ANALYTICAL ROBOTICS AND MECHATRONICS

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ABOUT THE AUTHOR

Wolfram Stadler was born in Germany, where he received all of his basic education. He emigrated to the United States at the age of 17. After a variety of jobs, including four years of service in the U.S. Air Force, he began his university studies at Georgia Institute of Technology, in Aerospace Engineering. There he earned a B.S. and an M.S. in Aerospace Engineering, as well as an M.S. and a Ph.D. in Engineering Science and Mechanics.

He was an Assistant Professor at Georgia Institute of Technology, with a joint appointment in Mathematics and Mechanics. Subsequently he went to the University of California at Berkeley as a post-doctoral fellow. There he began studies in optimal control and multicriteria optimization, which are still his main research areas. He has been at San Francisco State University since 1978.

Professor Stadler has been a visiting professor at the University of Munich, at the University of Bonn, and at Osaka University. (At the latter, he was the recipient of a senior research fellowship from the Japan Society for the Promotion of Science.) He has presented invited lectures all over the world.

He has more than 50 publications, on topics such as Newtonian dynamics, shell theory, control theory, and optimal structural design, as well as numerous contributions to multicriteria optimization, including surveys and historical articles. He has published four books and has contributed chapters to several others. He is an associate editor on three international journals dealing with control and optimization.

Professor Stadler has taught 23 different courses in Engineering and Mathematics, ranging from basic calculus to Laplace transforms and a graduate course in linear algebra, and from gas dynamics to courses in robotics, controls and optimization. He is bilingual (English and German), is conversant in Spanish and French, and has a nodding acquaintance with Russian.

PREFACE

In 1983 I received an offer I could not refuse: Teach robotics or be out of a job. At that time, junior/senior courses in robotics were not in evidence and neither were any texts dedicated to this level; so I began to write this textbook. Since similar offers are quite likely still being made, I hope to ease the task for others who cannot refuse.

My approach to the subject was a didactic one, with the goal of presenting the student with the background needed for any endeavor connected with robotics. Rather than emphasizing current and rapidly changing technology, the emphasis here is on established fundamental concepts. This ultimately leads to an understanding of any related evolving technology. The student should thus feel comfortable with *any* robot.

The basic concepts are no different for robotics than they are for the description of other physical phenomena. Robotics differs in the extensive integration of concepts from a variety of individual disciplines. Thus, concepts from solid-state physics, computer science, fluids, dynamics, controls, circuits, and machine design, to name a few, all play a role in robotics. This collection of separate parts is frequently termed *mechatronics*, with robotics as its central application.

The material of the book builds on a presumed background course each in circuits, in dynamics, and in systems analysis—a background common to all of our students at the end of their fifth semester (ideally speaking). An effort has been made throughout the textbook to tie in new topics to previous experience and expertise for both the students and the instructor. To ease this transition, many topics from mathematics and physics are reviewed and presented where they are needed. A "just in time" approach is taken, rather than relegating the transitions and background material to an appendix.

With the exception of this just-in-time approach, the book is written in a rather traditional textbook style, with discussion, examples, exercises, and numerous figures to aid in the visualization of topics. The book also lends itself to course structures tailored to an individual instructor's tastes and aims. The course offered at San Francisco State University is a one-semester course which serves as an elective for both electrical and mechanical engineering majors; this book could easily be used for a two-semester sequence. With some variations, the course here is usually comprised of the following chapters and sections: most of Chapters 1, 2, and 3, which deal with a synopsis of fundamental ideas and problems in robotics, and with motion fundamentals embodied in three-dimensional rigid body dynamics; selections from Chapter 4, including a discussion of semiconductors and the depletion region; a selection of several sensors, which usually includes accelerometers and force and tactile sensors, from Chapter 5; and most of Chapter 6, since I believe that an understanding of the limitations and promise of vision systems is essential. The remainder of the course deals with actuators, power transmission devices, and the planning and implementation of robot trajectories. The course also includes weekly homework, two exams, a final examination, a term project, and an essay on the social implications of automation and robotics. The course is not an easy course since it draws on virtually all of the student's background. However, when asked if he or she would feel comfortable in dealing with any robot, even the average student answers with a confident "yes."

Ideally, a robotics laboratory course should be taken concurrently with this course, to provide the needed hands-on experience. In fact, it should be made an integral part of the course. When this is not done, students tend to avoid the lab with the usual aversion to any laboratory experience.

Robotics has changed dramatically since my first foray into the subject in 1983, when a certain amount of science fiction still imbued the subject with an almost other-worldly atmosphere. There were industry projections of billions of dollars in sales, and the market contained more than 40 companies involved in robotics. Experts were making statements such as, "In 20 years we will have robots with intelligence and emotions equivalent to those of human beings." My projection in 1983 was that robots would begin to catch on in about 15 years after the general public—as well as engineers—had learned to routinely accept them in their work environment, and that no robot would act or feel like a human being in the foreseeable future. I believe that these projections are still true.

The primary purpose of the robot as a machine is controlled motion: If it does not move, it is not a robot. All of the robotic design endeavor has controlled, sensitive, and intelligent motion as its collective goal. The variety of uses for robots is increasing, although their main use still seems to reside in automobile manufacturing. The number of producers of robots has decreased considerably, so that now there are only between five to ten manufacturers left, the biggest market share being occupied by ABB (ASAE, Brown, Boveri) and by GMF (General Motors, Fanuc).

Now there is a consolidation of robotics, as well as a broadening to the mix of applied mechanics and electronics termed mechatronics. This is a collective viewpoint to which mechanics should have evolved long ago. Robotics and mechatronics have become part of most modern curricula in mechanical and electrical engineering. Although the technology will continue to evolve, the background needed to understand it will remain the same. I believe that this book provides that background.

Wolfram Stadler

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Robotics and mechatronics are a high-tech joining of a number of classical fields and engineering theories. Thus we stand not so much on the shoulders of a few giants as on a multitude of competent individuals who have managed to see classical results in a new light. The basic concepts have not changed; the way we view and combine them has.

This textbook could not have come to be without the numerous texts on robotics that preceded it. Their viewpoints influenced mine, and their emphases created a standard. There were two which proved particularly helpful, not so much because of their detailed treatment of individual topics, but more so because of the timeliness of their appearance and because of what they treated. One was Engelberger's book *Robotics in Practice*; the other was *Freiprogrammierbare Manipulatoren* by C. Blume and R. Dillmann.

As one reviewer remarked, a better treatment of diodes can be found in a basic electrical engineering text, and similar comments may well apply to much of what I have presented. To some extent, the electrical material was written for the mechanical engineer, and the mechanics for the electrical engineer; both of them may find the math and physics useful. Part of my contribution consists of putting it all together and presenting it in a unified form.

I have avoided citing large numbers of often irrelevant references. Instead, I have cited desk references, treating the specific topic and related ones in greater detail. Whenever feasible, I then adhered to the notation used in the cited reference. The viewpoints, treatments, and interpretations are my own (as are any errors). When I saw myself unable to improve upon a particularly lucid explanation, I quoted it.

By and large, I have treated homework problems and problems in general as part of the public domain; and I would like to offer those who find some of my problems particularly interesting or useful the freedom to use them in their own writings. In addition, I would encourage those who have some favorite problems they would like to see included in some future edition to send them to me with their solutions. If I find myself in agreement, I should like to include them, together with a proper citation of their authors.

Mechatronics is such an interdisciplinary subject that, even with a relatively broad background, I found myself constantly studying and learning new concepts and methods. Absorbing this information, assuring myself of its correctness, and then recording it in an acceptable form would not have been possible without my colleagues' willingness to share their expertise, listen to my questions, and study various segments of the manuscript. I am grateful to S. Franco, S. Hu, S. S. Liou, and R. Zimmerman for their critical reading of the material on electronics, computer logic, and electric motors; to J. Lockhart from the Physics Department for his help and patience with the Hall effect; to A. Wheeler and A. Ganji for their perusal of the segments on hydraulic and pneumatic actuators; and to V. Krishnan for his comments on the material concerning statistics and control theory. I am also grateful to my European colleagues W. Schiehlen and E. Kreuzer for sharing their robotics notes with me.

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My obligation to my students provided stimulation to continue writing, and their comments, criticisms, and corrections were essential contributions. My particular thanks go to Jon Moore, who read and commented upon much of the manuscript.

The active support and patience of the editors and staff of McGraw-Hill were an extremely positive influence. I appreciated the editors' work in searching out suitable and knowledgeable reviewers, whose remarks provided essential expert guidance with respect to content and completeness: Harvey Lipkin, Georgia Institute of Technology; Mahmood Nahvi, California Polytechnic State University; and Ronald A. Perez, University of Wisconsin, Milwaukee, as well as others who commented on incomplete versions of the book.

I am deeply grateful to my wife for her well nigh infinite patience and skill in typing and editing the many variants of this book as it evolved.

Finally, there is One without whom none of this would have been written. He prepared the beginning, provided the direction, sustained me when the task seemed onerous, and gave me the understanding to complete it: God.

Wolfram Stadler

AUTOMATION WITH A SOCIAL CONSCIENCE

We are discovering that the more triumphant our technology, the less does society function automatically.

—Eric Hoffer

For approximately 10 years I have used the last class of all my courses for a discussion of ethics—not engineering ethics, not business ethics, but simply ethics. I offered my first course in robotics in 1983, and since 1984 I have required that each student taking the course write an essay on the social impact of robotics and automation in society. No great literary pieces emerged; but the students did present me with a plethora of ideas and they were forced to take such issues under consideration. Every manager who implements automation should have to write an essay about the impact of his decision to automate a particular routine in the work cycles under his purview. Similarly, all who work on or promote concepts of automation should be made to consider the possible social impact of their work. Since I require it of others, I feel compelled to provide such an assessment of my own views on this topic.

Our physical existence demands that we have food and a place to lay our heads, and our social well being demands that we perform some useful function for society. If we do not produce our own food and dwelling, then we must acquire them indirectly by providing a product or service in exchange for food and lodging. If we consider these essential for all of humanity, then a modicum of mass production and automation is needed in an industrial society to achieve some uniform standard or level of existence for a given population segment. If this had been the sole aim, the needed modicum could have been achieved long ago.

In modern society, the capability to provide these basic needs has existed some time and could provide a reasonable living standard. The intent of this capability, however, is frequently usurped by greed and the obsession with the acquisition of wealth and individual power. Excessive advertising and manipulation of the society have continued to increase individual need far beyond the basic requirements in order to meet the economic dictum of growth. Not only has modern western society accepted this view, but it has also managed to infect the aspirations of the remaining nations of the world to make it their primary goal to acquire these same material comforts. We shall first look at the benefits or detriments of automation the way it is presently imposed upon society in this presumed state of the world.

If we deem it desirable to continue to raise the material living standard of ever-increasing segments of the human population, then mass production and the associated technology are essential. The "we" referred to is crucial here, presumably composed of those who benefit from automation. Potential beneficiaries are the producer and the stockholder, the salesperson and the worker, and society as a whole.

Suppose we begin the analysis by looking at producer and stockholder. Generally, efficiency, when applied to automation, may be taken to be equivalent to more, quicker, cheaper, and sometimes better quality, ultimately again meaning cheaper. The immediate savings (and increased profits) primarily derive from the elimination of a category of jobs. The decision is usually carried out with the assurance (lamely given) that more highly skilled and, presumably, better paying jobs will, of course, eventually be created in the not too distant future. But these jobs are *never* provided at the time when automation is introduced. Thus the corporation no longer pays salaries or provides insurance, retirement, or other benefits, and in some cases is even granted a tax write-off for work force reduction. More often than not, the initial cost of automation is amortized in less than two years. The short-term monetary benefits to corporation and stockholder thus are obvious.

This wholesale and indiscriminate elimination of segments of a corporate work force, frequently consisting of the elimination of whole departments whose expertise is deemed outdated, brings about a reduction of the technical capabilities, and eliminates the seeds of innovation, since the collective experience of the worker, his or her interaction and exchange of ideas with other workers, is also eliminated. This can be destructive in much the same way the now recognized arbitrary elimination of a segment of the ecological chain can have devastating effects. Machines simply do not discuss innovation or improvements, or anything else, for that matter.

Finally, excessive automation tends to stagnate an industry, since replacement and upgrading of an automated system will now involve real cost without the immediate savings derived from employees who were laid off. This should be evident from the almost biennial required upgrading of computational tools, which may cost companies far more now than upgrading the employees. A major effect of this stagnation and implied resistance to real change is that the public must now be manipulated with fads and fashions that imitate change and thus allow the company to continue making the same product. This can only be accomplished with ever-increasing marketing and advertising expenditures. Thus the net result is a shifting of expenditures from production to sales. The best examples are the relics of automobile industries and the clothing industry.

This brings us to the laid-off employee. The immediate benefits are zero, or negative. Those with a strong constitution adjust, possibly improve their skills, and move on to another job, which *always* requires a reduction in income. The employee's personal involvement in the next job will quite likely be reduced to loyalty to oneself. Those with weaker constitutions will tend to remain on state support for some time, and any subsequent job will be at considerably reduced pay. In summary, I can see few benefits to the laid-off employee (in spite of the occasional, somewhat random exception).

The benefits to society of this approach are also dubious. The laid-off individuals often become an immediate financial burden to society, not only in terms of actual employment benefits, for example, but they also no longer pay taxes, they may not be able to pay off their debts, and they are less likely to purchase anything even if they do have sufficient savings. More indirect effects are those on their children, who will lack proper care, and the strain that the situation puts on families. None of us is isolated from these effects.

The approach we are talking about also produces an enormously self-centered moral climate, where individuals are looked at as commodities or percentages in a battle-like scenario, and where we accept a percentage of people without jobs as normal as long as we can maintain our own relatively affluent (generally speaking) standard of living.

Based on the preceding analysis, only marketing, sales, and advertising reap direct benefits from this approach to automation. Regardless of whether this societal state is desirable or not, it cannot continue to exist without the continuous introduction of new technology and automation. In particular, competing members and proponents of this society will find it essential to continue to automate, with the attendant reduction in work force, in order to remain competitive—to create a pool of jobless in order to maintain the eventually excessive lifestyles of a few. The final result would seem to be an expert marketing and sales force, selling foreign products to those few still capable of buying them.

I think there is another approach to the introduction and use of automation in society. The effect on society as a whole must be of primary importance.

Automation and technology are inextricably linked; we cannot have one without the other. At present, new technology is often viewed like an old mountain: we use it and, in the case of technology produce it, because it is there. Nary a thought is given to the desirability of new technology and its effect on society. Our lives are expected to continuously adjust to new technology foisted upon us by impressionable management and by an ever-increasing sales force. Faced with this continuous adjustment, there is little time to consider the quality of life, the kind of life we should like to lead as enlightened and educated individuals.

Automation and technology can benefit all of us, but we need to maintain control rather than be pulled hither and yon by more and more things that we neither need nor want. Only few would wish to return to an agrarian society where virtually all have to till the soil in order to eat. Our food is abundant because of the mechanization of every aspect of food production.

We should learn to plan the evolution of society over several centuries and learn to plan in such a grand framework rather than the minute plans whose failures are constantly in evidence. We should visualize and plan this ideal society and then evolve the technology and introduce automation which harmonizes with this goal. This would require the will to say no to some technology and to accept new technology only after it has passed a societal impact statement of sorts. It is relatively easy to deduce some of the basic edicts of such a society, although their refinement and implementation may be difficult and arduous.

Clearly, every member of such a society would have to be considered essential and indispensable, and each individual would have to be given the opportunity to realize his or her implied potential. Automation would thus need to be an evolutionary process, not the warlike and revolutionary process it now tends to be. Rather than being used to increase competitiveness and profit, it should be used in the service of society; it should free society from a great many onerous or dangerous jobs. The greatest challenge then would be how to use the freedom gained in a productive, constructive, and sensitive manner.

Once a desire for a more peaceful and less disruptive introduction of automation has been established within a society, acceptable rules for its implementation can be established. It is clear what these rules must accomplish. At present, the brunt of the introduction of automation is borne by the displaced employee, with benefits mostly accruing to company and stockholder. A more equitable distribution of the burden as well as benefits must be achieved by these rules. It then falls upon both employees and management to adjust (which might include retraining) and to create a new and productive niche for those who are displaced by automation.

The introduction of automation must occur without the loss of jobs. Its purpose must be service rather than competition. As long as automation threatens the jobs of those whose work it is designed to perform, the efforts of management and employee should go into the smooth transition to an automated environment, with benefits to all of society and not just a select few.