

The ROV Manual

A User Guide for Remotely Operated Vehicles



Documents

Document Sharing Hub

Document shared on <https://www.docsity.com/pt/the-rov-manual-a-user-guide-for-remotely-operated-vehicles/4905470/>

The ROV Manual

A User Guide for Remotely Operated Vehicles

Second Edition

Robert D. Christ

Robert L. Wernli, Sr.



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Butterworth-Heinemann is an imprint of Elsevier



Butterworth-Heinemann is an imprint of Elsevier
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1 GB, UK

First edition 2007
Second edition 2014

Copyright © 2014 Robert D. Christ and Robert L. Wernli Sr. Published by Elsevier Ltd.
All rights reserved.

The right of Robert D. Christ and Robert L. Wernli Sr. to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods or professional practices, may become necessary. Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information or methods described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

ISBN: 978-0-08-098288-5

For information on all Butterworth–Heinemann publications visit
our website at <http://store.elsevier.com>

Printed and bound in the United States of America

14 15 16 17 18 10 9 8 7 6 5 4 3 2 1



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

Foreword

The world watched in horror in September 2005 as the video feeds from the hurricane-ravaged city of New Orleans were broadcast worldwide. As the city was struggling to recover from Hurricane Katrina, Hurricane Rita delivered the final blow to both the people on the coast of the Northern Gulf of Mexico as well as to the oilfield infrastructure. In the aftermath, close to 200 oil and gas production structures lay on the sea floor. The remaining structures fortunate enough to still stand incurred heavy damage.

In the midst of this crisis, we were busily trying to complete the first edition of this manual to meet an April 2006 publishing deadline. But the world changed for us on January 1, 2006 when the phone rang demanding Bob Christ's immediate travel to survey an oil barge that struck one of those 200 unmarked submerged platforms, which resulted in it spilling 72,000 barrels of fuel oil on the sea floor. Then a platform damage inspection was needed... dive support for decommissioning... structural repairs due to wind and wave stresses from hurricane force winds and seas... the publication deadline passed and yet Bob was still in the field. Bob Wernli was juggling his consulting, at-sea test support and a publication deadline for his second novel. Time was running out for both of us so we quickly buttoned up the first edition, although it was not as complete as we had originally envisioned.

In this second edition, we have come closer to our goal of producing a broad overview of ROV technology. Through the help of leaders and companies from throughout the industry, we have produced a solid survey of the current state of this capability. Our sincere gratitude and thanks go out to those who contributed to our quest. These contributors are recognized in the Acknowledgements section. What we envisioned from the beginning for this manual is a basic **How To** for ROV technology. The US Military has this type of top-level technology manual in their "Dash 10" series. The aviation industry has what is commonly known as the "Jeppesen Manual" (named for the company that wrote the original manual). We hope that we have achieved this goal through this edition of *The ROV Manual*.

This manual is a living breathing entity. Every book is a piece of history upon the publication date; therefore, we welcome comments on this edition. We hope to revise this manual in the future as the technology evolves and would like your comments for further refining this text if/when we put forth another edition. Each subject within this manual could fill an entire book in and of itself. We struggled with editing this manual (with a nominal word and text cap) to include all subjects in as short and succinct a manner as possible while still getting the point across. Although, due to the size constraints, we could not address the larger work-class ROVs as much as we desired, the technology, sensors, tools, manipulators, and related equipment apply across the board to all systems. We hope that this text will whet the reader's appetite for further research into the technologies, equipment, and systems discussed.

The entire body of knowledge encompassing ROV technology is evolving rapidly and the lines between ROV and AUV are quickly occluding as the field of robotics morphs from space to land to sea. The subsea oilfield is firmly embracing the land-based model of network interconnectivity bringing man (remotely) back into the harsh environment of the subsea world. The easy *finds* for the world's minerals have already been achieved and exploited. The frontier has moved from the

29% of the Earth covered by land to the 71% of the Earth covered by sea. The mineral riches of the world are hidden beneath those waves. The only way to get to them is with robotics. And that is where the fun starts!

Bob Christ

SeaTrepid

Covington, LA

www.SeaTrepid.com

Robert Wernli Sr

First Centurion Enterprises

San Diego, CA

www.wernlibooks.com

Acknowledgments

In the first edition, the authors performed all of the basic research with some participation from industry in the form of recommendations and figure submissions. However, in this edition we elicited considerable industry participation—and we certainly received it!

Arnt Olsen of Kongsberg again participated with the contribution of Kongsberg's seminal work on acoustic theory. Stephen Dodd of GRI Simulations contributed to Chapter 4. Tyler Schilling along with Peter MacInnes, Steve Barrow, and Matt Whitworth of Schilling Robotics were instrumental in the production of both the manipulator as well as the tooling chapters. Alasdair Murray and Steve Stepinoff of Sub-Atlantic and Chris Roper of Saab SeaEye supplied a plethora of materials for mid-sized vehicles and Jim Teague, J. Teague Enterprises, contributed to the chapter on floatation.

And a special thanks to pioneers of the cables and connector industry, Cal Peters, Kevin Hardy, and Brock Rosenthal, who completely drafted Chapter 8. Kevin Hardy is President of Global Ocean Design, specializing in free vehicle component technologies. He retired from the Scripps Institution of Oceanography/UCSD after 36 years in ocean engineering. Hardy's instruments have successfully operated from the Arctic Circle to the southern oceans, and from the Arctic surface to the deepest ocean trenches, including James Cameron's dive to the bottom of the Mariana Trench. Cal Peters is the Director of Engineering for Falmat (San Marcos, CA), a manufacturer of custom cables for the offshore industry and other markets. He has 32 years experience in the design and manufacture of EM, signal, power, faired, and neutrally buoyant underwater cables for diverse applications, including towed instruments, moorings, ROVs, and manned vehicles. Brock Rosenthal is the President and founder of Ocean Innovations (La Jolla, CA), a distributor of underwater connectors, cables, and other quality oceanographic hardware. Rosenthal has helped numerous end users clearly define their operational requirements before selecting their underwater equipment. Their support in this endeavor is truly appreciated.

But it did not stop there. Practically all of the titans of this industry volunteered their time and resources to this project. It is difficult to express our thanks in broad enough terms. All contributors are listed alphabetically by chapter below.

General

- | | |
|-------------------|--------------------------------|
| • Johnny Johnson | Oceaneering |
| • Noel Nelson | Remote Inspection Technologies |
| • Steve Stepinoff | Forum Energy Technologies |

Chapter 1: The ROV Business

- | | |
|------------------|---------------------------|
| • Brian Luzzi | VideoRay |
| • Drew Michel | Marine Technology Society |
| • Matt Whitworth | FMC Technologies |
| • Steve Walsh | SeaTrepid International |

Chapter 2: The Ocean Environment

- Steve Fondriest Fondriest Environmental

Chapter 3: Theory and Standards

- Alasdair Murrie Sub-Atlantic
- Brock Rosenthal Ocean Innovations
- Chris Roper Saab SeaEye
- Gordon Durward Forum Energy Technologies
- Peter MacInnes Schilling Robotics

Chapter 4: Vehicle Control and Simulation

- Ioseba Tena SeeByte
- Neil Noseworthy GRI Simulations
- Rick Cisneros CA Richards
- Steve Dodd GRI Simulations

Chapter 5: Vehicle Design and Stability

- Amanda Ellis Deep Sea Power & Light
- Jim Teague J Teague Enterprises
- Robert Kelly Trelleborg

Chapter 6: Thrusters

- Andrew Bazeley Tecnadyne
- Bob Gongwer Innerspace
- Chris Gibson VideoRay
- Dick Frisbie Oceaneering
- Ian Griffiths Soil Machine Dynamics
- Jesse Rodocker SeaBotix
- Scott Bentley VideoRay
- Steve Barrow Schilling Robotics
- Tyler Schilling Schilling Robotics

Chapter 7: Power and Telemetry

- George “Buddy”
 Mayfield Outland Technology
- Scott Allen MacArtney

Chapter 8: Cables and Connectors

- Brad Fisher SeaCon
- Brock Rosenthal Ocean Innovations

- Cal Peters Falmat
- Glenn Pollock SeaCon
- Kevin Hardy Global Ocean Design
- Shawn Amirehsani Falmat

Chapter 9: LARS and TMS

- Bill Kirkwood Monterey Bay Aquarium Research Institute
- David Owen Caley Ocean Systems
- Jeff Conger MacArtney
- Jesse Rodocker SeaBotix
- Jim Honey Shark Marine
- Joan Gravengaard MacArtney
- Joe Caba SeaTrepid International
- Kim Fulton-Bennett Monterey Bay Aquarium Research Institute
- Mike Obrien SeaTrepid International
- Rasmus Frøkjær Bonde MacArtney
- Steve Barrow Schilling Robotics
- Vergne Caldwell SeaTrepid International
- Wes Keepers Dynacon

Chapter 10: Video

- Pat McCallan Pat McCallan Graphics
- Rick Cisneros CA Richards

Chapter 11: Vehicle Sensors and Lighting

- Ronan Gray SubAqua Imaging Systems
- Cyril Poissonnet Remote Ocean Systems

Chapter 12: Sensor Theory

- Chris Roper Saab SeaEye
- Keith Pope Teledyne TSS
- Keith Wittie Entergy

Chapter 13: Communications

- Carl Schneider Grey Insurance
- Vergne Caldwell SeaTrepid International

Chapter 14: Underwater Acoustics

- Arnt-Helge Olsen Kongsberg Maritime

Chapter 15: Sonar

- Blair Cunningham Coda Octopus
- Helmut Lanziner Imagenex Technology
- Jan Trienekens Remote Inspection Technologies
- Jim O'Neill Coda Octopus
- Joe Burch Sound Metrics
- Joe Caba SeaTrepid International
- John Beekman FugroChance
- Maurice Fraser Tritech International
- Willy Wilhelmsen Imagenex Technology

Chapter 16: Acoustic Positioning

- Arnt-Helge Olsen Kongsberg Maritime
- Julian Rickards Sonardyne

Chapter 17: Navigational Sensors

- Margo Newcombe Teledyne RDI
- Paul Watson CDL
- Rick Cisneros CA Richards

Chapter 18: Ancillary Sensors

- Alistair Coutts Seatronics Group
- Chris Roper Saab SeaEye
- Euan Mackay Seatronics Group
- Jan Trienekens Remote Inspection Technologies
- Keith Pope Teledyne TSS
- Lori Strosnider Chevron
- Margo Newcombe RD Instruments (Maybe this is Margo in C17?)
- Rod Sanders Cygnus Instruments
- Scott Vidrine Tracerco
- Tony Landry SeaTrepid International

Chapter 19: Manipulators and Tooling

- Brett Kraft Kraft Telerobotics
- Chris Gibson VideoRay
- Don Rodocker SeaBotix
- Jesse Rodocker SeaBotix
- Jessica Montoya Schilling Robotics
- Matt Whitworth Schilling Robotics
- Megan Anderson Schilling Robotics
- Peter MacInnes Schilling Robotics

- Steve Stepinoff Forum Energy Technologies
- Tyler Schilling Schilling Robotics
- Wendy Glover Hydro-Lek

Chapter 20: Tooling and Sensor Deployment

- Andrew Bazeley Tecnadyne
- Antone Forneris Cavidyne
- Deborah Geisler Stanley Infrastructure Solutions
- Graham Sloane Planet Ocean
- John Clark Wachs Subsea
- John Merrifield Stanley Infrastructure Solutions
- Jonathan Bochner WEBTOOL—Variators Ltd.
- Mike Cardinal Stanley Infrastructure Solutions
- Noel Nelson Remote Inspection Technologies
- Scott Crosier Crosier Design
- Tom Ayars Seanic Ocean Systems
- Steve Barrow Schilling Robotics
- Susan Bazeley Tecnadyne
- Tim Sheehan Wachs Subsea

Chapter 21: Practical Applications

- Blades Robinson Dive Rescue International
- Brett Seymour US National Park Service
- Jack Fisher JW Fishers
- Julian Rickards Sonardyne
- Ken McDaniel US Department of Homeland Security
- Marco Flagg Desert Star Systems
- Willy Wilhemsen Imagenex Technology

Chapter 22: The Little Things That Matter

- Joe Caba SeaTrepid International
- Vergne Caldwell SeaTrepid International

Chapter 23: The Future of ROV Technology

- Alain FIDANI Cybernetix
- Andy Bowen Woods Hole Oceanographic Institution
- Art Schroeder Energy Valley
- Chris Nicholson Deep Sea Systems International
- Chris Roper Saab SeaEye
- Dan McLeod Lockheed Martin
- Deanna Talbot Bluefin Robotics
- Drew Michel Marine Technology Society

- Erika Fitzpatrick Woods Hole Oceanographic Institution
- Ian Crowther WFS Technologies
- Jake Klara C&C Technologies
- John Westwood Douglas-Westwood
- Lou Dennis Lockheed Martin
- Steve Cowen SPAWAR Systems Center Pacific

Introduction

This edition of *The ROV Manual* substantially expands upon the previous edition. This text is divided into five logical parts covering the industry and environment, the basics of ROV technology, payload sensors, intervention tooling as well as practical field applications. In the last chapter of the book, we look into the future in order to examine what industry analysts feel is the direction subsea technology is heading with a specific focus on the field of subsea robotics.

It is often said that *for every mathematical formula within a book, the population of book purchasers is halved*. As authors we certainly appreciate that thought, but seek to go from general terms to specific (as well as from simple to complex) toward reaching a broad readership for this subject. Some of the chapters are heavily focused on theory (e.g., Chapter 14 on underwater acoustics is heavily math-based) while others (e.g., Chapters 21 and 22, which focus on field applications and procedures) contain little or no mathematics. The general technology user should feel free to skip over the math-based sections, while those with a more academic bent or specific application should delve into the technical aspects of theory.

Chapters 1 and 2 (Part 1) seek to paint a background picture of the industry, as well as the environment, where ROVs operate and this technology applies. Chapters 3–11 (Part 2) drill down to the actual vehicle in a good bit of detail while Chapters 12–18 (Part 3) branch out into the broad subject of payload sensors. It is often said in this industry, “It is not about the vehicle, it is about the sensors and tooling.” Therefore, we additionally break out Part 4 (Chapters 19 and 20) to address the manipulators and tooling aspects of ROV technology while the final section (Part 5—Chapters 21–23) focuses on both practical applications and standard operating procedures, then closes with the authors’ take on the future of this technology.

While this text casts a wide net over the entire field of Remotely Operated Vehicle technology, we focus specifically on the classes of vehicle (narrowly defined in Chapter 3) in the observation class ROV (OCROV) and mid-sized ROV (MSROV) categories. The only subject missing to cover the full gamut of vehicles (i.e., the Work Class ROV, WCROV) is high-pressure hydraulics. And that subject will be left for a future iteration of this manual as we continue to refine this work while the industry (and technology) continues to evolve.

The divisions (parts) of this manual each address a separate readership. Part 1 is geared towards the business side and should be applicable to project managers making use of this technology while Part 2 focuses specifically on the ROV technician. Part 3 is addressed to the project manager but should also be of interest to the survey team as well as the ROV technician for gaining a general understanding of deployed sensor technologies. Part 4 is directed toward intervention technicians over a broad range of users (from Project Manager to Corporate Executive to Regulatory Officials to, of course, ROV Technicians). And Part 5 wraps it all up with both practical considerations and a look into the future.

No text of this size can do any measure of justice to the field of ROV technology. The authors have carefully carved out individual subjects in order to form an introduction into each field. We hope that you, the reader, come away with a general understanding of this industry and its advanced technologies, thus encouraging further investigation into your specific field of interest.

Welcome to the exciting field of subsea robotics!

The ROV Business

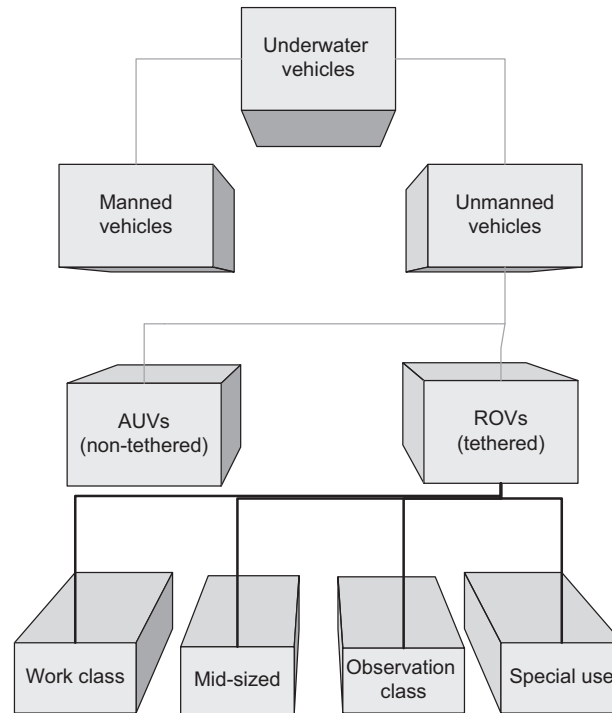
CHAPTER CONTENTS

1.1 The ROV	3
1.1.1 What is an ROV?.....	3
1.1.2 ROV size classifications	5
1.1.3 Vehicle shape versus mission.....	8
1.1.4 ROV depth rating by classification.....	9
1.1.5 Size versus ability to deploy sensors/tooling.....	9
1.2 Types of ROV services.....	11
1.2.1 Call out versus contract work	11
1.2.2 Day rate versus project management	12
1.2.3 Strategy for service package deployment	15
1.3 ROV economics.....	15
1.3.1 Capital expenditure (CAPEX) versus day rate.....	15
1.4 ROV services by industry	16
1.4.1 Science	16
1.4.2 Fisheries and aquaculture	17
1.4.3 Military.....	17
1.4.4 Homeland security.....	18
1.4.5 Public safety.....	18
1.4.6 O&G drill support	18
1.4.7 Inspection, repair, and maintenance.....	19
1.4.8 Construction (O&G as well as civil).....	19
1.5 Conclusions.....	19

1.1 The ROV

1.1.1 What is an ROV?

Currently, underwater vehicles fall into two basic categories (Figure 1.1): manned underwater vehicles and unmanned underwater vehicles (UUVs). The US Navy often uses the definition of UUV as synonymous with autonomous underwater vehicles (AUVs), although that definition is not a standard across the industry.

**FIGURE 1.1**

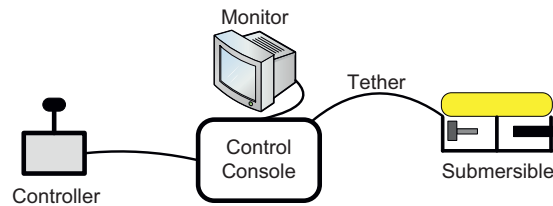
Underwater vehicles to ROVs.

According to the US Navy's UUV Master Plan (2004 edition, section 1.3), an "unmanned undersea vehicle" is defined as a:

Self-propelled submersible whose operation is either fully autonomous (preprogrammed or real-time adaptive mission control) or under minimal supervisory control and is untethered except, possibly, for data links such as a fiber-optic cable.

The civilian moniker for an untethered underwater vehicle is the AUV, which is free from a tether and can run either a preprogrammed or logic-driven course. The difference between the AUV and the remotely operated vehicle (ROV) is the presence (or absence) of a direct hardwire (for communication and/or power) between the vehicle and the surface. However, AUVs can also be (figuratively) linked to the surface for direct communication through an acoustic modem, or (while on the surface) via an RF (radio frequency) and/or an optical link. But in this book, we are concerned with the surface-directed, hard-wired (tethered) ROV.

The ROV falls within a broad range of mobile robotic vehicles generally termed "remotely controlled mobile robots." The motion of the vehicle can be via autonomous logic direction or remote operator control depending upon the vehicle's capability and the operator's degree of input. The

**FIGURE 1.2**

Basic ROV system components.

power of the vehicle can be onboard (i.e., battery or engine powered), offboard (i.e., power delivered through conductors within the tether), or a hybrid of both (e.g., onboard battery powered with a power recharge transmitted remotely through the tether).

Simplistically, an ROV is a camera mounted in a waterproof enclosure, with thrusters for maneuvering, attached to a cable to the surface over which a video signal and telemetry are transmitted (Figure 1.2). Practically all of today's vehicles use common industry standards for commercial off-the-shelf (COTS) components.

As the ROV goes from its simplest shallow water form toward the more complex deep water work vehicles, the required degree of sophistication of its operators as well as the depth of its support network climbs substantially in a similar fashion to that of aircraft or large surface vehicles.

The modern ROV is a mature technology with established standards of operator qualifications, safe operations, and a proven history of getting work done in the “dull, dirty and dangerous” work environments of the world's waters.

The following sections will provide a better understanding of the scope of this definition. Subsequent chapters will provide in-depth discussions of the design of ROV systems along with operational considerations.

1.1.2 ROV size classifications

ROVs can be more specifically described as teleoperated free-swimming robotic unmanned (or “uninhabited” for the more modern term) underwater vehicles. These are used in a variety of applications from diver support to heavy marine subsea construction. The market is substantially segmented into four broad categories based upon vehicle size and capabilities:

1. *Observation class ROVs (OCROV)*: These vehicles go from the smallest micro-ROVs to a vehicle weight of 200 pounds (100 kg). They (Figure 1.3) are generally smaller, DC-powered, inexpensive electrical vehicles used as either backup to divers or as a diver substitution for general shallow water inspection tasks. Vehicles in this classification are generally limited to depth ratings of less than 1000 ft (300 m) of seawater (fsw/msw) due to the weight of the power delivery components and one atmosphere pressure housings—which imposes limitations upon the vehicle size (i.e., neutral buoyancy must be maintained if the vehicle is to have the ability to swim). The vehicles within this class are typically hand launched and are free flown from the



FIGURE 1.3

Examples of OCROVs (Note: shoes atop for scaling).

(Courtesy SeaTrepid.)

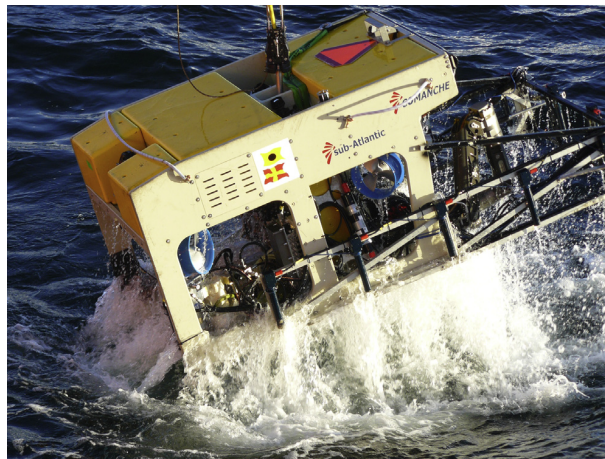


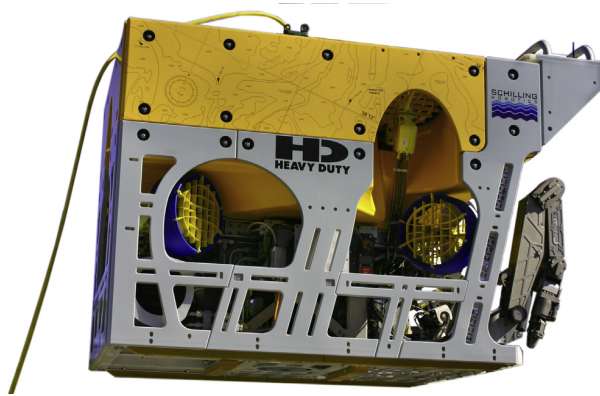
FIGURE 1.4

Example of MSROV.

(Courtesy Forum Energy Technologies.)

surface with hand tending of the tether. The older/antiquated term for vehicles of this classification is “low-cost ROVs.”

2. *Mid-sized ROVs (MSROV)*: These vehicles weigh from 200 pounds (100 kg) to up to 2000 pounds (1000 kg). They (Figure 1.4) are generally a deeper-rated version of the OCROVs with

**FIGURE 1.5**

Example of WCROV.

(Courtesy FMC Technologies.)

sufficient AC power delivery components and pressure housings capable of achieving deeper depths over longer tether/umbilical lengths. These also are generally all-electric vehicles (powering prime movers (thrusters) and camera movement controls) with some hydraulic power for the operation of manipulators and small tooling package options. The vehicle electrical power is stepped down to a manageable voltage for operation of the various components and can be either AC or DC power. Vehicles in this classification are sometimes termed “light work class” vehicles to fully differentiate them from OCROVs. Due to the weight of these vehicles, a launch and recovery system (LARS) as well as a tether management system (TMS) is often needed.

3. *Work class ROVs (WCROV)*: Vehicles in this category are generally heavy electromechanical vehicles running on high-voltage (>3000 V) AC circuits from the surface to the vehicle (Figure 1.5). The power delivered to the vehicle generally is changed immediately to mechanical (hydraulic) power at the vehicle for locomotion as well as all manipulation and tooling functions.
4. *Special-use vehicles*: Vehicles not falling under the main categories of ROVs due to their non-swimming nature such as crawling underwater vehicles, towed vehicles, or structurally compliant vehicles (i.e., non-free-swimming). The special-use vehicle coverage is outside the purview of this text.

The general difference between the OCROV and the MSROV is the power transmission and depth rating. The general difference between the MSROV and the WCROV is the size of the hydraulic power pack and the horsepower rating for the operation of manipulators and tooling. Both the MSROV and the WCROV are deep-rated vehicles and both can be delivered to deep work sites. The WCROV, however, can perform heavier tasks than the MSROV is capable of achieving due to the added muscle of hydraulic actuation of its components (versus the electrical actuation of the MSROV). There are a few “electrical WCROVs” on the market, but the vast majority of the

Table 1.1 ROV Classifications

Classification	General Capability
OCROV	Flying eyeball with limited intervention
MSROV	Full gigabit data throughput with light intervention
WCROV	Full gigabit data throughput with heavy intervention

Table 1.2 Representative Vehicle Characteristics

Size Category	Input Power	Vehicle Power	Telemetry Type	Depth Rating	Launch Method	TMS	Thruster/ Tooling	Tooling Fluid Flow
OCROV	110/220 VAC 1Φ	Low-voltage DC	Copper only	+/- 300 m (1000 ft)	Hand deploy	No	Electric/ electric	Electric only
MSROV	440/480 VAC 3Φ	Medium-voltage DC or AC	Copper or fiber	>1000 m (3000 ft)	Crane or A-frame	Optional	Electric/ hydraulic	15 lpm (4 gpm)
WCROV	440/480 VAC 3Φ	High-voltage AC	Fiber only	>3000 m (10,000 ft.)	A-frame	Yes	Hydraulic/ hydraulic	70 lpm (18 gpm)

worldwide population of WCROVs is hydraulic due to the power requirement and the inherent reliability of hydraulic systems over their electric counterparts within the seawater environment. OCROVs are generally called “flying eyeballs” as their main job is to function as a shallow water video platform. The MSROV has additional deepwater capabilities along with fiber optic telemetry for full gigabit sensor throughput. The WCROV possesses all of the attributes of both the OCROV and the MSROV along with high-powered hydraulic manipulators and tooling capabilities (Table 1.1).

Table 1.2 depicts representative vehicle configurations and power/telemetry requirements. Configurations vary within each category from vehicle to vehicle, but these represent the general characteristics of vehicles within the specified size category. For specific vehicle parameters, please consult the vehicle manufacturer’s technical specifications.

1.1.3 Vehicle shape versus mission

The length to width (termed “aspect”) ratio of the vehicle directly affects its hydrodynamics. Long slender vehicles generally have lower drag characteristics at higher speeds but exhibit poor station-holding capabilities. Short vehicles have much better station-keeping capabilities along with higher maneuverability in all three axes of travel ($x/y/z$) but have much higher drag profiles as the speed ramps up. AUVs typically exhibit the classical torpedo shape with a high aspect ratio and minimal number of thrusters coupled with control fins for long-distance travel at higher speeds. The ROV is typically used in station-keeping (or slow speed observation) tasks for close inspection and/or sensor and tooling delivery.

AUVs typically have a closed frame for uninterrupted fluid flow about the vehicle (for minimal drag at higher speeds) while ROVs typically have an open frame to allow for fluid flow through the frame due to a higher number of internally mounted thrusters.

Within the ROV group, vehicles with a higher aspect ratio are used for longer travel distances (e.g., pipeline surveys or regional transects) while lower aspect ratio vehicles are used for close inspections or tasks requiring station-keeping capabilities.

1.1.4 ROV depth rating by classification

General man and machine capabilities for working within the marine environment fall within the depth limitations provided in [Table 1.3](#).

At the current state of technology for telepresence with mobile robotic systems, man (a diver) in the environment will be much more capable than a machine. This is due to the *in situ* situational awareness provided by man as well as the ultimate dexterity of the end effector (a hand for a man and a manipulator claw for the machine). But the costs and danger of placing man in the high-pressure work environment of the deep sea are considerable. Within the commercial, scientific, and governmental industries, more and more customers are looking for a robotic solution to the ever-increasing requirements for subsea sensing and intervention; their goal is to limit the cost and liability exposure brought on from possibly harming “the man.” Look for vast future improvements in both the technology and demands for this category of robotics.

1.1.5 Size versus ability to deploy sensors/tooling

It is best to view any underwater vehicle as simply a “bus ride to the work site.” The purpose of the vehicle will always be the delivery of the sensor and/or tooling package to the work site in order to accomplish the mission. The question then becomes: “How large does the vehicle need to be in order to effectively accommodate the sensors and tooling package?”

In general, any ROV can float any sensor or tooling package—all that is necessary is to place ample flotation aboard the vehicle to offset the in-water weight of the payload. The size of the vehicle then needs to vary to optimally accommodate the prime mover (thrusters), tooling, and sensors while still powering these items and thrusting/moving the package. Also, communication capabilities must match the sensor bandwidth requirements to ensure sufficient data throughput exists to transmit the telemetry to the operator station for logging sensor data and controlling the tooling package.

Table 1.3 Capabilities Versus Depth

Category	Depth Limitation
Air diving	190 ft (60 m)
Mixed gas diving	300 ft (100 m)
Saturation diving	1000 ft (300 m)
Atmospheric diving system	2300 ft (700 m)
OCROV	1000 ft (300 m)
MSROV	>3000 ft (>1000 m)
WCROV	>10,000 ft (>3000 m)

Table 1.4 Sensors and Data Transmission Requirements

Sensor Type	Bandwidth	Protocol	Telemetry Type
Single beam sonar	Low	RS-232/422/485	Copper or optical fiber
2D multibeam sonar	Medium to high	Ethernet	Copper or optical fiber
3D multibeam sonar	High	Ethernet	Optical fiber
UT metal thickness	Low	RS-232/422/485	Copper or optical fiber
Standard-def. video	Medium	Composite	Copper or optical fiber
High-def. video	Medium to high	Ethernet	Optical fiber
Radiation sensor	Low	RS-232/422/485	Copper or optical fiber
Pipe tracker	Low	RS-232/422/485	Copper or optical fiber

Table 1.5 Tool Type Versus Vehicle Characteristics

Tool Type	Weight in-Water	Power	Minimum Vehicle Size
Single-function manipulator	Low	DC electrical	OCROV
Light duty 4-function manipulator	Medium	Low pressure/flow hydraulic	MSROV
Heavy-duty 7-function hydraulic manipulator	High	High-pressure/low-flow hydraulic	WCROV
Wire rope cutter	Medium	High-pressure/low-flow hydraulic	MSROV and WCROV
Hydraulic grinder	Medium	Low-pressure/high-flow hydraulic	MSROV and WCROV
Diamond wire saw	Low	High-pressure/high-flow hydraulic	WCROV

With the advent of fiber optic communication capabilities on smaller mobile platforms, sensor throughput capabilities have taken on a new dimension for the ROV as a sensor delivery platform. While data over copper is still the prevalent setup for OCROVs (due to its inherent short-distance transmission requirements and low-cost structure), fiber optics is the predominant telemetry conductor for MSROVs and WCROVs. A short sample of sensors along with their data transmission requirements and likely telemetry type is provided in [Table 1.4](#).

For tooling, the main difficulties are (i) the vehicle's ability to carry the tool as payload (i.e., the size of the vehicle vis-à-vis the tool itself) with a large enough vehicle-to-tool ratio so that the tool does not "wag the dog"—or provide so much drag that it renders the vehicle uncontrollable with the tool attached, (ii) the vehicle's power delivery capability is sufficient to power the tool while maintaining station, and (iii) the vehicle's ability to physically reach the work site. A short sample of tooling along with the typical payload and vehicle size requirements is provided in [Table 1.5](#).

1.2 Types of ROV services

1.2.1 Call-out versus contract work

ROV services are subdivided based upon a number of factors including whether the job is a primary versus supporting role, equipment footprint, duration of assignment, and other factors.

- *Primary versus supporting role:* An example of a primary function for an ROV is any diverless operation such as subsea structural inspection, deepwater remote intervention, subsea pipeline survey, and any other function where a diver is not present in the water or at the job site. A supporting role would be as diver backup, such as a tool delivery vehicle, diver support as backup, and for diver monitoring or monitoring of diver-mounted tooling.
- *Larger ROV spreads* require a larger footprint and higher support requirements. Whereas the OCROV can simply plug into the vessel's standard 110/220 VAC consumer-grade single-phase power source, the MSROV and larger WCROV spreads require independent high-voltage/high-service three-phase power sources. The OCROVs can be hand launched over the vessel bulwarks while larger ROVs require a LARS. Many LARS require special configuration in order to get the vehicle from the deck, into the water and back again in all sea states without damage to equipment and danger to personnel. Further, in order to deliver the vehicle to deep work sites, a TMS is required to manage the soft tether from the depressor weight (i.e., heavy weight holding the vehicle steady at the work site) to the vehicle and to protect the vehicle from damage during transit to the work site. This involves a separate electrical or hydraulic system, essentially requiring two control systems in the water (doubling complexity).
- *The two types of ROV assignments* are broadly defined as “contract” and “call-out” work.
 - *Contract work* involves long-term (greater than 6 months, duration) assignments that generally involve (and cost-justify) integrating the vehicle into the work platform with the requisite detailed and complicated mobilization. An example of a contract job would be a drill support assignment whereby a complete section of the rig is dedicated to the ROV spread. Another would be a dedicated ROV vessel with the LARS and control system integrated into the superstructure of the vehicle. Integrating an ROV spread into a vessel of opportunity can be a very expensive and time-consuming proposition undertaken only for jobs that will allow for mobilization cost amortization over a long period (lowering per work day mobilization costs).
 - *Call-out work* involves short-term (less than 6 months) assignments whereby minimal integration work (termed “bolt on” integration) is performed into the vessel of opportunity due to its limited duration. The exception to this would be a fully integrated ROV vessel performing short-term work.

The cost of mobilizing a WCROV spread can be substantial. The LARS must be trucked over roads with a special wide-load road permit; the work package (vehicle, TMS, LARS, and winch with umbilical) weighs in excess of 100,000 pounds (50,000 kg) on deck, and the spread is up to four vans (control, work, generator, and survey—in addition to the work package spread). The cost of mobilizing an OCROV spread is simply hand-carrying the cases onto the vessel of opportunity and plugging equipment into the vessel's readily available consumer power.

Most mobilizations require several days of working out equipment issues in the field (normally described as “tweaking the spread”) in order to achieve the optimum equipment configuration. This

problem is multiplied as the complexity of the equipment increases. In short, mobilizing a WCROV spread on a new vessel of opportunity for a short-term assignment is seldom worth the trouble or the expense. The only way to justify a WCROV spread for call-out work is to have a dedicated vessel with the ROV spread permanently integrated. But considering the relatively low vessel/vehicle utilization of call-out work, it is an expensive asset to have idle, moored at the dock.

The inland work is the realm of the OCROV and MSROV, but unless it is a construction project (requiring heavy-lift WCROV capability) it is generally call-out work. The offshore marketplace is generally populated with larger exploration and production (E&P) companies performing construction projects requiring heavy WCROV equipment. In most cases, a smaller ROV would be more than adequate to perform the scope of work for the project assignment but the engineering section of these E&P companies are used to paying more for their ROV services and do not object to the higher cost structure.

The market draw for OCROV and the MSROV services encompasses “the 80% solution” at a substantially lower cost structure than the larger ROVs. The nature of the call-out business is short-term and very profitable work. The upside to the call-out business is there are not many players to dilute the already industry-wide low utilization inherent in call-out work. The downside of the call-out business is the lack of any predictably sustainable work levels. It is, for the most part, either feast or famine.

1.2.2 Day rate versus project management

This discussion is more applicable to the offshore hydrocarbon mining industry since it dominates deepwater construction but also crosses to any deepwater construction industry (e.g., wind farms, and seafloor mining).

The deepwater offshore oil and gas (O&G) service industry begins with the seismic survey and ends with the gas pumping into the passenger car. The need for waterborne robotic services begins with the precasing survey and ends when the pipeline crosses the preselected 1000 fsw (300 msw) curve. The following is a sample list of services/tasks needed:

- Pipeline/umbilical/flowline pre-lay survey
- Subsea site survey
- Drill support
- Installation of wellhead valve trees
- Installation of subsea tie-back
- Inspection, repair, and maintenance (IRM) of subsea facilities
- Fabrication and installation of pull-tubes
- Subsea coiled tubing flowline procurement and installation
- Subsea wellhead control umbilical procurement and installation
- Subsea pipeline end terminations procurement and installation
- Spool piece measurements, fabrications, and installation
- Subsea umbilical termination assemblies procurement and installation
- Planning, management, and execution of pigging and testing flowline programs
- Conduct deepwater pipeline hot taps and deep tap projects
- Conduct deepwater diverless pipeline repairs utilizing ROVs onboard vessel

- Plug and abandonment (P&A) of subsea valve trees and templates
- Umbilical and pipeline system recovery and decommissioning
- Subsea development survey, salvage, installation of long baseline (LBL) acoustic arrays
- Jumper and flying lead installations
- Strake installations to tension leg platforms
- Hydrotesting and commissioning subsea field developments
- Steel catenary riser tie-in, inspection, repair, and maintenance
- Mattress installations and crossing of pipelines, flowlines, and umbilical
- Platform and pipeline inspections to regulatory standards

The clear-bottom “survey” functions can be accomplished with logic-driven equipment and fall more within the survey function than within the construction function. The logic-driven vehicles are the AUVs and fall more within the traditional services of the survey company (i.e., outside of the traditional service offerings of ROV service companies). Construction/IRM-type robotic services require a more active approach to subsea vehicle control—which requires a teleoperated vehicle (i.e., ROV) for active “man-in-the-loop” control.

As a day rate player, the ROV service company’s primary (some would say, “only”) function is to have “uptime.” As a project management company, the primary function is to get tasks accomplished. As a “day rater” (DR), the goal is to have sufficient equipment to get the job and stay on the job. As a “project manager” (PM), the goal is to have access to a large menu of services so as to have them available when needed in order to fulfill the end goal (a completed task). The PM company is farther up the proverbial “food chain” as it manages its own projects (as opposed to taking directions from a PM). The deepwater intervention market is the realm of the ROV. Required of the PM or DR company is ROVs with sufficient capability to deliver sensors and tooling for the deepwater environment.

The end product for a DR company is the delivery of either sensors or tooling to the work site with maximum uptime. The end product of a PM company is to accomplish an assigned project (as outlined by the customer). In the risk/reward curve, the PM company stands a much higher operational and financial risk with a corresponding potential for huge profits. The DR player has a much lower risk profile with a correspondingly lower profit upside.

The major players within the industry fall out to either day rate players or project management players. The smaller OCROV and MSROV service companies generally own and operate their equipment aboard the client’s vessel of opportunity. The typical day rate players in the WCROV space are boat companies who use the ROV to sell the boat due to the substantial cost of mobilizing the WCROV spread onto the vessel (Section 1.2.1). The typical project management company has the ROV services as one of the many tools within the tool chest.

On the day rate front, the investment (and hence the reward) is in the boat—not (significantly) in the ROV. The boat companies are willing to go to a very low (or zero!) day rate on the ROV by hiding the ROV’s day rate in the vessel day rate. This squeezes out any would-be purely day rate WCROV-only companies.

“Is it an ROV vessel or is it a boat with ROV capability?” This is an important question. It decides on the risk for downtime (the main purpose of a day rate company) should (when) the ROV encounter operational or maintenance issues. Most DR companies resolve this issue by splitting the customer contracts between the ROV company and the vessel company, thereby compartmentalizing

the downtime risk (to the customer's detriment). A project management company does not have that luxury since if the ROV is down the entire mission is compromised.

In a post-Macondo offshore minerals extraction world, there is a new concept within the field support vessel service that has arisen to address newer and more stringent regulations. The traditional platform supply vessel (PSV) is changing from a simple mud/chemical/fluids/bulk transfer vehicle to a fully integrated deepwater support vessel. The new paradigm reasons that all future field support vessels will require an ROV capability.

The move to deepwater O&G exploration and production has seen the movement of the well-head of the production platform from the surface to the seafloor requiring all IRM tasks to be accomplished robotically. All field support vessels will naturally be combined DR ROV companies as well as vessel companies. And the demand will rise rapidly in the oilfields of the developed world for the integrated deepwater support vessel.

So, the two choices are to be a DR player or a PM player. The equipment requirements for each follow:

DR player: The trend within the deepwater IRM market is for "dynamically positioned" (DP—in this case DP-2 for DP with redundancy) vessel capability in order for oil companies to allow PSVs to approach deepwater production platforms. At a minimum, all vessels from which ROVs operate in close proximity to deepwater production platforms will require a DP-2 capability. The typical DP-1 (dynamical positioning with no redundancy) vessel (for production support) remains within the 170 ft (55 m) length overall (LoA) range with a high of 205 ft (65 m) and a low of about 140 ft (45 m). The typical deepwater DP-2 platform supply vessel (PSV) is in the 300 ft (95 m) LoA range. For the ROV spread, a name-brand hydraulic vehicle (i.e., one of the major international WCROV manufacturers) with at least 150 hydraulic horsepower is required as most contracts specify a minimum horsepower rating (and many uninformed customers equate ROV horsepower with ROV capability).

PM player: This requirement is more task oriented as the risk of task completion borne by the PM company is much more logic driven (as opposed to market driven). And it all boils down to either a fiber (for sensor throughput and/or deepwater vehicle telemetry) or a pump (for remotely powering subsea tooling). For sensor delivery, the vehicle simply needs to be big enough to deliver the sensor while having a fiber for full gigabit data throughput. For tooling, the vehicle's auxiliary pump needs to be sized to drive the highest requirement tool anticipated.

Sensor delivery vehicle: This vehicle can be a small MSROV with electric thrusters and minimal tooling capability. The vehicle must have a fiber optic capability for data transmission along with some type of depressor to keep it at depth (most likely a cage or top-hat deployment system), pressure-compensated components and a high-voltage power system to handle the tether lengths/depths. Deepwater fiber optic-based electric MSROVs are certainly sufficient for practically all sensor delivery tasking. Hydraulic WCROVs certainly have the sensor delivery capability but are seen as expensive overkill for the sensor delivery task.

Tooling delivery vehicle: "It is all about the pump!" The highest anticipated tooling need for IRM and light intervention tasks is exemplified by the hydraulic flow requirement of a diamond wire saw as the hydraulic motor of the mid-sized saw requires both high pressure and high flow rate. Polling the various tooling manufacturers of diamond wire saws finds that the mid-sized diamond wire saw requires a 30 gpm (115 lpm) flow rate at 2000 psi (140 bar). The typical

45 cc auxiliary pump on a 150 hp WCROV provides 20 gpm (75 lpm) at 3000 psi (200 bar), which is the same hydraulic horsepower as 30 gpm (115 lpm) at 2000 psi (140 bar). The typical 150 hp WCROV should be sufficient to cover the highest draw tool initially anticipated for IRM (and most construction) tasks. If the ROV company is a DR company, the company has little choice other than to buy a name-brand system from a major manufacturer. If the ROV company is a PM company, the choice is open as to whether to buy the WCROVs or to manufacture the company's own proprietary design.

1.2.3 Strategy for service package deployment

There will be two separate strategies with regard to deployment of services for a DR company versus a PM company. Both will have some common requirements, but the PM company will have additional requirements above the DR company in order to field a "one stop shop" concept to its customer base. Further, the customer base for a PM company will be much more sophisticated with a much longer lead time for ordering services.

DR company: As explained above, it is useless to be a full-service DR WCROV company without full ownership of the deployment vessel as the boat makes the lion's share of the revenues/profits. For the MSROV and OCROV company (due to the call-out nature of the business), vessel ownership (while certainly an option) would probably be an expensive luxury as opposed to a necessity. At best, the ROV company could purchase vessels and dig into an unserved (or under-served) niche left open by the void between the larger international PSV companies (who offer ROV services as an added option to the vessel platform) and the smaller PSV companies (who only offer vessel-only charters).

PM company: The strategy for a PM company is the same as for a DR company with the addition of a project management function. It would be preferable to keep the DR and PM companies in relatively close geographical proximity to one another so that the engineering-to-deployment process is done with a teamwork approach allowing for maximum face time with minimal travel time.

1.3 ROV economics

1.3.1 Capital expenditure (CAPEX) versus day rate

Investment in ROV equipment can be quite expensive and financially risky. The cost of capital involves daily interest charges as well as financial carrying costs. In addition to the cost of capital, the equipment must be insured, maintained in an operationally ready status (when not in the field earning revenues), housed in a secure location, staffed by qualified and trained personnel, and operated periodically (the "use it or lose it" proposition) to verify full readiness. Further, anything that is put in the water has the chance of breaking free, becoming entangled, and/or becoming unrecoverable (equating to a full loss scenario). In short, not only does the ROV company require recapture of its cost of capital, it also requires sufficient revenues to counter the carrying costs of maintaining the vehicle during both revenue and nonrevenue days as well as compensation for risk involved

Table 1.6 CAPEX Versus Vehicle Sizes

Category	Typical Depth Rating	Typical Cost	Typical Day Rate	Type Work	Payback Period
OCROV	300 m (1000 ft)	\$100,000	\$750	Call out	133 days
MSROV	2000 m (6600 ft)	\$1.5 million	\$3000	Call out	500 days
WCROV	>3000 m (>10,000 ft)	\$5 million	\$5000	Contract	1000 days

Table 1.7 Utilization Rate Versus Recapture Time

Category	Typical Cost	Typical Day Rate	Payback Period	Utilization Per Year	Revenue Days Per Year	Years to Recapture
OCROV	\$100,000	\$750	133 days	10%	36 days	3.65
MSROV	\$1.5 million	\$3000	500 days	40%	146 days	3.42
WCROV	\$5 million	\$5000	1000 days	75%	274 days	3.65

along with some measure of profit. Table 1.6 describes a representative sample of day rates, costs, and recapture on the various size categories of vehicles.

There is a trade-off between utilization and day rate in order to achieve an acceptable annual return on investment (ROI) so as to substantiate the investment. Contract work typically enjoys a higher utilization percentage over its call-out counterpart. But a contract ROV with a 1000-day payback period (days, revenue to full recapture of the system cost) with a 75% utilization will take the same time period to recapture its investment as a call-out system with a 10% utilization depending upon the combined factors. Table 1.7 provides a sample of how the same recapture time is achieved between a high recapture percentage coupled with a low utilization as opposed to a high utilization coupled with a longer payback period. As demonstrated in Table 1.7, in the day rate world of ROV services, it is all about utilization!

1.4 ROV services by industry

In this section, the various typical missions by industry will be explored with a conclusion as to the typical vehicle type and sensor/tooling configurations for accomplishing those mission-related tasks.

1.4.1 Science

Industry description: The general need for governmental/university/industrial research organizations involves the gathering of sensor data and the taking of samples for the understanding of the subject environment. Often, scientific manned diving or manned submersibles are used for shallow and deeper water efforts. ROVs predominate as the robotic vehicle of choice for teleoperation due to

the lower cost structure over manned submersibles as well as the lower logistical requirements of the ROV versus manned submersibles.

Typical mission: ROV equipment is typically used in this application to take physical *in situ* samples and to deliver sensors for gathering data from the operational environment.

Typical vehicle type and configuration: As no significant heavy work is performed during science missions (other than geological sampling), minimal intervention is needed requiring small electric actuators, manipulators, and end effectors. Typical vehicles for this mission are the OCROV and/or MSROV with high data-throughput capabilities and small electrical manipulators/end effectors.

1.4.2 Fisheries and aquaculture

Industry description: As the world becomes increasingly more populous and the world's oceans remain over-exploited, fish farming has become much more pronounced in the production of food-stuff for the world's consumers. As a result, various usages of ROV equipment have become prevalent for both the production support at fish farms as well as use in regulatory compliance assurances by policing authorities in open water fisheries locations.

Typical mission: The typical service provided by ROVs in this industry is the inspection of fish cages within a fish farm and for various usages including checking nets for holes, assuring the integrity of moorings for the farm, and the retrieving of "morts" (dead fish) from the cage for health/sanitation purposes.

Typical vehicle type and configuration: As the intervention needs of this mission are minimal and the operational environment is predominantly shallow water, the "flying eyeball" OCROV with a simple video camera and a small manipulator is the vehicle/configuration of choice.

1.4.3 Military

Industry description: The predominant need and usage of ROVs in a military application involve the three basic functions: mine countermeasures (MCM), object retrieval/recovery, and inspection/security tasks.

Typical mission: For the MCM mission, the ROV is sent to a location of targets identified through other sensors or means (mine-hunting sonar, laser line scanners, intelligence, etc.). Once the mine is located, some form of end effector is required in order to neutralize the mine for final disposition. For the object retrieval function, much heavier vehicles are needed in order to rig heavy-lifting gear for retrieval to the surface. And for the inspection/security function, a simple video camera along with basic sensors is needed.

Typical vehicle type and configuration: For the MCM mission, the predominant vehicle is a special-use explosives delivery platform whereby the vehicle delivers a charge and then egresses the area for detonation or (for the more poignant "suicidal" approach) the vehicle carries the charge within close proximity of the mine and then detonates itself and (hopefully) the mine simultaneously. This single-shot MCM vehicle is clearly an OCROV (hopefully of minimal cost) while the charge delivery-then-evacuation vehicle is typically an MSROV with a dexterous electric manipulator capability. For the object retrieval ROV, a heavy-duty WCROV is needed along with hydraulic

manipulators and deepwater capabilities. The inspection/security vehicle is clearly an OCROV with minimal sensor and tooling requirements.

1.4.4 Homeland security

Industry description: Homeland security needs involve the periodic inspection of various vulnerable locations for structural integrity and presence (hopefully, absence) of security threats.

Typical mission: ROVs are typically used in this application for periodic ship hull and pier security inspections and sweeps.

Typical vehicle type and configuration: This function is clearly the realm of the OCROV with minimal sensor and tooling capabilities. The cheaper the per inspection cost the more likely and often the inspection will take place (thus increasing the security proportionately).

1.4.5 Public safety

Industry description: The public safety industry is typically the realm of the police and fire department. Every year, recreational boaters drown, often requiring first responders to perform search and rescue (more often “search and recovery”) in response to public needs.

Typical mission: Many public safety diving (PSD) teams are attached to various municipalities and/or regional governmental authorities. In many cases, the PSD team has an ROV capability assigned to a team member to augment the team’s capability. By the time the ROV is typically called in, however, the team is in full recovery mode (as opposed to rescue mode). The typical mission of a PSD team is search and gathering/recovery of crime scene evidence or recovery of inaccessible items (e.g., drowning victim).

Typical vehicle type and configuration: The budgets of most municipalities obviate the funding for anything other than OCROVs with minimal tooling and sensor capabilities; therefore, the OCROV dominates this function.

1.4.6 O&G drill support

Industry description: Support of drilling operations has become a requirement as the search for hydrocarbons has pushed into deeper waters off the coasts of the world’s continents. In waters deeper than 1000 fsw (300 msw), the wellhead and blowout preventer stack have moved from the surface to the seafloor, requiring all intervention tasks be performed robotically. The requirement for ROV support during all drilling functions in deepwater has become the industry standard.

Typical mission: ROVs for drill support are used from the first spud-in (initial drill bit penetration into the ocean bottom) through to well completion. Missions include observation of the seafloor environment, mounting of well casing seals and guides, guiding of tooling and drill equipment into the well along with various other operations. Recent regulations, in the wake of the April 2010 Macondo oil spill in the northern Gulf of Mexico, have required a second standby ROV, operated from a vessel separate from the drilling rig, to manually operate the BOP should there be a service interruption on the main drilling rig.

Typical vehicle type and configuration: The typical ROV size and configuration for drill support are a larger MSROV or a light WCROV. A drill support operation typically requires a

drill-rig-located ROV with a 7-function hydraulic manipulator along with a second 5-function manipulator/grabber for steadying the vehicle during work. As the heavy-lifting functions are mostly handled from the surface, the vehicle does not require the muscle of a construction project, thus allowing the vehicle to be in the 50–100 hp range.

1.4.7 Inspection, repair, and maintenance

Industry description: The inspection, repair, and maintenance (IRM) market (also referred to as “IMR,” or inspection, maintenance, and repair) broadly comprises the IRM of subsea fixed or floating structures for various industries. These industries include offshore wind farms, fish farms (although this is considered under [Section 1.4.2](#)), civil engineering projects (marine deepwater intakes, outfalls, tidal energy production structures, etc.), ship husbandry, and IMR of various offshore O&G industry support structures.

Typical mission: The typical mission for inspection of subsea structures involves the visual and nondestructive testing/evaluation of various man-made items for safety, security, structural integrity, and functionality of the fixture as well as primary and supporting systems. The repair and maintenance functions are carried out during the course of the asset’s life through various techniques for supporting the life of the project.

Typical vehicle type and configuration: The ROV need during the inspection phase varies depending upon the operating environment (depth, currents, surface conditions, etc.) and the type of inspection being conducted (e.g., high-bandwidth acoustic mapping, structural flooded member detection, and cathodic potential measurement). For basic visual shallow water inspections, a small OCROV will be sufficient, but for higher-bandwidth sensor delivery and/or deepwater operations in harsh conditions, an MSROV will be required. For the repair and maintenance functions, most operations can be accomplished with an MSROV with light intervention and tooling capabilities. As the need for further mechanical tasks becomes heavier, the project may have periodic need for a WCROV, but in most cases the MSROV will suffice.

1.4.8 Construction (O&G as well as civil)

Industry description: The marine subsea construction industry encompasses the full gamut of heavy-lift ROV needs for the setting and assembling of subsea structures.

Typical mission: ROVs for use in this mission typically are tasked with setting and pulling rigging, guiding large construction pieces into place, moving heavy pieces from location to location, laying and burying cables and pipelines and setting mattresses as well as the various tasks outlined in [Section 1.2.2](#).

Typical vehicle type and configuration: Vehicles in use for the subsea construction tasking are typically higher powered (>150 hydraulic hp) and specification WCROVs with dual 7-function manipulators and high pressure/flow remote tooling delivery capabilities.

1.5 CONCLUSIONS

The business aspect of the ROV service industry can be just as challenging as the technical aspect. It is quite daunting to the un-indoctrinated. Like the aviation and maritime counterparts to the ROV business, the support structure requires not only a deep equipment and spares pool, it also requires

a thorough training program, procedures, controls, and a commitment to service quality. It is a financially risky business rife with pitfalls. But the rewards are clear and evident for the entrepreneur willing to navigate the regulatory and economic minefields.

Field personnel must be properly trained with a positive “can do” attitude with thorough troubleshooting skills and a trained eye toward accomplishing the task in a safe and cost-effective manner. In this business, it is all about the people!

What follows in the remainder of the manual is the fun part—the technical aspects of the ROV system and its use.



The Ocean Environment

CHAPTER CONTENTS

2.1 Physical oceanography	22
2.1.1 Distribution of water on earth	22
2.1.2 Coastal zone classifications and bottom types	22
2.2 Chemical oceanography	24
2.2.1 Salinity.....	24
2.2.1.1 Salt water.....	24
2.2.1.2 Fresh water.....	27
2.2.2 Pressure	28
2.2.3 Compressibility	28
2.2.4 Conductivity.....	28
2.2.5 Water temperature.....	30
2.2.6 Density.....	30
2.2.7 Depth	32
2.2.7.1 Echo sounder.....	32
2.2.7.2 Optic–acoustic seabed classification	34
2.2.8 Sonic velocity and sound channels.....	35
2.2.9 Viscosity	38
2.2.10 Water flow	38
2.2.11 Turbidity	38
2.2.12 Chlorophyll	38
2.2.13 Water quality.....	38
2.2.13.1 Alkalinity and pH.....	38
2.2.13.2 Oxidation reduction potential.....	40
2.2.13.3 Rhodamine	40
2.2.13.4 Specific conductance	40
2.2.13.5 Total dissolved solids	40
2.2.14 Dissolved gases	40
2.2.15 Ionic concentration.....	43
2.2.16 Solar radiation	43
2.2.17 Light and other electromagnetic transmissions through water	43
2.2.17.1 Absorption.....	43

2.2.17.2 Refraction	44
2.2.17.3 Scattering	44
2.3 Ocean dynamics.....	45
2.3.1 Circulation	45
2.3.1.1 Currents.....	46
2.3.1.2 Tides.....	47
2.3.1.3 Water velocity.....	48
2.3.1.4 Waves and the Beaufort scale.....	48
2.3.2 Effects of wave pattern upon ROV operation.....	51

In order to comprehend the concepts of operating in the ocean world, an understanding of the details of this environment is needed. The content of this chapter explores the makeup of fresh water and seawater and then goes into the interaction of this substance with the world of robotics. We will explore the basic concepts of water density, ocean circulation, currents and tides and how each of these affects the operation of ROV equipment. Armed with a general knowledge of oceanography, work site predictions may be made on such variables as turbidity (affecting camera optics), temperature/salinity (affecting acoustic equipment and vehicle buoyancy), tide and current flows (affecting drag computations on the submersible/tether combination), and dissolved gases (affecting biological population). This section condenses information from complete college curriculums; therefore, for further details, please see the references in the bibliography. Special thanks go to Steve Fondriest of Fondriest Environmental, Inc. for his contribution to the fundamentals of environmental monitoring and data collection instrumentation.

2.1 Physical oceanography

2.1.1 Distribution of water on earth

Earth is the only planet known to have water resident in all three states (solid, liquid, and gas). It is also the only planet to have known liquid water currently at its surface. Distribution of the earth's water supply is given in [Table 2.1](#).

As shown in [Table 2.1](#), most (97%) of the world's water supply is in the oceans. Water can dissolve more substances (and in greater quantities) than any other liquid. It is essential to sustain life and is a moderator of our planet's temperature, a major contributor to global weather patterns, and, of course, essential for operation of an ROV.

The oceans cover 70.8% of the earth's surface, far overreaching earth's land mass. Of the ocean coverage, the Atlantic covers 16.2%, the Pacific 32.4%, the Indian Ocean 14.4%, and the margin and adjacent areas the balance of 7.8%. It is also interesting to note that the Pacific Ocean alone covers 3.2% more surface area on earth than all of the land masses combined.

2.1.2 Coastal zone classifications and bottom types

General coastal characteristics tend to be similar for thousands of kilometers. Most coasts can be classified as either erosional or depositional depending upon whether their primary features were

Table 2.1 Earth's Water Supply

Water Source	Water Volume, in Cubic Miles	Water Volume, in Cubic Kilometers	Percent of Fresh water	Percent of Total Water
Oceans, seas, and bays	321,000,000	1,338,000,000	—	96.5
Ice caps, glaciers, and permanent snow	5,773,000	24,064,000	68.7	1.74
Groundwater				
Fresh	2,526,000	10,530,000	30.1	0.76
Saline	3,088,000	12,870,000	—	0.94
Soil moisture	3959	16,500	0.05	0.001
Ground ice and permafrost	71,970	300,000	0.86	0.022
Lakes				
Fresh	21,830	91,000	0.26	0.007
Saline	20,490	85,400	—	0.006
Atmosphere	3095	12,900	0.04	0.001
Swamp water	2752	11,470	0.03	0.0008
Rivers	509	2120	0.006	0.0002
Biological water	269	1120	0.003	0.0001

Source: US Geological Survey.

created by erosion of land or deposition of eroded materials. Erosional coasts have developed where the shore is actively eroded by wave action or where rivers or glaciers caused erosion when the sea level was lower than its present level. Depositional coasts have developed where sediments accumulate either from a local source or after being transported to the area in rivers and glaciers or by ocean currents and waves.

Of primary interest to the ROV pilot, with regard to coastal zones, is the general classification of these zones and its effect upon general water turbidity in the operational area. Depositional coasts tend to have a higher quantity of suspended solids in the water column, thus a higher turbidity and degraded camera performance. Erosional coasts tend to possess fewer suspended particles, thus featuring better camera optics. Further, the depositional source will greatly affect the level of turbidity since mud deposited from a river estuary will have a higher turbidity than a rock and sand drainage area.

As stated earlier, oceans cover 70.8% of the earth's surface. Of that composition, the distribution between continental margins and deep-sea basins is provided in [Table 2.2](#).

A substantial amount of scientific and oil exploration/production work is done in the continental margins with ROVs. The continental margins are, in large part, depositional features. Their characteristics are driven by runoff deposited from the adjacent continent.

Sediments are carried from the marine estuaries and then deposited onto the continental shelf. As the seafloor spreads due to tectonic forces, the sediments fall down the continental slope and come to rest on the abyssal plain. Substantial amounts of oil and gas deposits are locked in these

Table 2.2 Ocean Coverage Distribution

	10 ⁶ km ²	Percentage of Earth's Surface Area
Continental margin	93	18.2
Deep basins	268	52.6
Total	361	70.8

sediments and are the focus of exploration and production efforts. The general bottom characteristics of this shelf are mud and sediment.

2.2 Chemical oceanography

Water is known as the “universal solvent.” While pure water is the basis for life on earth, as more impurities are added to that fluid the physical and chemical properties change drastically. The chemical makeup of the water mixture in which the ROV operates will directly dictate operational procedures and parameters if a successful operation is to be achieved.

Two everyday examples of water’s physical properties and their effect on our lives are (i) ice floats in water and (ii) we salt our roads in wintertime to “melt” snow on the road. Clearly, it is important to understand the operating environment and its effect on ROV operations. To accomplish this, the properties and chemical aspects of water and how they are measured will be addressed to determine their overall effect on the ROV.

The early method of obtaining environmental information was by gathering water samples for later analysis in a laboratory. Today, the basic parameters of water are measured with a common instrument named the “CTD sonde.” Some of the newest sensors can analyze a host of parameters logged on a single compact sensing unit.

Fresh water is an insulator, with the degree of electrical conductivity increasing as more salts are added to the solution. By measuring the water’s degree of electrical conductivity, a highly accurate measure of salinity can be derived. Temperature is measured via electronic methods, and depth is measured with a simple water pressure transducer. The CTD probe measures “conductivity/temperature/depth,” which are the basic parameters in the sonic velocity equation. Newer environmental probes are available for measuring any number of water quality parameters such as pH, dissolved oxygen and CO₂, turbidity, and other parameters.

The measurable parameters of water are needed for various reasons. A discussion of the most common measurement variables the commercial or scientific ROV pilot will encounter, the information those parameters provide, and the tools/techniques to measure them follows.

2.2.1 Salinity

2.2.1.1 Salt water

The world’s water supply consists of everything from pure water to water plus any number of dissolved substances due to water’s soluble nature. Water quality researchers measure salinity to assess the purity of drinking water, monitor salt water intrusion into fresh water marshes and groundwater aquifers, and research how the salinity will affect the ecosystem.

Table 2.3 Dissolved Salts in Water

Component	Weight in Grams
Pure water	965.31
Major constituents	
Chlorine	19.10
Sodium	10.62
Magnesium	1.28
Sulfur	2.66
Calcium	0.40
Potassium	0.38
Minor constituents	0.24
Trace constituents	0.01
Total (in grams)	1000.00

The two largest dissolved components of typical seawater are chlorine (56% of total) and sodium (31% of total), with the total of all lumped under the designation of “salts.” Components of typical ocean water dissolved salts are comprised of major constituents, minor constituents, and trace constituents. An analysis of 1 kg of seawater (detailing only the major constituents of dissolved salts) is provided in [Table 2.3](#).

The total quantity of dissolved salts in seawater is expressed as salinity, which can be calculated from conductivity and temperature readings. Salinity was historically expressed quantitatively as grams of dissolved salts per kilogram of water (expressed as percentage) or, more commonly, in parts per thousand (ppt). To improve the precision of salinity measurements, salinity is now defined as a ratio of the electrical conductivity of the seawater to the electrical conductivity of a standard concentration of potassium chloride solution. Thus, salinity is now defined in practical salinity units (PSU), although one may still find the older measure of salt concentration in a solution as parts per thousand or percentage used in the field.

Ocean water has a fairly consistent makeup, with 99% having between 33 and 37 PSU in dissolved salts. Generally, rain enters the water cycle as pure water and then gains various dissolved minerals as it travels toward the ocean. Water enters the cycle with a salt content of 0 PSU, mixes with various salts to form brackish water (in the range of 0.5–30 PSU) as it blends with rivers and estuaries, homogenizes with the ocean water (75% of the ocean’s waters have between 33 and 34 PSU of dissolved salts) as the cycle ends, and then renews with evaporation.

Just as a layer of rapid change in temperature (the thermocline) traps sound and other energy, so does an area of rapid change in salinity, known as a “halocline.” These haloclines are present both horizontally (see cenote example later in this chapter) and vertically (e.g., rip tides at river estuaries).

As the salinity of water increases, the freezing point decreases. As an anecdote to salinity, there are brine pools under the Antarctic ice amid the glaciers in the many lakes of Antarctica’s McMurdo Dry Valleys. A team recently found a liquid lake of super-concentrated salt water, seven times saltier than normal seawater, locked beneath 62 ft (19 m) of lake ice—a record for lake ice cover on earth.

Salts dissolved in water change the density of the resultant seawater for these reasons:

- The ions and molecules of the dissolved substances are of a higher density than water.
- Dissolved substances inhibit the clustering of water molecules (particularly near the freezing point), thus increasing the density and lowering the freezing point.

Unlike fresh water, ocean water continues to increase in density up to its freezing point of approximately -2°C . At 0 PSU (i.e., fresh water), maximum density is approximately 4°C with a freezing point of 0°C . At 24.7 PSU and above, ocean water has a freezing point of its maximum density; therefore, there is no maximum density temperature above the freezing point. The maximum density point scales in a linear fashion between 0 and 24.7 PSU (Figure 2.1).

Thus, ocean water continues to increase in density as it cools and sinks in the open ocean. As a result, the deepwaters of the world's oceans are uniformly cold.

Comparisons of salinity and temperature effects upon water density yield the following:

- At a constant temperature, variation of the salinity from 0 to 40 PSU changes the density by about 0.035 specific gravity (or about 3.5% of the density for 0 PSU water at 4°C).
- At a constant salinity (i.e., 0 PSU), raising the temperature from 4°C (maximum density) to 30°C (highest temperature generally found in surface water) yields a decrease in density of 0.0043 (1.000–0.9957) for a change of 0.4%.

Clearly, salinity has a much higher effect upon water density than does temperature.

As a practical example, suppose a 220 pound (100 kg) ROV is ballasted for 4°C fresh water at exactly neutral buoyancy. If that same submersible were to be transferred to salt water, an additional ballasting weight of approximately 7.7 pounds (3.5 kg) would be required to maintain that vehicle at neutral buoyancy.

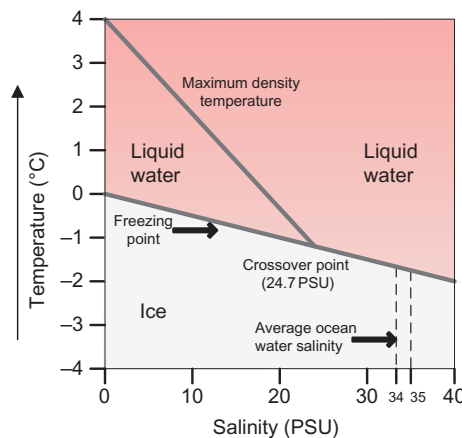


FIGURE 2.1

Salt water density, salinity versus temperature.

Ice at 0°C has a density of 57.25 lb/ft³ (0.917 g/cm³), which is about 8% less than that of water at the same temperature. Obviously, water expands when it freezes, bursting pipes and breaking apart water-encrusted rocks, thus producing revenues for marine and land plumbing contractors.

2.2.1.2 Fresh water

A vast majority of the world's fresh water supply is locked within the ice caps and glaciers of the high Arctic and Antarctic regions. Fresh water is vital to man's survival, and thus most human endeavors surround areas of fresh water. Due to the shallow water nature of the fresh water collection points, man has placed various items of machinery, structures, and tooling in and around these locations. The ROV pilot will, in all likelihood, have plenty of opportunity to operate within the fresh water environment.

The properties of water directly affect the operation of ROV equipment in the form of temperature (affecting components and electronics), chemistry (affecting seals, incurring oxidation, and degrading machinery operation), and specific gravity (buoyancy and performance). These parameters will determine the buoyancy of vehicles, the efficiency of thrusters, the numbers and types of biological specimens encountered, as well as the freezing and boiling points of the operational environment. The water density will further affect sound propagation characteristics, directly impacting the operation of sonar and acoustic positioning equipment.

Fresh water has a specific gravity of 1.000 at its maximum density. As water temperature rises, molecular agitation increases the water's volume, thus lowering the density of the fluid per unit volume. In the range between 3.98°C and the freezing point of water, the molecular lattice structure (in the form of ice crystals) again increases the overall volume, thus lowering its density per unit volume (remember, ice floats). The point of maximum density for fresh water occurs at 3.98°C (the point just before the formation of ice crystals). At the freezing point of water, the lattice structure rapidly completes, thus significantly expanding the volume per unit mass and lowering the density at that temperature point. A graph describing the temperature/density relationship of pure water is shown in Figure 2.2.

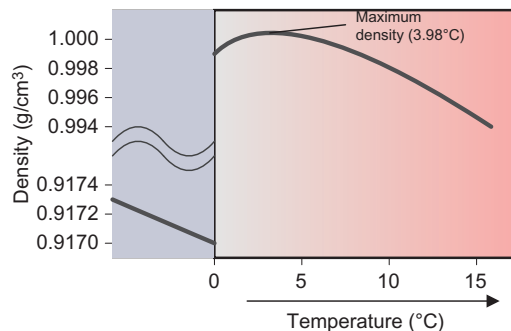


FIGURE 2.2

Water density versus temperature.

Fresh water has a maximum density at approximately 4°C (Figure 2.1) yet ocean water has no maximum density above the freezing point. As a result, lakes and rivers behave differently at the freezing point than ocean water. As the weather cools with the approach of winter, the surface water of a fresh water lake is cooled and its density is increased. Surface water sinks and displaces bottom water upward to be cooled in turn. This convection process is called “overturning.” This overturning process continues until the maximum density is achieved, thus stopping the convection churning process at 4°C. As the lake continues to cool, the crystal structure in the water forms, thus allowing the cooler water at the surface to decrease in density, driving still further the cooler (less dense) surface water upward, allowing ice to form at the surface.

2.2.2 Pressure

The SI unit for pressure is the kilopascal (expressed as kPa). One pascal is equal to one newton per square meter. However, oceanographers normally use ocean pressure with reference to sea-level atmospheric pressure. The imperial unit is one atmosphere. The SI unit is the bar. The decibar is a useful measure of water pressure and is equal to 1/10 bar. Seawater generally increases by one atmosphere of pressure for every 33 ft of depth (approximately equaling 10 m). Therefore, one decibar is approximately equal to one meter of depth in seawater (Figure 2.3).

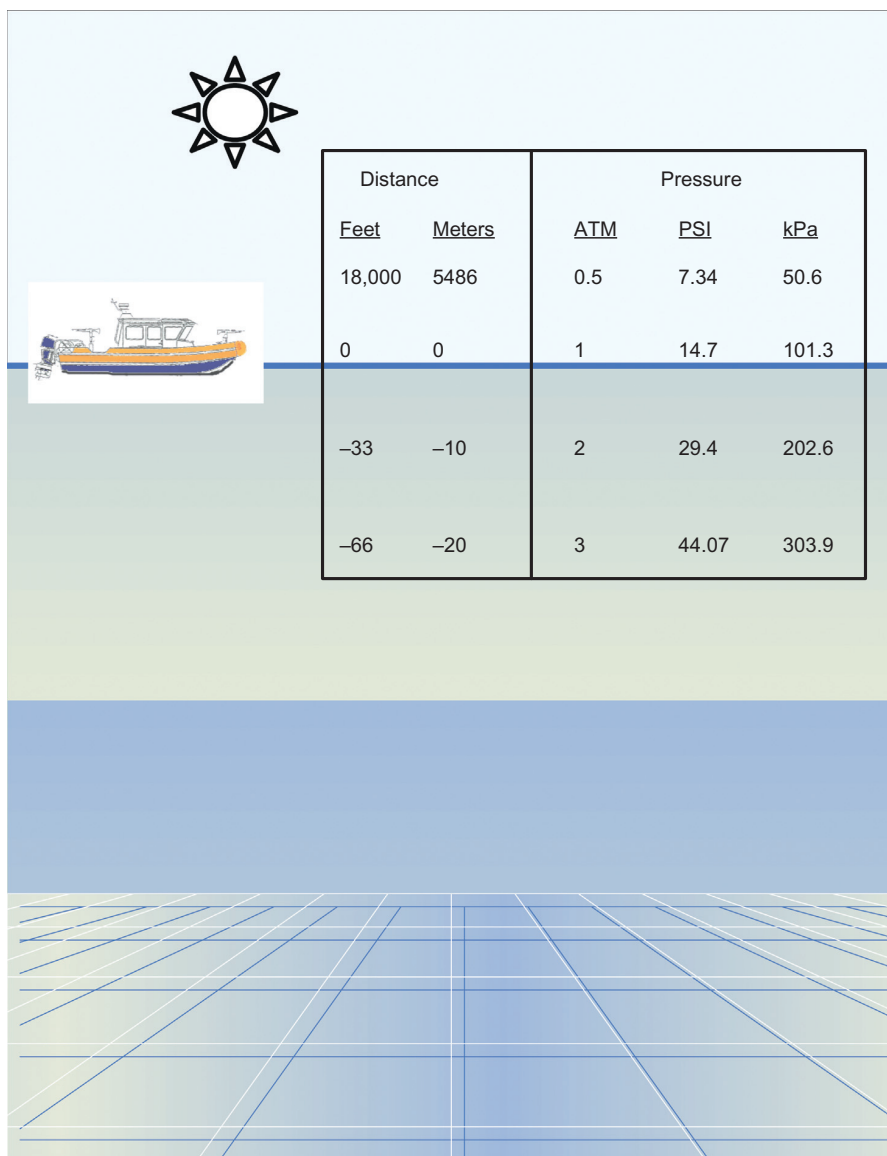
As an ROV pilot, seawater pressure directly affects all aspects of submersible operation. The design of the submersible’s air-filled components must withstand the pressures of depth, the flotation must stand up to the pressure without significant deformation (thus losing buoyancy and sinking the vehicle), and tethers must be sturdy enough to withstand the depth while maintaining their neutral buoyancy.

2.2.3 Compressibility

For the purposes of ROV operations, seawater is essentially incompressible. There is a slight compressibility factor, however, that does directly affect the propagation of sound through water. This compressibility factor will affect the sonic velocity computations at varying depths (see Section 2.2.8 later in this chapter).

2.2.4 Conductivity

Conductivity is the measure of electrical current flow potential through a solution. In addition, because conductivity and ion concentration are highly correlated, conductivity measurements are used to calculate ion concentration in solutions. Commercial and military operators observe conductivity for gauging water density (for vehicle ballasting and such) and for determining sonic velocity profiles (for acoustic positioning and sonar use). Water quality researchers take conductivity readings to determine the purity of water, to watch for sudden changes in natural or wastewater, and to determine how the water sample will react in other chemical analyses. In each of these applications, water quality researchers count on conductivity sensors and computer software to sense environmental waters, log and analyze data, and present this data.

**FIGURE 2.3**

Pressure in atmospheres from various levels.

2.2.5 Water temperature

Water temperature is a measure of the kinetic energy of water and is expressed in degrees Fahrenheit (F) or Celsius (C). Water temperature varies according to season, depth, and, in some cases, time of day. Because most aquatic organisms are cold blooded, they require a certain temperature range to survive. Some organisms prefer colder temperatures and others prefer warmer temperatures. Temperature also affects the water's ability to dissolve gases, including oxygen. The lower the temperature, the higher the solubility. Thermal pollution, the artificial warming of a body of water because of industrial waste or runoff from streets and parking lots, is becoming a common threat to the environment. This artificially heated water decreases the amount of dissolved oxygen and can be harmful to cold water organisms.

In limnological research, water temperature measurements as a function of depth are often required. Many reservoirs are controlled by selective withdrawal dams, and temperature monitoring at various depths provides operators with information to control gate positions. Power utility and industrial effluents may have significant ecological impact with elevated temperature discharges. Industrial plants often require water temperature data for process, use, and heat transfer calculations.

Pure water freezes at 32°F (0°C) and boils at 212°F (100°C). ROV operations do not normally function in boiling water environments; therefore, the focus here will be upon the temperature ranges in which most ROV systems operate (i.e., 32°F to 86°F or 0°C to 30°C). The examination of salinity will be in the range from fresh water to the upper limit of seawater.

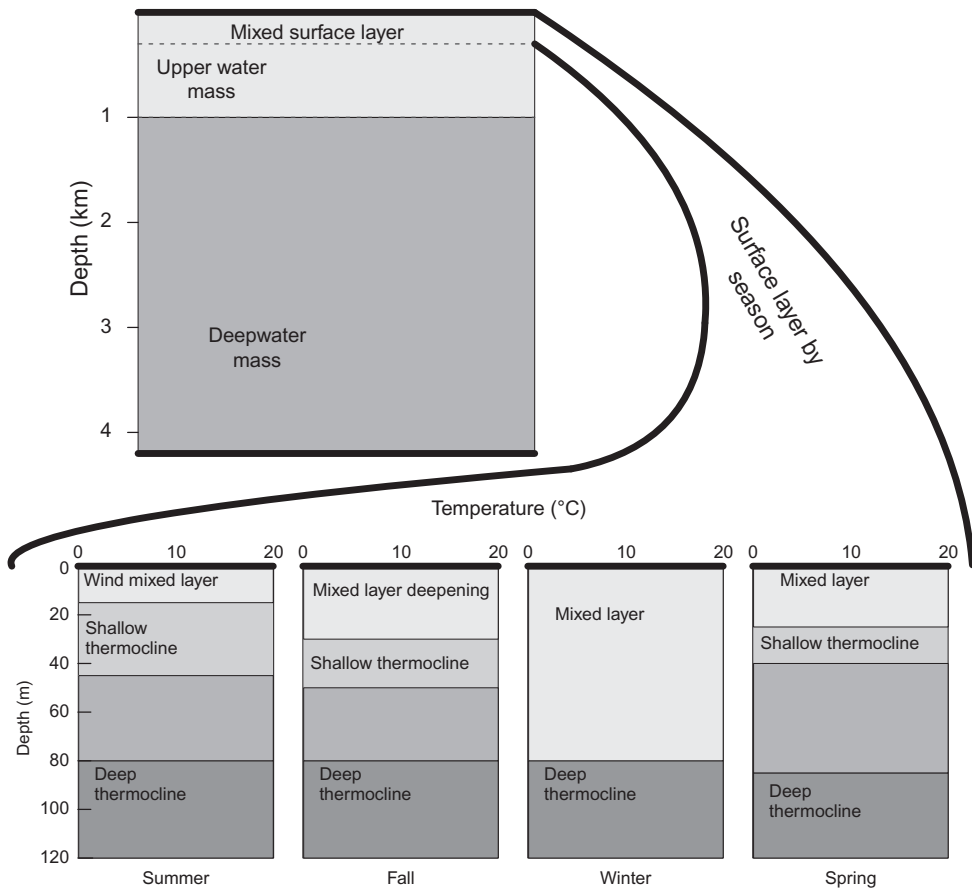
Temperature in the oceans varies widely both horizontally and vertically. On the high temperature side, the Persian Gulf region during summertime will achieve a maximum of approximately 90°F (32°C). The lowest possible value is at the freezing point of 28.4°F (−2°C) experienced in polar region(s).

The vertical temperature distribution nearly everywhere (except the polar regions) displays a profile of decreasing water temperature with increasing depth. Assuming constant salinity, colder water will be denser and will sink below the warmer water at the surface.

There is usually a mixed layer of isothermal (constant temperature) water from the surface to some near-surface depth due to wind mixing and convective overturning (thermally driven vertical density mixing) that changes with the seasons (Figure 2.4). The layer is thin at the equator and thick at the poles. The layer where there is a rapid change in temperature over a short distance is termed a “thermocline” and has some interesting characteristics. Due to the rapid temperature gradient, this thermocline forms a barrier that can trap sound energy, light energy, and any number of suspended particles. The degree of perviousness of the barrier is determined by the relative strength or degree of change over distance. For the ROV pilot, a thermocline in the area of operation can hinder the function of acoustic positioning, sonar, and any sounding equipment aboard attempting to burn through the layer. It is especially of concern to anti-submarine warfare technicians.

2.2.6 Density

Density is mass per unit volume measured in SI units in kilograms per cubic meter (or, on a smaller scale, grams per cubic centimeter). The density of seawater depends upon salinity, temperature, and pressure. At a constant temperature and pressure, density varies with water salinity. This measure is of particular importance to the ROV pilot for the determination of neutral buoyancy for the vehicle.

**FIGURE 2.4**

Surface layer mixing by season.

The density range for seawater is from 1.02200 to 1.030000 g/cm³ (Thurman, 1994). In an idealized stable system, the higher density water sinks to the bottom while the lower density water floats to the surface. Water under the extreme pressure of depth will naturally be denser than surface water, with the change in pressure (through motion between depths) being realized as heat. Just as the balance of pressure/volume/temperature is prevalent in the atmosphere, so is the temperature/salinity/pressure model in the oceans.

A rapid change in density over a short distance is termed a “pycnocline” and can trap any number of energy sources from crossing this barrier, including sound (sonar and acoustic positioning systems), current, and neutrally buoyant objects in the water column (underwater vehicles). Changing operational area from a lower latitude to a higher latitude produces a mean temperature change in

the surface layer. As stated previously, the deep ocean is uniformly cold due to the higher density cold water sinking to the bottom of the world's oceans. The temperature change from the warm surface at the tropics to the lower cold water can be extreme, causing a rapid temperature swing within a few meters of the surface. This surface layer remains near the surface, causing a small tight "surface duct" in the lower latitudes. In the higher latitudes, however, the difference between ambient surface temperature and the temperature of the cold depth is less pronounced. The thermal mixing layer at these latitudes, as a result, is much larger (over a broader range of depth between the surface and the isothermal lower depths) and less pronounced (Figure 2.5). In Figure 2.5(a), density profiles by latitude and depth are examined to display the varying effects of deepwater temperature/density profiles versus ambient surface temperatures. Figure 2.5(b) and (c) looks at the same profiles only focusing on temperature and salinity. Figure 2.5(d) demonstrates a general profile for density at low to midlatitudes (the mixed layer is water of constant temperature due to the effects of wave mechanics/mixing).

A good example of the effect of density on ROV operations comes from a scientific mission conducted in 2003 in conjunction with *National Geographic* magazine. The mission was to the cenotes (sinkholes) of the Northern Yucatan in Mexico. Cenotes are a series of pressure holes in a circular arrangement, centered around Chicxulub (the theoretical meteor impact point), purportedly left over from the K–T event from 65 million years ago that killed the dinosaurs.

The top water in the cenote is fresh water from rain runoff, with the bottom of the cenote becoming salt water due to communication (via an underground cave network) with the open ocean. This column of still water is a near perfect unmixed column of fresh water on top with salt water below. A micro-ROV was being used to examine the bottom of the cenote as well as to sample the salt water/fresh water (halocline) layer. The submersible was ballasted to the fresh water on the top layer. When the vehicle came to the salt water layer, the submersible's vertical thruster had insufficient downward thrust to penetrate into the salt water below and kept "bouncing" off the halocline. The submersible had to be re-ballasted for salt water in order to get into that layer and take the measurements, but the vehicle was useless on the way down due to its being too heavily ballasted to operate in fresh water.

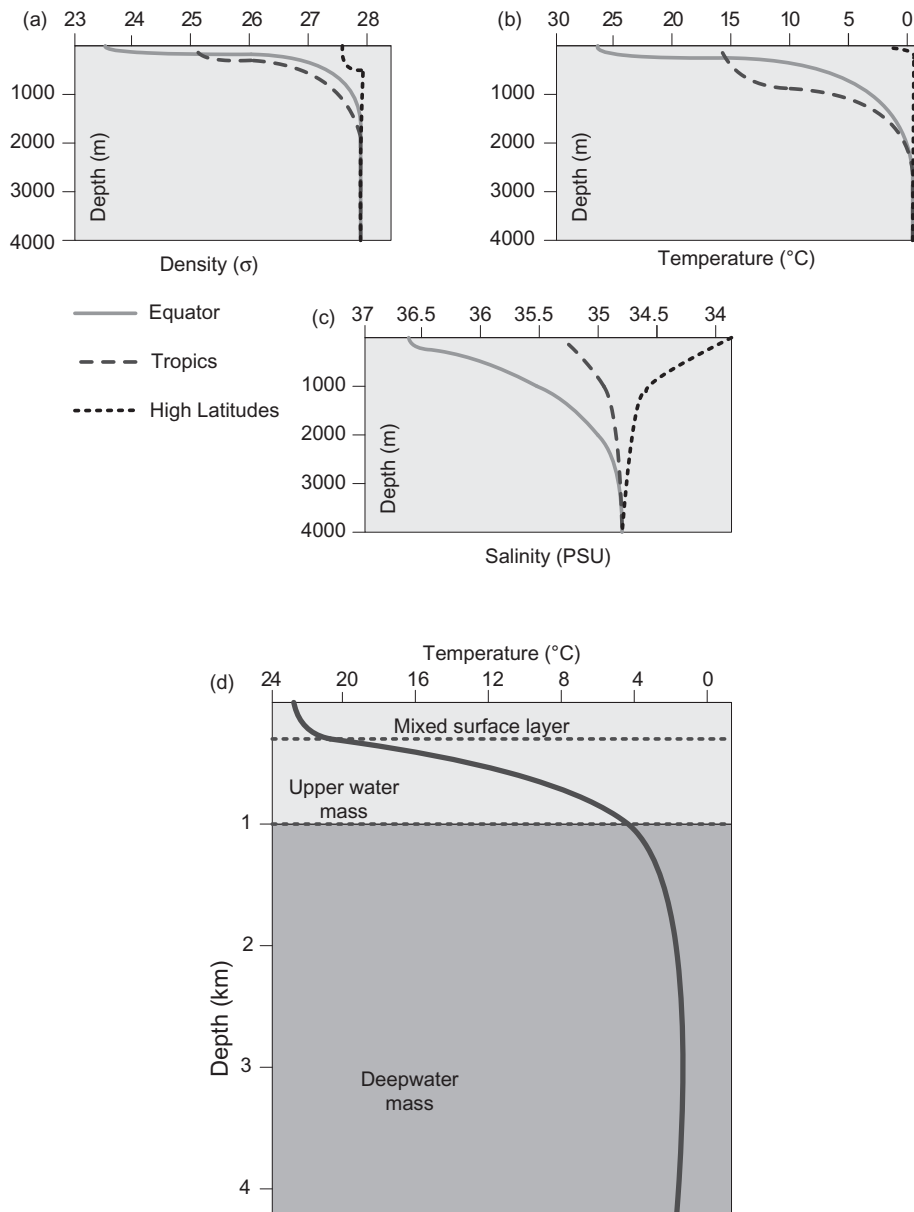
2.2.7 Depth

Depth sensors, discussed below, measure the distance from the surface of a body of water to a given point beneath the surface, either the bottom or any intermediate level. Depth readings are used by researchers and engineers in coastal and ocean profiling, dredging, erosion and flood monitoring, and construction applications.

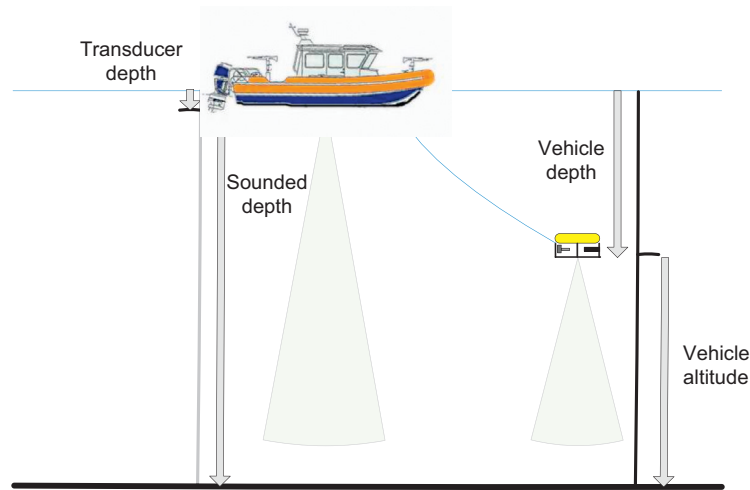
Bathymetry is the measurement of depth in bodies of water. Further, it is the underwater version of topography in geography. Bottom contour mapping details the shape of the seafloor, showing the features, characteristics, and general outlay. Tools for bathymetry and sea bottom characterization are as follows.

2.2.7.1 Echo sounder

An echo sounder measures the round trip time it takes for a pulse of sound to travel from the source at the measuring platform (surface vessel or on the bottom of the submersible) to the sea bottom and return. When mounted on a vessel, this device is generally termed a "fathometer" and when mounted on a submersible it is termed an "altimeter."

**FIGURE 2.5**

Individual sound velocity components (a) density, (b) temperature, and (c) salinity combined into a composite (d) sound velocity curve by depth.

**FIGURE 2.6**

Vessel-mounted and sub-mounted sounders.

According to Bowditch (2002), “the major difference between various types of echo sounders is in the frequency they use. Transducers can be classified according to their beam width, frequency, and power rating. The sound radiates from the transducer in a cone, with about 50 percent actually reaching the sea bottom. Beam width is determined by the frequency of the pulse and the size of the transducer. In general, lower frequencies produce a wider beam, and at a given frequency, a smaller transducer will produce a wider beam. Lower frequencies penetrate deeper into the water, but have less resolution in depth. Higher frequencies have a greater resolution in depth, but less range, so the choice is a trade-off. Higher frequencies also require a smaller transducer. A typical low-frequency transducer operates at 12 kHz and a high-frequency one at 200 kHz.” Many smaller ROV systems have altimeters, such as the Imagenex 852, on the same frequency as their imaging system for easier software integration (the same software can be used for processing both signals) and reduced cost (Figure 2.6).

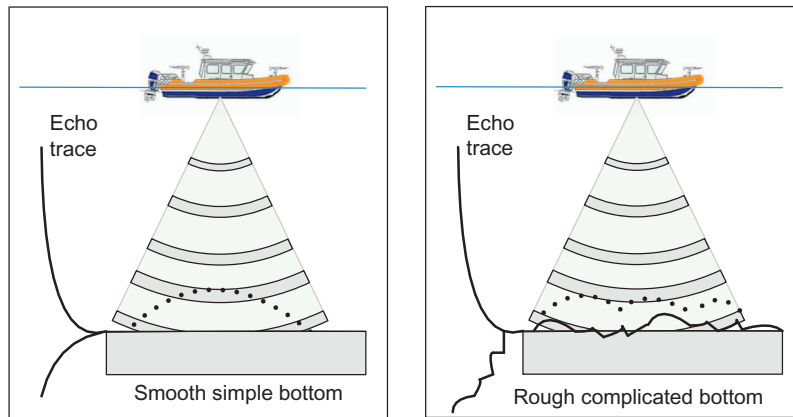
Computation of depth as determined by an echo sounder is determined via the following formula:

$$D = (V \times T/2) + K + D_r$$

where D is depth below the surface (or from the measuring platform), V is the mean velocity of sound in the water column, T is time for the round trip pulse, K is the system index constant, and D_r is the depth of the transducer below the surface.

2.2.7.2 Optic–acoustic seabed classification

Traditional seafloor classification methods have, until recently, relied upon the use of mechanical sampling, aerial photography, or multiband sensors (such as Landsat™) for major bottom-type

**FIGURE 2.7**

Acoustic seabed classification.

discrimination (e.g., mud, sand, rock, sea grass, and corals). Newer acoustic techniques for collecting hyperspectral imagery are now available through processing of acoustic backscatter.

Acoustic seabed classification analyzes the amplitude and shape of acoustic backscatter echoed from the sea bottom for the determination of bottom texture and makeup (Figure 2.7). Seafloor roughness causes impedance mismatch between the water and the sediment. Further, reverberation within the substrate can be analyzed in determining the overall composition of the bottom being insonified. Acoustic data acquisition systems and a set of algorithms that analyze the data allow for determining the seabed acoustic class.

2.2.8 Sonic velocity and sound channels

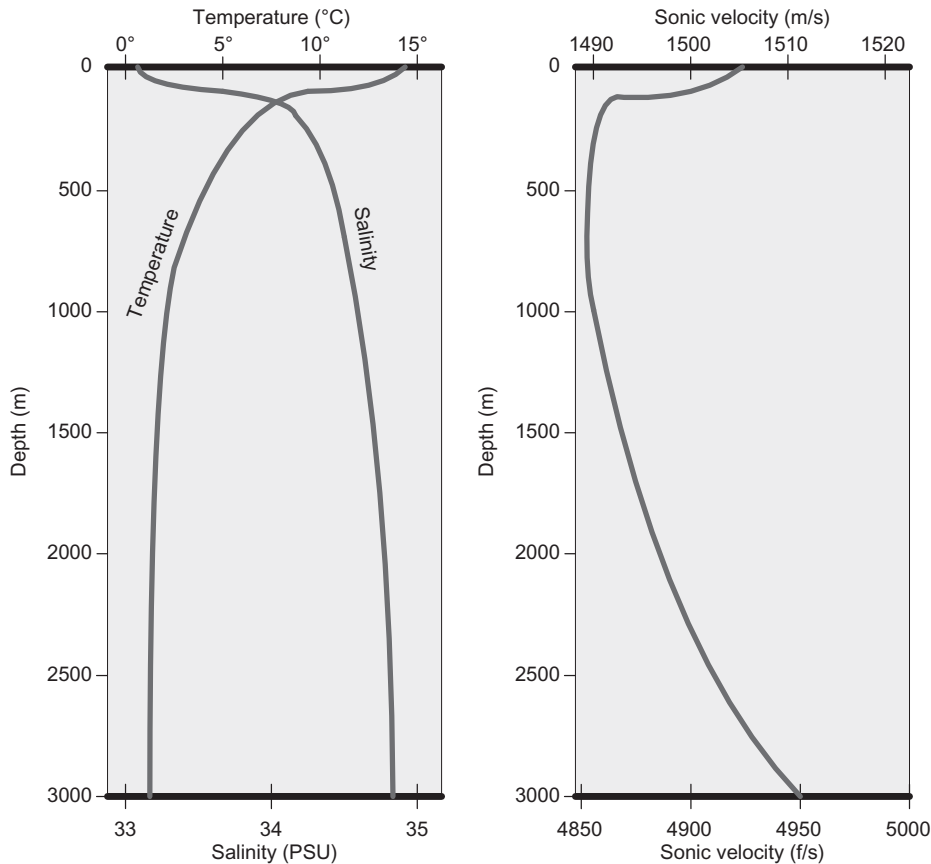
Sound propagation (vector and intensity) in water is a function of its velocity. And velocity is a function of water density and compressibility. As such, sound velocity is dependent upon temperature, salinity, and pressure and is normally derived expressing these three variables (Figure 2.8). The speed of sound in water changes by 3–5 m/s/°C, by approximately 1.3 m/s/PSU salinity change, and by about 1.7 m/s/100 m change in depth (compression). The speed of sound in seawater increases with increasing pressure, temperature, and salinity (and vice versa).

The generally accepted underwater sonic velocity model was derived by W. D. Wilson in 1960. A simplified version of Wilson's (1960) formula on the speed of sound in water follows:

$$c = 1449 + 4.6T - 0.055T^2 + 0.0003T^3 + 1.39(S - 35) + 0.017D$$

where c is the speed of sound in meters per second, T is the temperature in degrees Celsius, S is the salinity in PSU, and D is the depth in meters.

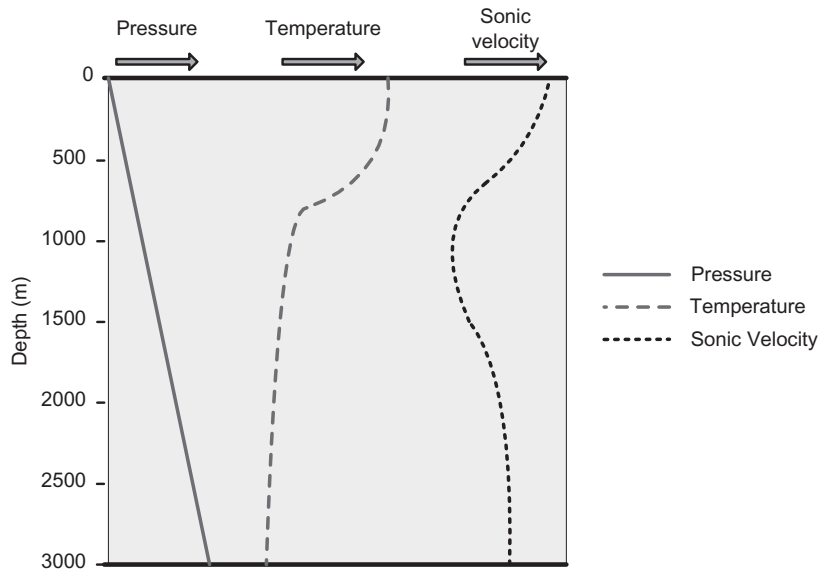
Temperature/salinity/density profiles are important measurements for sensor operations in many underwater environments, and they have a dramatic effect on the transmission of sound in the

**FIGURE 2.8**

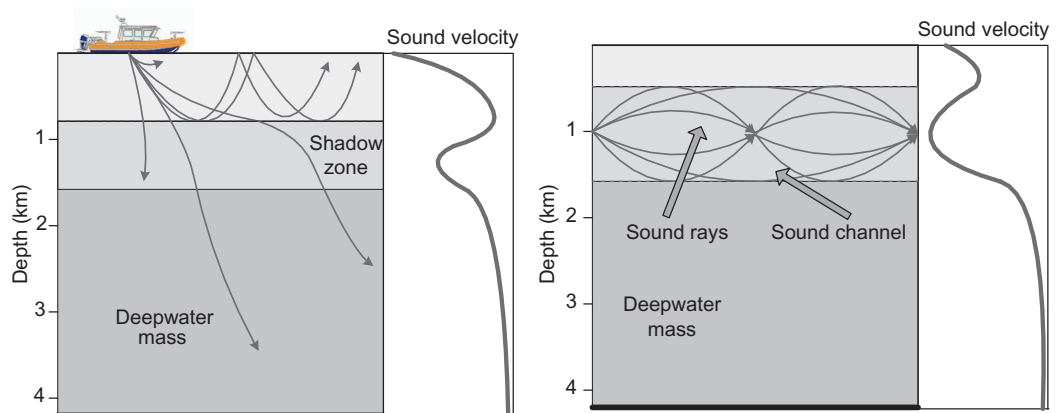
Sonic velocity profiles with varying temperature/salinity/depth.

ocean. A change in overall water density over short range due to any of these three variables (or in combination) is termed a “pycnocline.” Overall variations of pressure and temperature are depicted graphically in Figure 2.9.

This layering within the ocean, due to relatively impervious density barriers, causes the formation of sound channels within bodies of water. These “channels” trap sound, thus directing it over possibly long ranges. Sound will refract based upon its travel across varying density layers, bending toward the denser water and affecting both range and bearing computations for acoustics (Figure 2.10). Over short ranges (tens or hundreds of meters) this may not be a substantial number and can possibly be disregarded, but for the longer distances of some larger ROV systems, this becomes increasingly a factor to be considered.

**FIGURE 2.9**

Variations of pressure and temperature with depth producing sound velocity changes.

**FIGURE 2.10**

Sound velocity profiles and channeling at various depths and layers.

2.2.9 Viscosity

Viscosity is a liquid's measure of internal resistance to flow or resistance of objects to movement within the fluid. Viscosity varies with changes in temperature/salinity, as does density. Seawater is more viscous than fresh water, which will slightly affect the computations of vehicle drag.

2.2.10 Water flow

Water flow is the rate at which a volume of water moves or flows across a certain cross-sectional area during a specified time and is typically measured in cubic feet per second/cubic meters per second (cfs/cms). The flow rate changes based upon the amount of water and the size of the river or stream being monitored. Environmental researchers monitor water flow in order to estimate pollutant spread, to monitor groundwater flow, to measure river discharge, to manage water resources, and to evaluate the effects of flooding.

2.2.11 Turbidity

Turbidity (which causes light scattering—see [Section 2.2.17.3](#)), the measure of the content of suspended solids in water, is also referred to as the “cloudiness” of the water. Turbidity is measured by shining a beam of light into the solution. The light scattered off the particles suspended in the solution is then measured, and the turbidity reading is given in nephelometric turbidity units. Water quality researchers take turbidity readings to monitor dredging and construction projects, examine microscopic aquatic plant life, and monitor surface, storm, and wastewater.

2.2.12 Chlorophyll

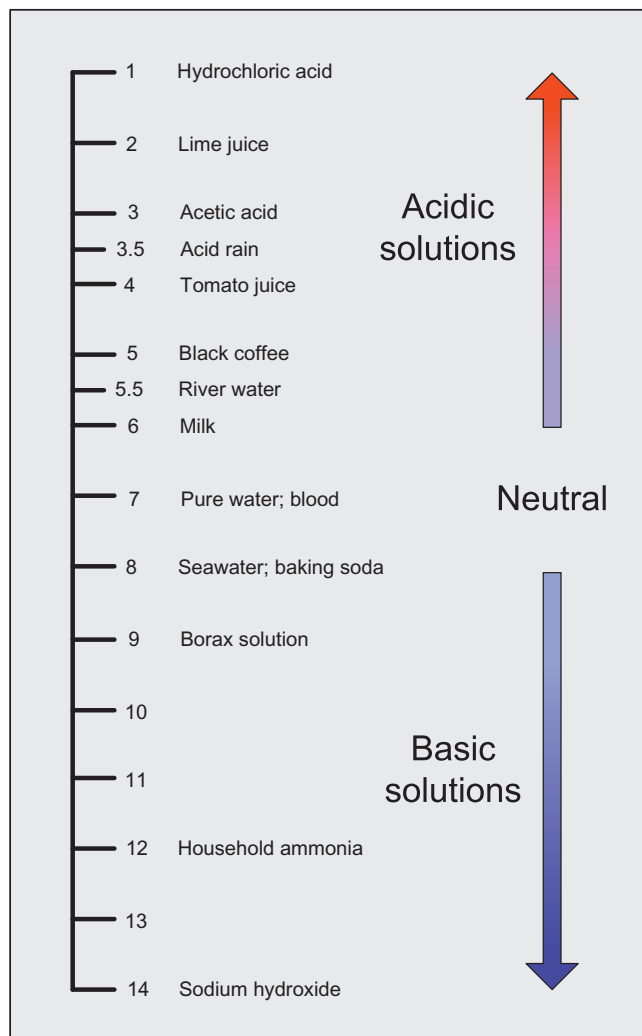
In various forms, chlorophyll is bound within the living cells of algae and other phytoplankton found in surface water. Chlorophyll is a key biochemical component in the molecular apparatus that is responsible for photosynthesis, the critical process in which the energy from sunlight is used to produce life-sustaining oxygen. In the photosynthetic reaction, carbon dioxide is reduced by water, and chlorophyll assists this transfer.

2.2.13 Water quality

Water quality researchers count on sensors and computer software to sense environmental waters and log and analyze data. Factors to be considered in water quality measurement are discussed below.

2.2.13.1 Alkalinity and pH

The acidity or alkalinity of water is expressed as pH (potential of hydrogen). This is a measure of the concentration of hydrogen (H^+) ions. Water's pH is expressed as the logarithm of the reciprocal of the hydrogen ion concentration, which increases as the hydrogen ion concentration decreases (and vice versa). When measured on a logarithmic scale of 0–14, a pH of 0 is the highest acidity, a pH of 14 is the highest alkalinity, and a pH of 7 is neutral ([Figure 2.11](#)). Pure water is pH neutral, with seawater normally at a pH of 8 (mildly alkaline).

**FIGURE 2.11**

Graphical presentation of common items with their accompanying pH.

pH measurements help determine the safety of water. The sample must be between a certain pH to be considered drinkable, and a rise or fall in pH may indicate a chemical pollutant. Changes in pH affect all life in the oceans; therefore, it is most important to aquatic biology to maintain a near-neutral pH. As an example, shellfish cannot develop calcium carbonate hard shells in an acidic environment.