Robotics Research

The Fourth International Symposium

edited by
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and
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Series Foreword

Artificial intelligence is the study of intelligence using the ideas and methods of computation. Unfortunately, a definition of intelligence seems impossible at the moment because itelligence appears to be an amalgam of so many information-processing and information-representation abilities.

Of course psychology, philosophy, linguistics, and related disciplines offer various perspectives and methodologies for studying intelligence. For the most part, however, the theories proposed in these fields are too incomplete and too vaguely stated to be realized in computational terms. Something more is needed, even though valuable ideas, relationships, and constraints can be gleaned from traditional studies of what are, after all, impressive existence proofs that intelligence is in fact possible.

Artificial intelligence offers a new perspective and a new methodology. Its central goal is to make computers intelligent, both to make them more useful and to understand the principles that make intelligence possible. That intelligent computers will be extremely useful is obvious. The more profound point is that artificial intelligence aims to understand intelligence using the ideas and methods of computation, thus offering a radically new and different basis for theory formation. Most of the people doing work in artificial intelligence believe that these theories will apply to any intelligent information processor, whether biological or solid state.

There are side effects that deserve attention, too. Any program that will successfully model even a small part of intelligence will be inherently massive and complex. Consequently, artificial intelligence continually confronts the limits of computer-science technology. The problems encountered have been hard enough and interesting enough to seduce artificial-intelligence people into working on them with enthusiasm. It is natural, then, that there has been a steady flow of ideas from artificial intelligence to computer science, and the flow shows no sign of abating.

The purpose of this MIT Press Series in Artificial Intelligence is to provide people in many areas, both professionals and students, with timely, detailed information about what is happening on the frontiers in research centers all over the world.

Patrick Henry Winston
J. Michael Brady

Preface

The papers in this volume are a record of the Fourth International Symposium on Robotics Research, held at the University of California at Santa Cruz on August 9 through August 14, 1987. The participants, who came from Australia, Europe, Japan, and the United States, discussed their research and shared their views on the current state of robotics. The symposium was scheduled so that all participants could attend the presentation of each paper; there were no parallel sessions. In addition, blocks of time were set aside for individuals or small groups to discuss research informally, to make new friendships, and to take part in athletic activities. The relaxed atmosphere generated by these informal activities carried over into the formal sessions, encouraging the free interchange of ideas and opinions. The symposium was sponsored jointly by the National Science Foundation and the System Development Foundation.

This series of symposia has been a great success; in fact, we believe it has been the major catalyst in the establishment of the close ties that now link the members of the international robotics-research community. (Some tangible indications of these ties are the increase in the number of robotics researchers who have worked in foreign countries, the increase in the number of papers published under joint international authorship, and the increase in the number of references to foreign research.) The proceedings of these symposia have provided the entire robotics community with descriptions of the latest research results and directions.

The organization of this volume differs from that of the symposium. As the table of contents shows, we have arranged the papers in eight parts. Part I contains descriptions of four state-of-the-art robotic systems, including one that plays ping-pong and another that can turn a somersault. Part II includes papers describing new actuators, sensors, and other devices (among them a magnetically levitated wrist). Part III covers control strategies, some of which combine teleoperation and autonomous techniques. Part IV contains papers describing the kinematics of arms and hands and procedures for calibrating these devices. The papers in part V describe techniques for visually recognizing objects and techniques for automatically programming vision systems to recognize an object when given a three-dimensional model of it. Part VI concentrates on error models and on techniques for estimating task parameters from image sequences. Part VII includes a number of papers describing high-level programming techniques for manipulators. The final papers, in part VIII, describe algorithms for planning collision-free paths through complex environments.

As at previous symposia, the number of participants was limited to encourage scientifically rewarding interactions. The difficult decisions about whom to invite were made by an international committee consisting of S. Arimoto, R. Bolles, M. Brady, O. Faugeras, G. Giralt, H. Miura, L. Paul, and B. Roth. This committee proposed a list of invitees based on technical, institutional, and geographic criteria. The committee selected 68 symposium participants and four observers from the sponsoring organizations.

The symposium banquet was held at the Monterey Bay Aquarium in Monterey, California. During this event a best-paper award was presented to Victor Scheinman for his description of an automatic assembly system called Robotworld. The judging panel for this award was composed of the members of the editorial board of the *International Journal of Robotics Research.*

Many people helped make the symposium a success. We particularly want to thank Cherry Powers-Moser, who did a tremendous amount of planning and then helped to ensure that the meeting ran smoothly by handling numerous details. We also want to thank Prasad Akella, who helped in the day-to-day running of the meeting.

The goal of the International Symposia on Robotics Research is to provide an informal forum for the open exchange of ideas and for the continuing development of close links among researchers from various countries. Over the years, the paper-selection committees have attempted to incorporate new, young researchers into the community and to restrict the publication of papers by authors who have contributed to previous volumes. We continue to search for ways to broaden the participation base while maintaining both the high quality and the personal interactions that have been hallmarks of the first four symposia. We will issue an open call for papers to be presented at the fifth symposium. All papers will be subjected to peer review. To maintain the workshop-like atmosphere of the first four symposia, attendance will be by invitation only and will be limited to approximately 100 researchers, including the authors selected through the peer-review process. The fifth symposium will be held in Tokyo on August 28 through August 31, 1989; the deadline for the submission of papers is January 15, 1989.

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Contents

I SYSTEMS

The integration of hardware and software into a working system is the essence of robotics. All four of the papers in part I describe state-of-the-art systems. Although they were designed for different tasks and with different motivations, they share the distinction of being at the forefront of robotics research and its application.

Hodgins and Raibert describe recent results from Raibert's ongoing efforts to understand locomotion by constructing legged systems and analyzing the scientific principles that govern their performance. The videotape that accompanied the presentation of their paper featured a biped running in a circle and then, while still in full stride, responding to an operator command by bounding into the air and performing a complete somersault. Although the paper describes this action nicely, it cannot convey the delight generated by the videotape.

In a similar vein, the papers by Andersson and Scheinman describe systems that have to be seen to be appreciated. Andersson combines vision and manipulation in his tour-de-force application of robot technology to the playing of ping-pong against a human opponent. Scheinman describes Robotworld, a novel, self-contained world for assembly and inspection robots. Using as many as twenty magnetically levitated, lightweight, fast-moving, simple robot manipulators and vision systems, he has created a miniature factory of the future.

Lozano-Pérez et al. describe a robot system that recognizes and manipulates (mostly) planar-faced objects that can be jumbled together in a pile. In addition, they discuss the difficult choices involved in designing and implementing such complex systems.

Biped Gymnastics

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In this paper we examine the nature of the forward flip and a variant called the front aerial, and we describe how a hydraulically powered biped running machine executes them. We found that the control system can produce a flip by using a fixed pattern of open-loop actuator commands together with algorithms described previously for the control of normal running.

1 Introduction

The forward somersault or *flip* is a gymnastic maneuver in which the performer runs forward, springs off the ground with both feet, rotates the body forward through 360 degrees, and lands in a balanced posture on one or both feet. See figure 1. Human gymnasts can do a forward flip as an isolated maneuver or as part of a floor routine in which the flip is preceded and followed by other maneuvers. The best gymnasts can do double flips. The average teenager can learn to do a forward flip in a few weeks with proper coaching and practice.

To perform a flip, the biped machine runs forward, thrusts with both legs to jump while pitching the body forward, shortens its legs to tuck once airborne, untucks in time to land on its feet, and continues running. The process is initiated by a human operator who uses a joystick to specify the desired running speed on the approach. Once the system reaches an acceptable speed, the operator presses a button that enables the flip sequence—the control program initiates the maneuver when the machine passes a specified location on the circular track in the laboratory. On a good day the machine completes nine out of ten flips successfully.

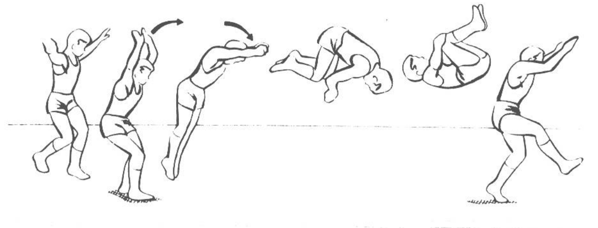

Figure 1: Forward somersault or *flip* as performed by a human gymnast. Drawings reprinted from Tonry (1983).

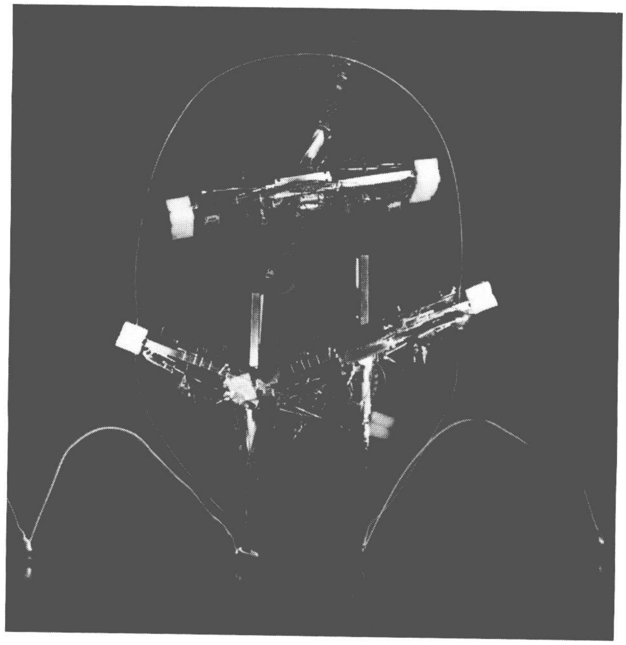

Figure 2: Photograph of planar biped doing a flip. Lines indicate the path of a foot and the flashes are synchronized with liftoff, the highest point of flight, and touchdown. The machine was running from right to left.

The experiments reported in this paper show that a relatively simple control program can accomplish a forward flip. The operations used to perform a flip are each similar to actions that are routinely used to produce normal running. The entire flip maneuver is accomplished by modifying three strides in an otherwise normal sequence of strides. The method used to provide pitch acceleration and maximum thrust to produce a flip depends on predetermined open-loop control data. Symmetries used to simplify the dynamics of normal running also apply to flips and aerials, and were used to develop the control.

In this paper we examine the nature of the forward flip and a variant called the front aerial, and describe how a planar biped running machine executes them. The flip is interesting to study because it is an extremely dynamic form of locomotion that incorporates an extended ballistic phase. It provides an opportunity to examine control techniques for such dynamic activity and to assess their strengths and weaknesses. We developed the control programs that produce flips and aerials by extending previous methods for controlling locomotion. So a second reason we find flips interesting is that they serve to further validate the generality and utility of the previous locomotion control algorithms. Finally, the challenging nature of the project and the visual impact of the result make it lots of fun.

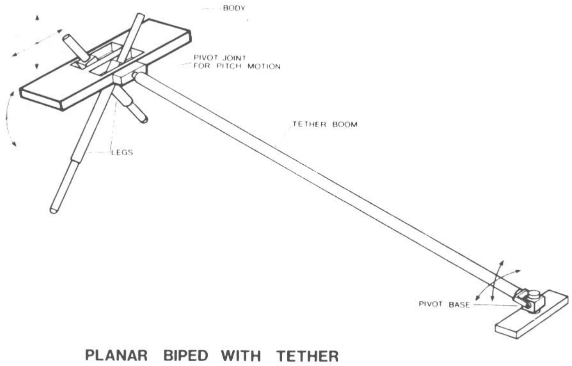

Figure 3: Diagram of planar biped used for experiments. The machine travels by running on a 2.5 m radius circle on the laboratory floor. The body is an aluminum frame on which are mounted hip actuators, hydraulic accumulators, and computer interface electronics. The hip has two low friction hydraulic actuators that position the legs fore and aft. Actuators within the legs change the leg lengths and air springs make the legs springy in the axial direction. Onboard accumulators on the hydraulic supply and return lines increase the instantaneous actuator rate. Sensors on the machine measure the lengths of the legs and air springs, the positions and velocities of the hydraulic hip actuators, and contact between each foot and the floor. A tether mechanism constrains the body to move with three degrees of freedom—fore and aft, up and down, and pitch rotation. Sensors on the tether mechanism measure vertical displacement of the body, forward displacement, and pitch rotation. The tether also supports an umbilical cable that carries hydraulic connections, electrical power, and a connection to the control computer.

2 Mechanics of the Flip

The planar biped running machine, shown in figure 3, has two telescoping legs connected to the body by pivot joints that form hips. Each hip has a hydraulic actuator that positions the leg fore and aft. An actuator within each leg changes the leg length, while an air spring makes the leg springy in the axial direction. The biped's motion is constrained to be planar by a tether mechanism that allows it to move fore and aft, up and down, and to rotate about the pitch axis. The biped is described more fully in Hodgins, Koechling, and Raibert (1985).

A flip is a maneuver in which the flight phase includes one full rotation of the body and legs. The control of such maneuvers must ensure that the system neither over-rotates nor under-rotates. A basic equation governing the behavior

Figure 4: Cartoon of planar biped doing a forward flip. The machine was running from right to left. 1) Approach with normal alternating gait, 2) hurdle step to gain altitude and prepare for double support, 3) the body has accelerated forward to initiate the flip and the legs have shortened to increase pitch rate, 4) landing step reduces pitch and vertical rates, and 5) resume normal alternating gait. The body configurations are from actual data recorded during a flip. The dots indicate the path of the center of mass at 12 ms intervals.

of the body during the flight phase of a flip is

$$n\pi = \frac{\dot{\phi}\dot{z}}{g}, \tag{1}$$

where

- n is the number of full pitch rotations of the body,
- $\dot{\phi}$ is the pitch rate of the body,
- $\dot{z}$ is the vertical velocity of the body, and
- g is the acceleration of gravity.

Equation (1) relates the vertical velocity of the body to its angular velocity. For n full rotations of the body during the flight phase, the rate of body pitch rotation $\dot{\phi}$, times the duration of the flight phase $2\dot{z}/g$, equals the angular displacement of the body $2n\pi$.

Equation (1) relies on several simplifying assumptions. We assume that the legs do not swing with respect to the body during the flight phase, so $\dot{\phi}$ represents the angular rates of both the body and the legs. We further assume that the pitch angle of the body is zero at both liftoff and touchdown, the altitude of the body is the same at liftoff as it is at touchdown, and that there is negligible wind resistance and, therefore, constant angular momentum during flight.

We also assume the pitch rate of the system is constant during the flip. Actually, angular rate may change even though angular momentum is constant. For instance, humans reduce their moment of inertia to increase their rotation rate by tucking the arms and legs. The ice skater's spin is a most dramatic demonstration of this phenomena. Tucking reduces the moment of inertia by concentrating the masses nearer to the center of mass of the system than when untucked.

If the angular rate and moment of inertia of the system in the untucked configuration are $\dot{\phi}_1$ and J_1 and the moment of inertia in the tucked configuration is J_2, then conservation of angular momentum requires the angular rate in the tucked configuration to be $\dot{\phi}_2 = (J_1/J_2)\dot{\phi}_1$. The planar biped tucks † by shortening its legs to minimum length during the

† In describing the actions of the biped running machine we use the terminology of gymnastics. When the biped *tucks* it reduces its moment of inertia by shortening its legs. When it *throws* the body a hip torque is applied that increases the body's rotation rate. We use the gymnastic terminology with some trepidation, lest we oversimplify and mislead the reader by suggesting too strong an analogy between the planar biped and a human. The human versions of each of these actions and the human's physical system itself are substantially richer and more elaborate than the planar biped versions we describe here. Moreover, we may find that the suggested functional analogies are