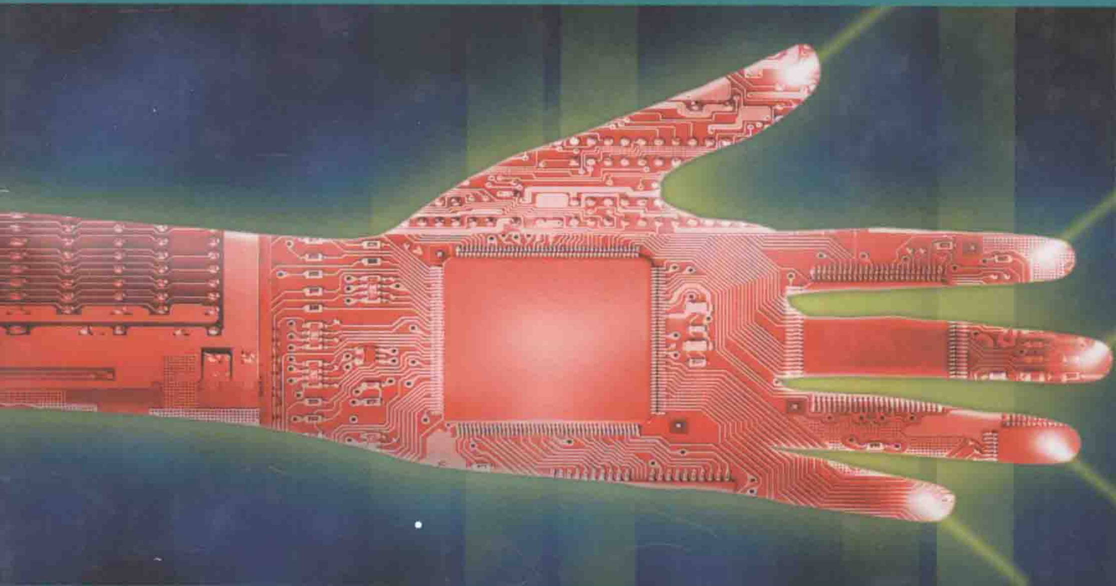

Microrobotics for Micromanipulation

Edited by

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Microrobotics for Micromanipulation

Foreword

Robotics, as established over the last 40 years, has relied on the idea that imitation of manual actions by humans is the best strategy for creating manipulators able to replace the work of humans for highly repetitive tasks in the manufacturing industry. Subsequently, with the advent of mobile robots, it was human and animal locomotion that inspired researchers. Almost anything conceived by nature has been copied in robots, from jumping robots to eel-like robots and robotic coloscopes imitating caterpillars.

As the dimensions of these robots decrease, adhesive problems come to dominate over problems related strictly to mobility. Here again, bio-inspired approaches have flourished. Again, in the context of the exploration of the gastrointestinal tract, for recent endoscopic video capsules ingested by the patient, the challenge has been to understand sliding effects in order to control its movement, or to temporarily attach it to a wall in order to perform a biopsy. Various types of interface have been designed for controlling adhesive effects, based on biomimetic models. One example is the hierarchical lattices of micro- and nanofibers – inspired by those found on the feet of geckos – which exploit van der Waals type forces. Another is that of microfiber lattices covered with a hydrophobic liquid – the secretion of which is triggered by the pressure of a foot resting on the ground, as observed in crickets and cockroaches – an effect that relies on capillary forces. These two examples illustrate the continuity between robotics in the macroworld, whose theoretical and technological underpinnings are well understood in most ways, and robotics in the microworld, where the first steps are only just being taken.

This book reveals the complexities inherent in microrobotics compared to the more familiar macrorobotics. The first difference is the complexity of the theory of the physics of the microworld compared to the macroworld: in the macroworld, gravity and inertial forces behave in a relatively simple manner; the underlying models are within the grasp of any user with a Master's level university education in mechanics or robotics. In the microworld, on the other hand, the surface forces and contact forces that hold sway require a much more sophisticated understanding of physics – in particular electrostatics, thermodynamics, fluid physics, material science, etc. The behavioral laws for fluids, models of friction and roughness must be translated to these small scales. The sorts of effects seen on this scale cannot be reduced to analytical equations whose coefficients are "easily" identifiable physical parameters. The models used introduce empirical or experimental constants that are difficult to quantify, and depend on the materials involved in the interaction, their shapes, and their environment.

The next difference is in terms of experiments: the measured forces may be tens of nano-Newtons; motion can range from microns to millimeters, with resolutions between 0.1 μm and 25 μm and as small as a microradian in orientation. Under these sorts of constraints, environmental conditions play a strong role. For example, a change in temperature of just 5° leads to an expansion of 15 μm in a 100 mm aluminum rod. Humidity also has a strong effect on these interaction forces. It is thus clear that microrobot design, and that of the associated support structures (from working stations up to microfactories), is a whole new field of research beyond conventional robotics, and one that considerably borrows from microelectronics and microsystems.

The final difference is in the nature and diversity of applications for micromanipulation: these can range from the assembly of mechanical, electronic or optical components for products in everyday use, which are being increasingly miniaturized, to the exploration of the living world through the design of micro-instruments, microprobes, microsensors, etc. for diagnostics, monitoring, therapy, surgery, manipulation of cells in their natural environment, and so on. Microrobotics also contributes to the expansion of scientific and technological frontiers by contributing to the development and characterization of novel actuators, materials and processes. Whatever the objectives, it is clear that between the specified need and the integration of a microrobotic solution, a multidisciplinary approach encapsulating a broad spectrum of skills will be called for.

Microrobotics for Micromanipulation is an ambitious work offering a thorough overview of the field and a detailed discussion of specific problems. It reveals a whole new world, along with its limitations, achievements and future prospects, over the course of a thorough state of the art that includes well over 350 references. The theoretical underpinnings are illustrated with real experiments on platforms such as those developed at the ISIR/SI, Paris (formerly LRP) and the FEMTO-ST AS2M, Besançon (formerly LAB). These are used to give a better understanding of the observed phenomena and their complexity. The presentation is clear, rigorous and well illustrated, with a wide range of examples of prototypes and industrial products. Chapters 1–4 end with a series of exercises and answers, something unusual and which deserves special mention in such books. This adds to the undeniable pedagogical qualities of the book.

It was with great interest that I read this book, and it is with great confidence that I recommend it to the reader. It is the fruit of considerable collective effort that includes contributions from the main players in the field (at ISIR and at FEMTO-ST, but also at CEA/LIST, Fontenay aux Roses, IEMN/ISEN, Lille and the Université Libre de Bruxelles). The effort was led by two French pioneers of microrobotics, Stéphane Régnier and Nicolas Chaillet. It deserves to become a definitive reference for future designers and users of microrobots, whether qualified engineers or students in the course of Master's-level study, and whether or not they have prior training in robotics. It will also be a mine of information for doctoral students, qualified researchers and industrial researchers, particularly those who have been regular participants in the French GDR Robotique (robotics research group) working on multiscale manipulation.

I also finished the book with a feeling of nostalgia, remembering the late Alain Bourjault, who launched this theme in 1995 and who supported it throughout his life with great determination. This book definitely owes a great deal to him.

Étienne DOMBRE, DR CNRS, LIRMM, Head of the Robotics Research Group,
CNRS, France

Introduction

Microrobotics is a recent field that has developed over the last 20 years. Following on from an earlier work published in 2002, *La microrobotique* [BOU 02], and in light of recent results within the field, we decided to write a new book targeted at engineers, students and researchers. This book would present a specific field of microrobotics in greater detail that is specifically involved with the manipulation of micron-sized objects.

Generally speaking, a microrobot is a robot that performs tasks in the microworld – in other words the world of micron-sized objects, also known as micro-objects. A microrobot can:

– manipulate micro-objects, in which case it is known as a micromanipulator.

Although a micromanipulator is not necessarily itself micron-sized, it is generally preferable that it should be small, in particular for reasons of structural rigidity and position resolution. This resolution must be submicron so that it can manipulate and position micron-sized objects. The effector of a micromanipulator must, on the other hand, necessarily be micron-sized, since it is immersed in the microworld, interacting with micro-robjects. All or part of such a microrobot may be based on deformable structures; this avoids the backlash and friction inherent in articulated mechanisms, which, bearing in mind the scale we are working on, are liable to catastrophically degrade the resolution;

– be totally immersed in the microworld, in which case the microrobot itself is micron-sized.

Such robots are generally mobile, able to move in a confined environment (such as within the human body) in order to carry out a task (which might be the transport of micro-objects).

This book very much focuses on the first type, i.e. the manipulation of micron-sized objects, also known as micromanipulation. Given the increasing miniaturization of everyday consumer products, the need for micromanipulation is growing, and in particular for microassembly. Micromechanisms (watches, medical, etc.), microsystems, optics, microelectronics and biology are increasingly in need of efficient and reliable methods of micromanipulation. This book obviously has a bias towards the manipulation of objects by robotic means: inspired by methods that have been tried and tested on macroscopic scales, microrobotics offer the flexibility required in the fabrication of products that have some degree of variability.

Self-assembly, which involves exploiting forces that can cause several micro-objects to position themselves spontaneously at predetermined positions on a surface (making use of long-range forces such as electrostatic forces, or contact forces such as capillary forces), is not within the scope of the present book. This book will concentrate on manipulation by microrobots (which is by nature serial, in contrast to self-assembly, which is parallel but at present still not very flexible).

It should be noted that a microrobot is not necessarily a "MEMS" (*Micro-Electro-Mechanical System*), in other words a microsystem mostly fabricated using microfabrication technologies coming from microelectronics. It may, however, make use of microfabrication technologies, integrating one or more MEMSs, especially for its effectors. If the whole robot is micron-sized, it may itself be a MEMS.

The physical scales discussed in this book span a broad range: the microworld covers the range of 1 μm–1 mm, which is three whole orders of magnitude! It is clear that the physical effects underlying the static and dynamic behaviors involved will vary in strength over such a large range of scales. It is thus important to recognize and understand them as much as possible. Furthermore, many micromanipulation solutions have appeared in recent years that make use of phenomena specific to the scales they operate on. Each solution has its own advantages and disadvantages, but to date no one solution has shown enough clear advantages to raise it clearly above the others. As a result, an understanding of the physics of the microworld is a crucial element of microrobotics, both to understand the behavior of objects on this scale and to appreciate the specific effects used in a given microprehensor. The first chapter of this book describes in detail this physics and the forces involved.

In order to achieve very high positioning resolutions, and consequently very high repeatabilities and precisions, specific actuators may be used, and in particular ones based on active materials such as piezoelectric ceramics, which are currently without question the most widely used material for driving micromanipulators. Chapter 2 presents some of these actuator materials, along with a discussion of guiding with the use of compliant structures.

Generally speaking, the change in the balance of forces involved on the macroscopic scale (where volume-based forces such as weight and inertia dominate) and on the microscopic scale (where surface-based forces such as capillary and electrostatic forces dominate) renders the problem of prehension a particularly delicate one. Chapter 3 therefore discusses microprehensors and micromanipulation strategies applicable in this context.

Beyond the crucial issue of prehension, the scale we are working on also introduces requirements on manipulators. In addition, given that a human cannot directly view the workspace, and cannot feel forces on the microscopic scale, a micromanipulation station must incorporate a vision system and suitable force measurement apparatus. Even if the station is not to be fully automatic, these are crucial for remote operation. All this, along with some elements of control theory, is presented in Chapter 4.

Chapter 5 describes fabrication technologies suitable for microsystems and particularly useful for the fabrication of all or part of a microrobot.

Chapter 6 offers two future directions for micromanipulation:

– further reduction in the scale of the objects to be manipulated, extending the manipulation to nanometer-sized objects. This field of nanorobotics, still in its infancy, is likely to prove an extremely useful complement to the growth of nanotechnologies;

– integration of micromanipulators into a more complete miniaturized production system for microproducts. Such a production system, still very much in the early research stages, is commonly referred to as a microfactory.

Throughout this book, a recurring theme is that of scaling effects. Compared to the macroscopic scale, these introduce a very marked evolution in the dynamics of objects, and require a complete rethink of their function and the techniques used to manipulate them. The three scientific principles underlying this development are:

– knowledge of the dynamics of the microworld, in order to understand it and exploit specific phenomena;

– (micro)mechatronics, for the construction of suitable microrobotic components and structures;

– control of microrobotic systems, and associated perception functions.

We hope that this book, with its detailed review of microrobotics in the sense of robotics for micromanipulation, and its exercises to help the reader understand and master the field, will help engineers, students and researchers to become familiar with this recent field, and to contribute to its development through their scientific and technological work.

Nicolas CHAILLET and Stéphane RÉGNIER

Table of Contents