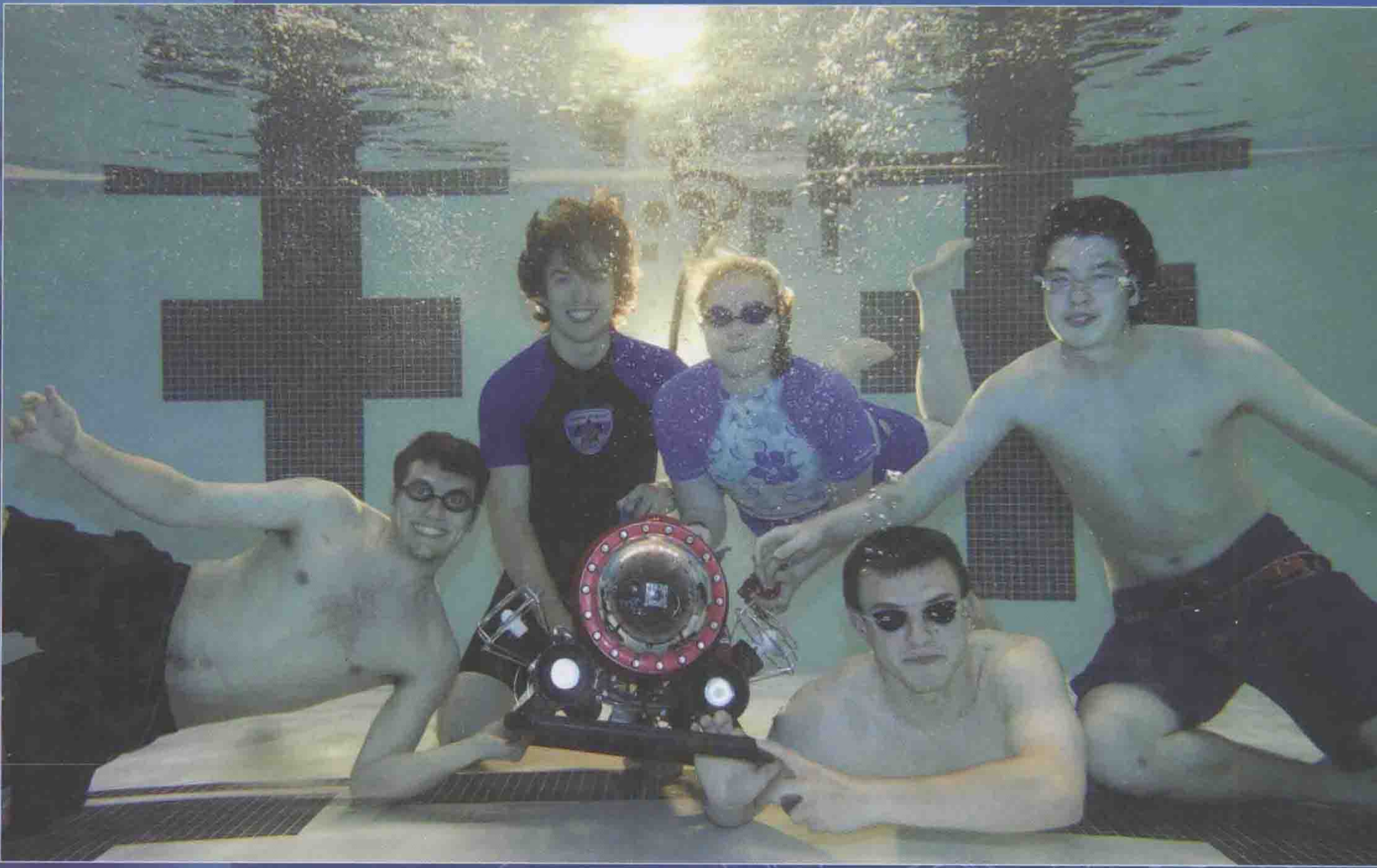

Underwater Robotics

Science, Design & Fabrication

Steven W. Moore
Harry Bohm
Vickie Jensen

MATE
MARINE ADVANCED TECHNOLOGY EDUCATION CENTER

NSF

Underwater Robotics

Science, Design & Fabrication

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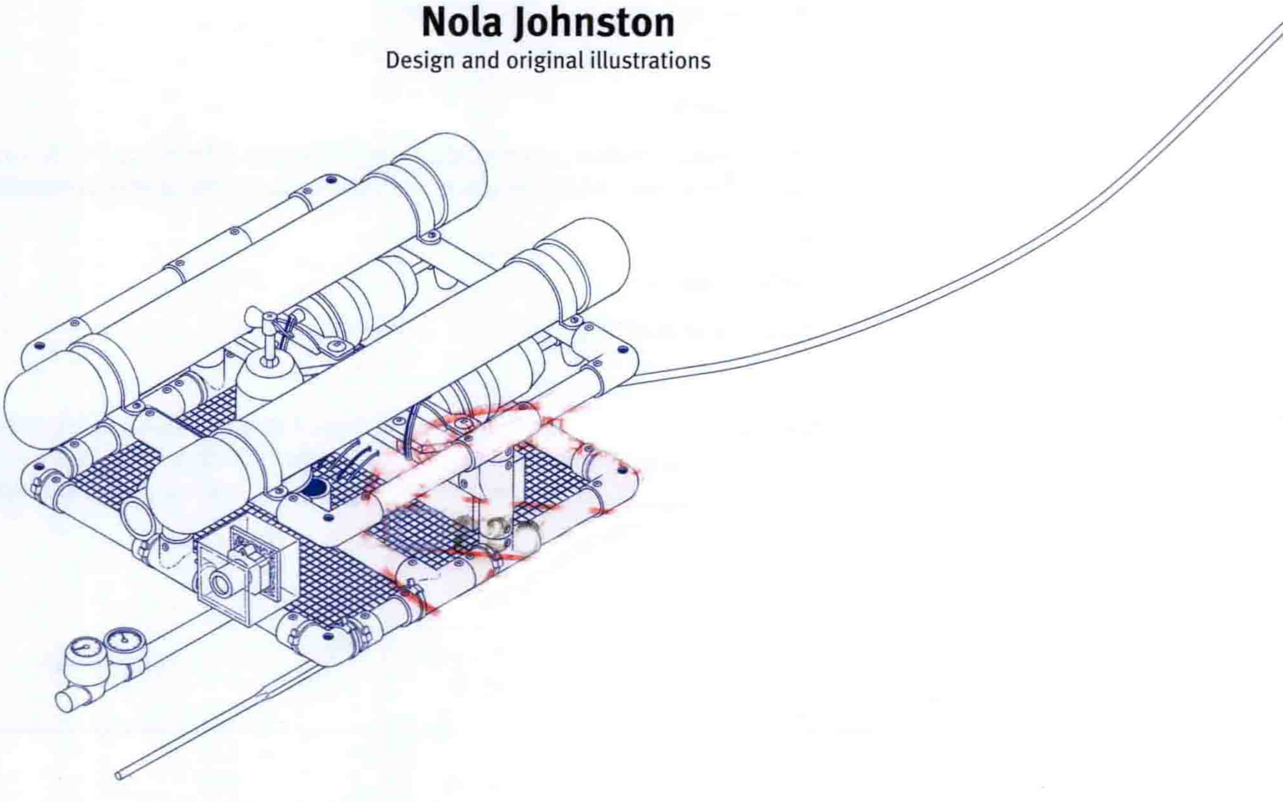

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Underwater Robotics

Science, Design & Fabrication

PREFACE BY DREW MICHEL

Life member and fellow in the Marine Technology Society (MTS), chair of the MTS ROV Committee since 1992, co-chair of the annual Underwater Intervention Conference, senior member of the Institute of Electrical and Electronic Engineers (IEEE). Drew Michel has worked for over four decades in the undersea industry.

Underwater Robotics: Science, Design & Fabrication is the text and reference book that underwater robotics educators have been waiting for. Best of all, it lives up to expectations, with an amazing collection of technical information, stories, and photos in one convenient place.

The primary purpose of this book is to introduce newcomers to the very complex world of subsea technology, but it is also a fascinating look back at the development of subsea inventions for work and exploration. This text explains where we are today, explores possibilities for the future, and encourages individuals to consider careers in this field. Equally as important, the book provides readers with a sense of perspective—a look back at where we've traveled on this long subsea journey and the interesting characters who led the way. It starts with understanding the consequences of human exposure to pressure, moves through the courageous era of sitting in cramped submersibles, and arrives at today's reality of telepresence in the undersea world.

Underwater Robotics: Science, Design & Fabrication is an invaluable tool for young minds working on starter projects and provides the material to help them move to advanced options and continue to learn. It is also a reference book for those working in the industry and will be a valuable addition to the collections of those who have had long careers in the undersea arena. Picture a young student learning how to solder for the first time. Then see that student a year later, wiring the control system on his or her team's entry in the MATE International ROV Competition. Then, fast-forward 10 years to that same person, now an ROV supervisor, browsing through a well-worn copy of the book while sitting in the ROV control room of a major offshore energy project or scientific expedition. This book has the potential to inspire and enable those dreams.

Finally, a word about those who made this book happen. There are people in this world who go to work every day to earn enough money to be able to live and do the things they enjoy. Then there are others whose work is their love. The educators I have had the good fortune to deal with in my 44 years in this industry fit that latter category. The people at the MATE Center and many others who worked long and hard to make this book a reality certainly are part of that fraternity. They deserve high praise for their perseverance and dedication.

PREFACE BY DON WALSH, PhD

Captain USN (ret), oceanographer, marine policy specialist, former dean and professor (University of Southern California), Honorary President of the Explorers Club, and member of U.S. National Academy of Engineering. In 1960, Don Walsh and Jacques Piccard piloted the U.S. Navy bathyscaph Trieste *to the deepest point in the world's oceans, a feat never repeated.*

Underwater Robotics: Science, Design & Fabrication is most welcome in the world of ocean engineering. It is a well-organized survey of all major aspects of underwater engineering, and it leads students, educators, industry professionals, technology enthusiasts, and other interested readers through each subject area in an intelligent and engaging way.

Ocean engineering is a relatively new field of study. It is also an interdisciplinary field, in which a basic knowledge of mathematics, earth sciences, physics, computer technology, business, and the engineering arts and sciences is required, even for entry-level and support staff. While there are many excellent academic programs throughout the world that train ocean engineers and offer degrees in oceanography, the area of technical education for professionals who support ocean engineering work is still in the early stages of development. Qualified professionals are in high demand, yet few comprehensive training programs or learning materials are available—until now.

This book fills a real need for a broad introduction to oceanographic work. The stories, technical information, scientific knowledge, and projects provide an excellent "tour of the horizon" of this fascinating, wide-ranging interdisciplinary field. Some of the essential concepts and principles that apply to underwater technology can be daunting to those who are new to this work; the authors are to be congratulated for providing easy access to complicated material.

Underwater Robotics: Science, Design & Fabrication is produced by the Marine Advanced Technology Education (MATE) Center at Monterey Peninsula College in California. Supported by the National Science Foundation since 1997, the MATE Center works with schools and colleges nationwide to raise awareness of ocean science, technology, and engineering fields. MATE also strives to provide education and professional development for individuals working in these fields, and to recruit and train new technical professionals. This book is a significant contribution to that mission.

INTRODUCTION

There is a story behind every good book, and this one is no exception. Our story begins in 1999 with the MATE Center's discovery of the book *Build Your Own Underwater Robot and Other Wet Projects*, co-authored by Harry Bohm and Vickie Jensen. It was perfect timing, as our marine workforce studies indicated that the skills needed to design, build, and operate underwater vehicles (and other "wet" technologies) were in high demand. We immediately contacted Harry about expanding the book into a series of modules for a new college-level course on underwater robots at Monterey Peninsula College. Harry wrote those modules, keeping one step ahead of instructor Frank Barrows; both finished up amazed at the enthusiasm and learning going on in that classroom. In the summer of 2000, Harry delivered MATE's first summer institute focused on ROVs. The teachers who participated were also hooked. We knew that we were on to something!

Later that year, MATE asked Vickie and Harry to edit the modules into a full-scale textbook. As that book started to take shape, so did MATE's very first ROV competition. MATE called upon Harry's knowledge and expertise in the development of that program as well. From engineering the underwater props to creating the stories that put the mission tasks in context, Harry helped to build the competition from the ground up—just as he helped so many of the students to build their first ROVs.

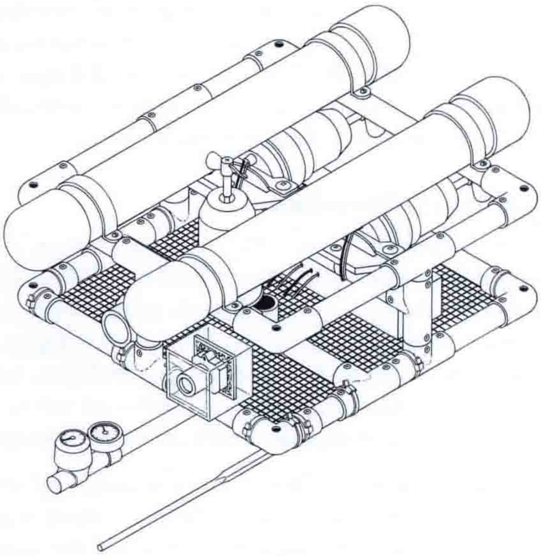
As the competition gained momentum over the next few years, so did the textbook. In 2003, Dr. Steve Moore joined the writing team. His content expertise and classroom teaching experience were perfect complements to Harry's ability to think outside of the box and turn everyday materials into incredible inventions and Vickie's editorial prowess, organizational skills, and ability to channel creativity into words on a page.

Building underwater robots often takes more time, more prototypes, more money, and more effort than ever envisioned at the start of the project. It turns out that the same is true for underwater robot textbooks! The process of this writing project has taken us on an incredible journey of underwater robotics education, one that saw the modules MATE commissioned for our very first college course grow into this 769-page textbook. It also involved our summer faculty development institutes and MATE's annual competition program that engages thousands of teachers and students from around the world.

Underwater Robotics: Science, Design & Fabrication wouldn't have been possible without Harry setting the vision and Steve and Vickie contributing their knowledge and expertise to carry it out. The MATE Center is forever grateful to these individuals and the contributions that they have made to our mission.

And this is where our story ends—or, rather, begins with you and the book that you hold in your hands. We look forward to seeing how you write the next chapters.

—Jill Zande, MATE Associate Director and textbook project coordinator



HOW TO USE THIS BOOK

Underwater Robotics: Science, Design & Fabrication welcomes you to the exciting world of underwater vehicle technology! This book provides an engaging blend of real-life stories, up-to-date technical information, and pragmatic "how-to" advice. It also guides you through the process of designing, building, and diving your own small custom-made, remotely-controlled underwater craft. You can use the *SeaMATE* ROV to carry out various underwater missions, from basic exploration to challenging search and recovery adventures.

The book is written primarily for high school and college students who want to have fun while developing marketable technical and teamwork skills. It is also a handy reference for educators, hobbyists, and others interested in marine technology, electronics, robotics, and similar topics. As an introductory book, this text assumes no prior experience with robotics or underwater vehicles; however, it does presume a working knowledge of high school algebra and geometry.

This textbook is structured to be highly flexible. If you are new to underwater vehicle design and construction (as many readers will be), it's probably best to read the chapters in order, since each builds to some extent on the previous chapters. On the other hand, if you already have experience with much of the material covered in this book, you may find it more useful to use this text as a reference and jump directly to the chapter you need at the moment. The choice is up to you.

How the Text is Organized

Underwater Robotics: Science, Design & Fabrication is not a conventional textbook, but then subsea technology is not a conventional academic discipline—it's interdisciplinary! So this book covers physics, marine biology, oceanography, math, chemistry, construction, tool use, design strategies, trouble-shooting, project planning, and teamwork—all subjects that will help you create more successful underwater vehicles.

Chapters 1–2 provide an introductory overview of manned and unmanned underwater craft (from earliest times to modern day) and offer pragmatic strategies for designing underwater robots.

Chapters 3–10 introduce the opportunities and challenges of working under water, then focus on specific technical solutions, ranging from structure and materials to power systems and payloads. Each of these chapters introduces relevant science and engineering concepts, as well as their pragmatic application to underwater robotics. There are ample visual and textual examples, from basic home-built robotic vehicles to complex commercial craft.

Chapter 11 is a different kind of technical chapter, one that moves beyond vehicle design and concentrates on the real world of subsea work and the logistics of preparing for and carrying out simple missions.

Chapter 12 provides you with an opportunity for guided hands-on learning, with detailed plans and instructions for assembling a "build-as-you-learn" ROV called *SeaMATE*. Readers can either construct this shallow-diving project in stages, coordinating it with their progress through each of the technical chapters, or they can tackle it independent of the other chapters. Chapter 12 also discusses options for upgrading *SeaMATE* or for building even more sophisticated ROVs or AUVs.

Textual Aids and Information

- Each of the chapters begins with a section called *Stories from Real Life* that highlights a real-world event related to the main focus of that chapter.
- All chapters also include an outline, a list of learning outcomes, the main text of the chapter, and a summary.
- The text features more than 500 photographs and illustrations. This wealth of color photographs helps readers connect with actual examples of subsea robotics. The straightforward illustrations are designed to expand and explain textual concepts.
- The authentic examples in this text help bridge the gap between theory and the excitement of on-the-job experience. While many of these focus on North America, the authors stress the worldwide application of underwater technology and exploration. Teachers and students are encouraged to supplement this text with other, locally relevant examples.
- Most measurements are given in metric units, such as meters and newtons; however, imperial equivalents are usually provided to assist those readers who may be more familiar with imperial (English) units, such as feet and pounds.
- The glossary contains definitions of hundreds of key terms. These are emboldened when first presented or explained in the text.
- A set of appendices provides helpful tables of information, useful facts, equations, and suggestions for sourcing parts, materials, and additional resources.
- A complete index helps locate page references to relevant topics as well as types and properties of vehicles, plus names of people, institutions, and individual craft.

UPDATES AND ORDERS

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Updates and Comments

In the interest of keeping future editions of this book as accurate and current as possible, please forward any comments, corrections, or updates to the MATE Center.

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Views Expressed

Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and the Marine Advanced Technology Education (MATE) Center and do not necessarily reflect the views of the National Science Foundation or the Marine Technology Society's ROV Committee.

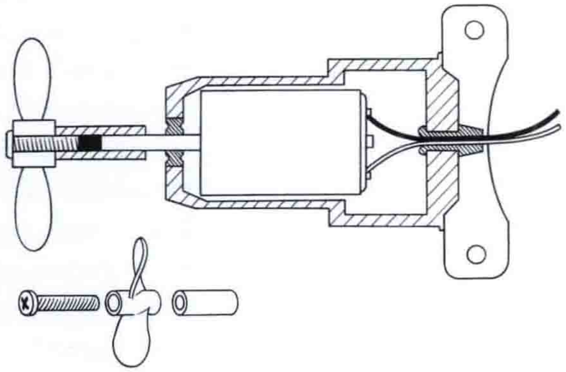
Safety Alert

Throughout the text, the authors have made a good-faith effort to alert readers to potential hazards and have stressed the importance of safety and common sense. However, it is not possible to anticipate and discuss every conceivable situation that might arise during the construction, testing, or operation of an underwater vehicle. Ultimately, it is up to each individual to make sure that he or she is aware of potential hazards and is operating within his or her safe limits.

Therefore, the authors and the Marine Advanced Technology Education (MATE) Center can accept no liability for accidents or injuries incurred during or in association with the construction, testing, or operation of any of the projects suggested herein. In particular, note that this book does NOT provide instruction in the design, construction, testing, operation, or maintenance of submersibles that carry living passengers. Likewise it does not cover boating and water safety skills or the safe use of high voltage power sources.

Endorsements

Today there are thousands of excellent parts and materials that are designed for or can be adapted to use in underwater robotics projects. The textbook has endeavored to give a representative sampling, however it is not possible to include mention of every product manufacturer or distributor. Note that where there is mention of a commercial product or citation of a trade name it does not constitute an official endorsement of that product by the authors or the Marine Advanced Technology Education (MATE) Center. Readers are always encouraged to conduct their own product research. *Appendix V: How to Find Parts* provides tips and suggestions for locating parts and materials suitable for a variety of underwater projects.



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Heartfelt thanks to you all,

—Jill Zande, MATE Associate Director and textbook project coordinator

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As we sorted through thousands of photographs for this project, we tried to provide correct credit and caption references. If we've inadvertently erred, please contact us so that we can make the correction in future printings.

Principle Photographers

Randall Fox and Steve Van Meter/VideoRay LLC deserve special thanks for their extensive photo documentation of numerous MATE regional and international competitions. The authors have also given freely from their personal photo collections and produced a number of new images to illustrate or clarify concepts presented in the text. All of these photographs make a significant contribution to the educational impact of this textbook.

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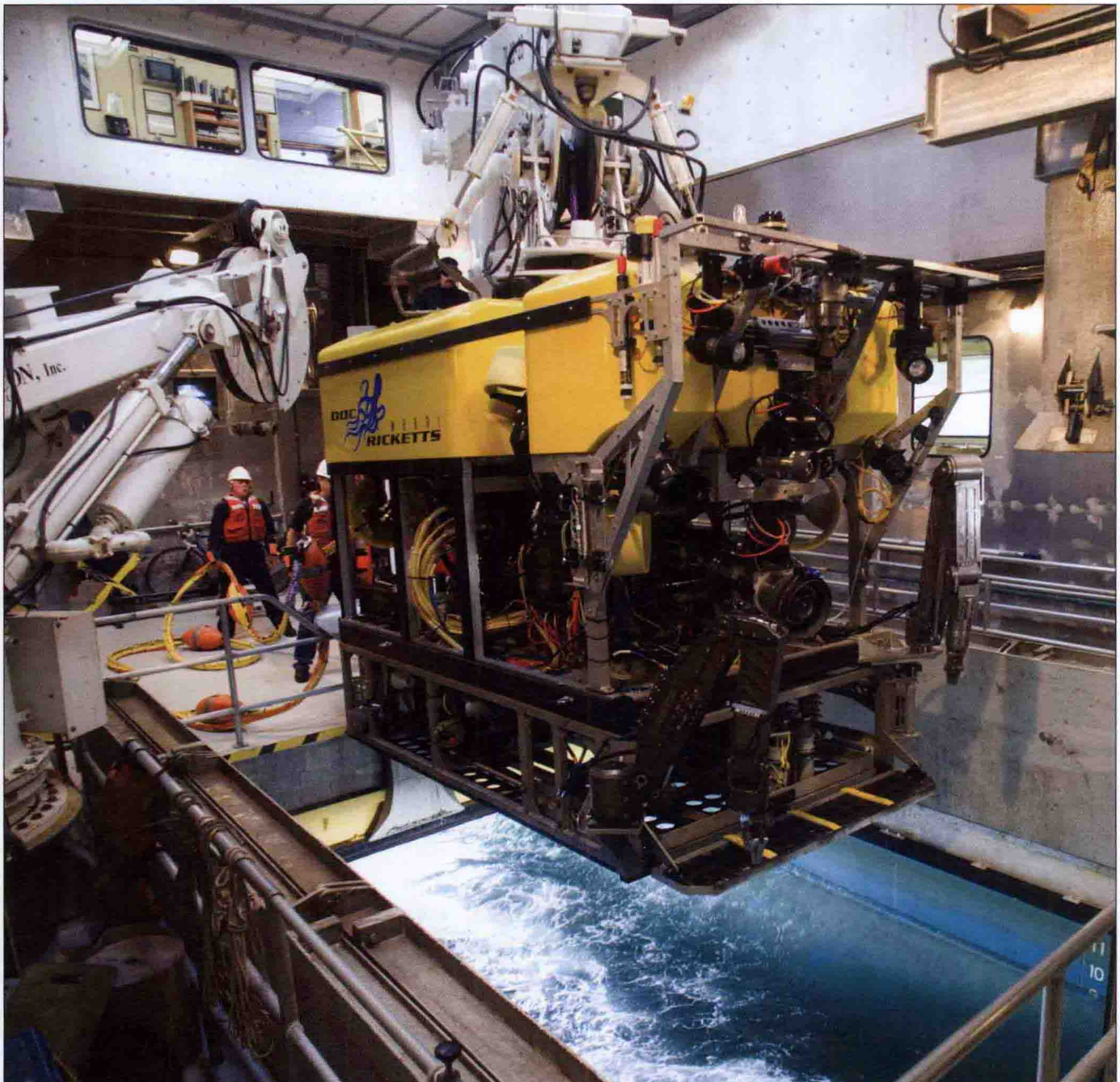

Underwater Vehicles

Chapter 1: **Underwater Vehicles**

Stories From Real Life: Cousteau and the Underwater World

Chapter Outline

Chapter Learning Outcomes

- Describe the common types and uses of modern underwater vehicles.
- Identify motivating factors and key historic events in the evolution of underwater vehicles.
- Describe some of the major challenges confronted by developers of early underwater vehicles and describe how they were overcome.
- Name and describe the major subsystems of a modern work class ROV.

Figure 1.1.cover: MBARI's New* Doc Ricketts *ROV

The ROV Doc Ricketts *is the newest underwater research vehicle for the Monterey Bay Aquarium Research Institute (MBARI). It is shown here on a 2009 test dive, with launch through the moonpool of the research vessel* Western Flyer.

The Doc Ricketts *replaced the ROV* Tiburon, *which was built by MBARI staff in 1996. The new ROV features more sophisticated control systems and can handle much heavier loads. The* Doc Ricketts *was named after local marine biologist Ed Ricketts, who was made famous by John Steinbeck's book,* Cannery Row.

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STORIES FROM REAL LIFE: Cousteau and the Underwater World

In the 1950s and '60s, the world's attention was captivated by rockets, satellites, and the conquest of space. Suddenly, newspapers and TV broadcasts were full of images, scientific terminology, and even firsthand accounts of this previously unknown realm. The Space Race of the '60s was possible because of huge technological advances, particularly in data transmission, miniaturization, lightweight materials, and remote control of rockets.

These same significant advances were quickly adapted to another equally remarkable and little-known frontier—that of the ocean depths. The abyss was suddenly accessible. The star of this new era of oceanography was a Frenchman, Jacques-Yves Cousteau.

From an early age, Jacques Cousteau had two main preoccupations: water and photography. These passions would shape the course of his life. A sickly child, he pored over tales of the sea, reveling in the daring exploits of pearl divers, pirates, and smugglers. Against the advice of his family doctor, Cousteau learned to swim and tried out some of the underwater exploits he had read about. He quickly discovered the difference between the facts of diving and the fiction of diving storybooks.

Cousteau spent many an hour watching ocean-going ships and wondering why they didn't sink under their heavy loads. He was a boy who loved to tinker, and used his allowance to buy one of the first movie cameras available in France. Cousteau frequently took the camera apart and put it back together again. He was fascinated by the hardware, the chemicals, and the process of developing the film and making his own movies. When he was only 11 years old, his father brought home a blueprint for a marine crane. The boy used the drawings to build a 4-foot model of the crane. His proud papa showed it to an engineer, who pointed out that the boy had added his own improvement to the original design.

When it came time to choose a career, Cousteau opted to become a naval officer and documented his year-long working cruise with the same trusty movie camera. At the age of 26, a serious automobile accident ended his training as a navy flier and nearly cost him his life. Doctors wanted to amputate his left arm, but Cousteau refused and fought to recuperate. After eight months of painful therapy, he succeeded in wiggling one finger. He was on the mend! The French navy sent the young officer to recuperate on the Mediterranean coast, where Cousteau met Philippe Tailliez, another navy lieutenant, and Frédéric Dumas, a champion spear fisherman. The three became partners in adventure.

Tailliez encouraged Cousteau to swim in the sea, to strengthen his arm, and to take up the new sport of "goggling," the precursor to scuba diving. Cousteau vividly recalled the magic of his first clear view of the underwater world: "Sometimes we are lucky enough to know that our lives have been changed. It happened to me that summer's day, when my eyes opened to the world beneath the surface of the sea."

Scuba Gear

In the early 1940s, as World War II raged in Europe, Cousteau and his first wife, Simone, along with Dumas and Tailliez, cobbled together underwater diving masks, snorkels, and rubberized suits. Cousteau was determined to photograph under water, but couldn't find any easy way to do so. No quick solution presented itself, so he shot his first underwater movie without any breathing apparatus and by sealing the camera in a large glass jar!

These early frustrations pushed Cousteau to experiment with rebreathing apparatus. A French naval captain, Yves le Prieur, had already developed a type of diving gear that consisted of a cylinder of compressed air on the diver's back, connected by a hose to his face mask. But without any way to coordinate air pressure with water pressure, a diver was still restricted to shallow water. Using forged papers, Cousteau traveled to Paris in 1942, where he met Émile Gagnan in the Paris office of L'Air Liquide. The two men began joint experiments, adapting a type of regulator—one that allowed wartime automobiles to run on cooking gas instead of scarce gasoline—to one that would feed compressed air to a diver at his slightest intake of breath. The first test of their device in January 1943 was not completely successful, but they corrected the problems and patented the device as the Aqua-Lung. Their invention