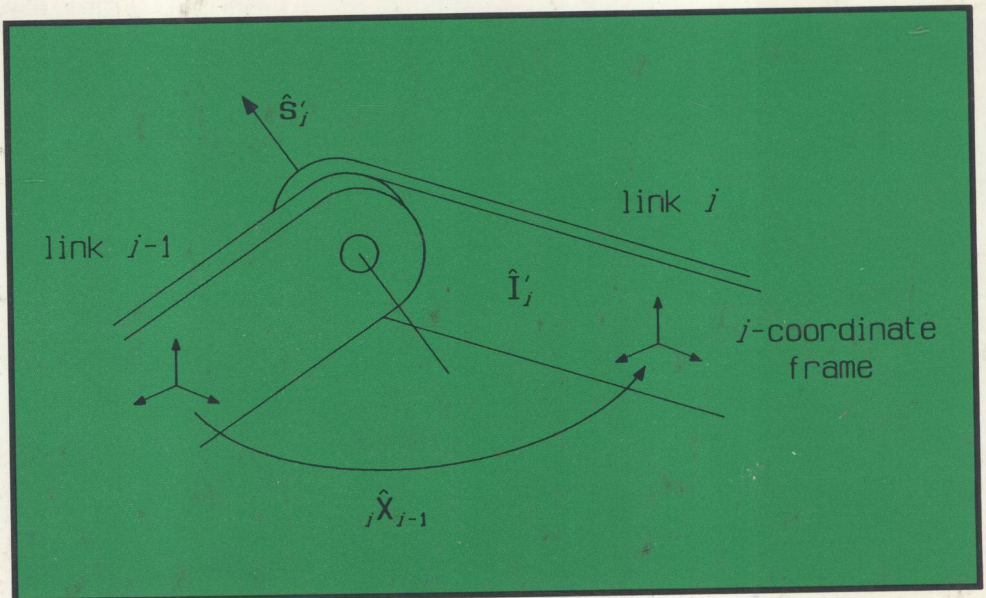
Robot Dynamics Algorithms

Roy Featherstone



Kluwer Academic Publishers

ROBOT DYNAMICS ALGORITHMS

by

Roy Featherstone
Edinburgh University

Kluwer Academic Publishers
Boston/Dordrecht/Lancaster

Distributors for North America:
Kluwer Academic Publishers
101 Philip Drive
Assinippi Park
Norwell, MA 02061, USA

Distributors for the UK and Ireland:
Kluwer Academic Publishers
MTP Press Limited
Falcon House, Queen Square
Lancaster LA1 1RN, UNITED KINGDOM

Distributors for all other countries:
Kluwer Academic Publishers Group
Distribution Centre
Post Office Box 322
3300 AH Dordrecht, THE NETHERLANDS

Library of Congress Cataloging-in-Publication Data

Featherstone, Roy.
Robot dynamics algorithms.

(The Kluwer international series in engineering and computer science ; SECS 22. Robotics)
Based on the author's thesis—Edinburgh University, 1984.
Bibliography: p.
Includes index.
1. Robots—Dynamics. 2. Dynamics, Rigid. 3. Recursive functions. I. Title. II. Series: Kluwer international series in engineering and computer science ; SECS 22. III. Series: Kluwer international series in engineering and computer science. Robotics.
TJ211.4.F43 1987 629.8'92 87-3260
ISBN 0-89838-230-0

Printed in the United States of America

ROBOT DYNAMICS ALGORITHMS

THE KLUWER INTERNATIONAL SERIES IN ENGINEERING AND COMPUTER SCIENCE

ROBOTICS: VISION, MANIPULATION AND SENSORS

Consulting Editor

TAKEO KANADE

Other books in the series:

Robotic Grasping and Fine Manipulation, M. Cutkosky.
ISBN 0-89838-200-9

Shadows and Silhouettes in Computer Vision, S. Shafer.
ISBN 0-89838-167-3

Perceptual Organization and Visual Recognition, D. Lowe
ISBN 0-89838-172-X

Three-Dimensional Machine Vision, T. Kanade, Editor.
ISBN 0-89838-188-6

Preface

The purpose of this book is to present computationally efficient algorithms for calculating the dynamics of robot mechanisms represented as systems of rigid bodies. The efficiency is achieved by the use of recursive formulations of the equations of motion, i.e. formulations in which the equations of motion are expressed implicitly in terms of recurrence relations between the quantities describing the system. The use of recursive formulations in dynamics is fairly new, so the principles of their operation and reasons for their efficiency are explained.

Three main algorithms are described: the recursive Newton-Euler formulation for inverse dynamics (the calculation of the forces given the accelerations), and the composite-rigid-body and articulated-body methods for forward dynamics (the calculation of the accelerations given the forces). These algorithms are initially described in terms of an un-branched, open-loop kinematic chain -- a typical serial robot mechanism. This is done to keep the descriptions of the algorithms simple, and is in line with descriptions appearing in the literature. Once the basic algorithms have been introduced, the restrictions on the mechanism are lifted and the algorithms are extended to cope with kinematic trees and loops, and general constraints at the joints. The problem of simulating the effect of contact between a robot and its environment is also considered. Some consideration is given to the details and practical problems of implementing these algorithms on a computer.

The algorithms are presented using a six-dimensional vector notation called spatial notation, which is similar to the use of screw coordinates to represent vector and tensor quantities. This notation greatly simplifies the analysis of rigid-body dynamics by reducing the number and size of the equations involved. It simplifies the process of formulating the algorithms and allows the finished algorithms to be expressed clearly and concisely.

The reader is assumed to have a knowledge of vectorial mechanics. A knowledge of Lagrangian mechanics would be helpful, but is not necessary. No prior knowledge of robot dynamics, or the dynamics of any other kind of rigid-body system, is required.

Acknowledgments

My thanks to John Hallam and Robert Gray, who read through the draft version of this book and made many useful comments; and also to Magdalena Müller, who took on the arduous task of formatting the equations.

Table of Contents

ROBOT DYNAMICS ALGORITHMS

NOTE: Where Greek letters have been used to denote vectors or matrices, it was intended that they should appear in a bold typeface to distinguish them from scalars. Unfortunately this has not happened, and it is possible that some confusion may arise where the same letter has been used to denote both a vector and a scalar.

Chapter 1
Introduction

1.1. Scope and Contents

This book is concerned with mathematical formulations of the dynamics of robot mechanisms which produce efficient algorithms when implemented on a computer. A robot mechanism is assumed to be a system of rigid bodies connected by ideal joints and powered by ideal force generators. In the sense that a robot mechanism is a rigid-body system, the algorithms described here for robot dynamics are also algorithms for the dynamics of certain classes of rigid-body system.

The efficiency derives from the use of recursive formulations of the equations of motion; i.e., formulations in which the equations of motion of the system as a whole are expressed implicitly in terms of recurrence relations between quantities describing properties of the system. The mathematical formulations are derived with the aid of a 6-dimensional vector notation, called spatial notation, which greatly facilitates the analysis of rigid-body dynamics by reducing the size and number of equations involved. This notation is similar to the use of screw coordinates to represent vector and tensor quantities.

The book is organised into two parts. Part one deals with the spatial notation and its application to spatial rigid-body dynamics, and part two deals with the robot dynamics algorithms.

Three main algorithms are described: the recursive Newton-Euler method for inverse dynamics, and the composite-rigid-body and articulated-body methods for forward dynamics. Inverse dynamics is the problem of finding the joint forces required to produce a given acceleration, and finds application in robot control; whereas forward dynamics is the problem of finding the instantaneous acceleration of a robot given the applied forces, and finds application in simulation.

The algorithms are described initially for an un-branched, open-loop kinematic chain, which is typical of a serial robot mechanism. The descriptions of the algorithms are kept as simple as possible. Once the basic algorithms have been introduced, modifications are described which enable them to cope with branched kinematic chains and a greater variety of constraints at the joints. The details of implementing the algorithms on a computer are then considered; and finally, algorithms are described for calculating the forward dynamics of robot mechanisms with kinematic loops, and for simulating the effect of contact between a robot and its environment.

This book is concerned only with presenting exact, general-purpose, numerical algorithms. Approximate algorithms, special-purpose algorithms (i.e., special to a particular manipulator geometry), and techniques for manual or automatic derivation and simplification of the symbolic equations of motion are not considered. Applications of the dynamics algorithms are mentioned, since the algorithms are designed to be of practical use, but no particular application is described in any detail.

1.2. The Robot Dynamics Problem

In principle, solving the robot dynamics problem presents no difficulty -- a robot mechanism is just a system of rigid bodies, and the equations of motion of such systems have been known for a long time. The real problem is the practical one of finding formulations of robot dynamics that lead to efficient computation algorithms.

In its simplest form, the equation of motion for a robot mechanism can be expressed as a vector differential equation