SUBMERSIBLE VEHICLE SYSTEMS DESIGN

Written by
a Group of Authorities

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Published by

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Jersey City, N. J. 07306
1990

Library of Congress Catalog Card Number: 89-64294

ISBN 0-939773-06-6

Preface

The purpose of this book is to present, for the first time, a comprehensive and cohesive work on the major elements of manned submersible design. It is intended to be of use to individuals and organizations concerned with the design, construction, operation, and/or certification/classification of these underwater vehicles as well as to those who may be involved in the planning or management of ocean systems utilizing them. The book should also be of use to those with paralleling interests in unmanned submersibles, either remotely operated vehicles (ROVs) or untethered autonomous underwater vehicles (AUVs), since numerous subjects discussed are pertinent to the design of all underwater vehicles.

The title of the book, *Submersible Vehicle Systems Design*, is indicative of its orientation and scope. The use of *Submersible Vehicle* identifies its focus on the design of small, low speed, short endurance, underwater craft which are heavily dependent on external sources of support, such as surface ships, to accomplish their mission. In contrast, the term "submarine" is associated, by popular usage, with large, high speed, long endurance, self-sufficient vehicles used almost exclusively for military missions. However, the type of submersible considered in this book and the submarine have certain characteristics in common—both are untethered, or "free swimming," manned vehicles possessing neutral buoyancy in the so-called submerged design condition. Consequently, a number of design principles are valid for both of these categories of vehicles. Indeed, much of the technology applied to the design and construction of these submersibles was developed initially for submarines.

The *Systems Design* portion of the title indicates the book's orientation toward the "systems approach" to submersible design as presented in Chapter I—"The Basic Design Process." This chapter focuses on the design of a submersible not as an isolated system but as one of perhaps several individual systems comprising the total, or mission, system. Emphasized is the fundamental that it is the design of the mission system which must satisfy a given set of mission requirements in an optimal manner. *Design*, in the title, also indicates the book's orientation toward a synthesizing procedure in which knowledge and techniques pertinent to the design process are assembled and utilized as "tools" without undue concern for associated theory. Consequently, this book is not intended to be a treatise on hydromechanics, structural analysis or other theoretical areas of interest. Rather, it is concerned essentially with the application of theory—the presentation of theory itself being held to a minimum consistent with the clear development of the subject at hand. Where appropriate, theory and other background material are found in references at the end of the chapters.

The book is composed of eight chapters—seven of them providing essential input to the submersible design process discussed in Chapter I. Very brief overviews of these chapters are given to provide an overall perspective of the book.

Chapter I, "The Basic Design Process," is initially concerned with the entire design process for the mission system of which the submersible is but one of its individual systems. The submersible system is then isolated from the mission system for a detailed consideration of the design process involved and of essential input to this process. Basic design procedures, involving the conceptual and preliminary design phases, are discussed with guidelines for conceptual design being presented.

Chapter II, "Characteristics and Development of Submersibles," is introduced with a historical review of submarine development to provide background on the source of much of the technology which has been applied to submersible development. Modern submersible development and various types of submersibles, both manned and unmanned, are presented to give an overview of this field of technology. Specific examples of submersibles designed and constructed in the United States and abroad are given and data listed to provide the reader with some appreciation of the range of submersible characteristics.

Chapter III, "The Environment," provides essential information on the nature of the environment in which submersibles operate—this environment being subdivided into the atmosphere, air/sea interface and the water column. The physical properties of sea water and the dynamical processes occurring in these subdivisions of the environment are sources of so-called mission external design constraints on the submersible design which must be thoroughly understood by the designer. Of pertinent, but more general, interest is the Chapter's section on the geography of the world's oceans which discusses the nature of the sea floor areas of the world.

Chapter IV, "Materials," contains a detailed discussion of materials used for submersible structural, buoyancy/ballast, and other systems. As was the case for environmental factors, the characteristics of materials in the presence of these factors, particularly pressure, temperature, and salinity, become mission external design constraints which must be understood by the designer in making correct selections of materials for particular applications. The Chapter contains extensive data and other information on materials to provide design guidelines.

Chapter V, "Hydromechanical Principles," focuses on engineering principles associated with the hydrostatic and hydrodynamic naval architectural aspects of submersible design. Various types of submersibles from the hydromechanical viewpoint, both manned and unmanned, are discussed as introductory background. Details of submersible hydrostatics are presented based on the type of submersible having these criteria for the so-called submerged design condition—neutral buoyancy, zero trim/list, and positive statical stability. Hydrodynamic principles presented are those related to the resistance/propulsion and motion stability/control aspects of design.

Chapter VI, "Structural Principles," is concerned with engineering principles underlying the structural design of submersibles. In this regard, three categories of structure are considered—the pressure hull, exostructure or main structure external to the pressure hull, and appendages to the main body of the submersible. Examples of various types of these structures are provided.

Chapter VII, "Submersible Vehicle Support Systems," considers systems other than the submersible which may comprise a mission system—specifically, land, air, and sea transportation systems, handling systems, navigational and positioning systems, and maintenance and repair facility systems. The Chapter's purpose is twofold—1) to aid in the selection of support systems to form, with the submersible system, a mission system meeting mission requirements within specified constraints and 2) to provide information on the constraints, called mission internal design constraints, which these systems place on each other, particularly on the submersible.

Chapter VIII, "Design and Operating Safety," is the third chapter in this book to discuss sources of mission external design constraints placed on the design of a submersible—the sources, in this instance, being rules and regulations pertaining to safety considerations for the design and, additionally, the operation of the submersible's systems. Background is given on entities concerned with submersible safety, such as the U.S. Navy and classification societies, and specific safety requirements of these entities are given.

Acknowledgments

This book is the result of the volunteer efforts of a number of individuals who are especially qualified to write on the subject material of their particular chapters or chapter sections. These authors, identified at the beginning of their respective chapters, deserve the gratitude of all who read this book for sharing their considerable knowledge on various aspects of submersible design. The Editor also wishes to record his appreciation to all the authors. It was indeed a pleasure to work with them in completing this book.

The Editor is greatly indebted to the book's Control Committee. Their individual and combined expertise in submersible and submarine design, construction, and operation were invaluable in completing the extensive and exacting review process. The Committee's unstinting commitment to this publication, in terms of time, effort, and support of the Editor's activities, is sincerely appreciated.

The input and support of the Society's MS-2 (Submersibles) Panel of the Marine Systems Committee are acknowledged with appreciation. In particular, the Editor would like to sincerely thank the Panel's chairman, Mr. John Pritzlaff, for his untiring support and for facilitating the publication of this book in numerous ways.

The Editor is indeed grateful for the encouragement and fiscal support of Perry Offshore, Inc. (then Perry Oceanographics, Inc.) and for the good offices of Mr. H. A. (HAP) Perry in this regard. Mr. Ralph Draper, then an employee of Perry Oceanographics, Inc., devoted considerable time and effort in advancing the best interests of this book in many ways which are very much appreciated.

The late Dr. Edwin A. Link of Harbor Branch Foundation made the Foundation's submersible personnel and facilities available to the Editor during early days of this undertaking. His interest in and support of this effort are gratefully acknowledged.

A primary reference for this book is *Manned Submersibles* by R. Frank Busby of Busby Associates, Inc. Mr. Busby facilitated access to certain material in his book and provided encouragement and advice on this work for which the Editor is grateful.

The Editor is indebted to Mr. Terence Flanagan of Flanagan Associates and his staff for their part in bringing this book into being. Their work is much appreciated.

Numerous other individuals and organizations have aided and abetted in the development of this project—from offering moral support to providing advice on chapter content and granting permission to use photographs and other material. The Editor sincerely thanks all who were so involved.

Finally, the Editor acknowledges with deep gratitude the essential support provided by his wife, Ann. Her actual and supportive involvement were manifested in many ways which served the very best interest of this undertaking.

E. Eugene Allmendinger
Editor

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Chapter I
The Basic Design Process

E. E. Allmendinger

1. Introduction

THIS CHAPTER is concerned with the basic design of manned submersible vehicle systems and, in a general sense, with the overall systems of which they are a part. There are many ways of pursuing the design process, each varying in detail according to time-honored procedures followed by design organizations and to the simplicity or complexity of the overall system in question. Consequently, no attempt is made herein to present *the* way of pursuing this process. Rather, guidelines are presented illustrating fundamentals and concepts that may be applied, in one form or another, to a broad spectrum of approaches to the design of these systems. Certain of these fundamentals are also useful in the design of unmanned submersibles, or remote-controlled vehicles as they are usually called.

Section 2 presents perspectives of the submersible and its supporting systems, the total system being called the *mission system*, and the overall design and associated processes involved in the development of this system. The pertinence of this perspective becomes apparent when one considers the fact that small submersibles, unlike large submarines, are incapable of operating alone. They must be assisted by other systems in order to accomplish underwater tasks. At the very least, they must be supported by shore-based facilities, housing maintenance, repair and administrative activities, and by ships providing transportation, launching and retrieval services, underwater navigational support, and at-sea maintenance and repair facilities. More complex mission systems may also include other support systems such as land-transport vehicles, air-transport vehicles, satellites, seafloor-based transponders, and even submarines. The submersible and other systems constituting the mission system, whatever it may be, must work in concert with each other to accomplish the mission tasks in the most efficient manner possible. Thus, it is important to view this collection of individual systems as a whole—being aware of their interactions and remembering that the cost of accomplishing underwater tasks is the cost of the mission system and not the submersible's cost alone.

Section 2 presents, in Fig. 1, a way of viewing the submersible and its supporting systems, both as individual systems and as they are combined to form the mission system. This view facilitates discussions of the design goals which involve design optimization and consideration of design constraints. The background of design optimization is developed as based on cost-effectiveness criteria and is diagrammed in Fig. 2. Constraints on the design of the mission system, as will be seen, include *mission external* and *mission internal design constraints* and *design criteria*. They are indicated in Fig. 1.

Section 2 also discusses three processes associated with mission system design or the design of any of its individual systems including the submersible—the *pre-design*, *design*, and *post-design* processes which are diagrammed in Fig. 3. The pre-design process involves the potential user/owner of the system to be designed and is concerned with the development of the primary input to the design process—the *mission statement* and *mission requirements*. The design process conceives the mission system that is feasible and meets the mission requirements in as optimal a manner as possible. It is divided into *basic*, *contract*, and *detail design* phases—basic design being subdivided into *conceptual* and *preliminary design* stages. An overview of conceptual design, essentially involving feasibility studies, is diagrammed in Fig. 4. Finally, the post-design process is composed of three activities which are discussed briefly—*construction* and *alteration* of "new" and "existing" individual systems of the mission system, *test* and *evaluation*, and *operation*. Experiences gained from these activities form, collectively, important "feedback" input to the design of future systems.

Succeeding sections of this chapter focus exclusively on the basic design of manned submersibles. Section 3 provides a description of submersibles in general—considering these systems, in turn, to be composed of a number of individual systems as illustrated in Fig. 1. The titles of these systems are derived from the U.S. Navy's "Ship Work Breakdown Structure" (SWBS)—this document also being followed, to the extent feasible, in discussions of system components.

Section 4 discusses inputs to submersible design, dividing them into two categories—inputs which furnish *guidance* for the design and those which impose *constraints* on it. Guidance inputs discussed include *mission/performance requirements*, the latter being derived from the former, and *post-design experiences*. Constraint inputs, as discussed for mission systems, are imposed by *mission external* and *internal design constraints* and *design criteria*. As will become evident, constraints come from many sources, making a comprehensive treatment of them beyond the scope of this chapter. Consequently, the presentation of this subject is detailed only to the extent necessary to convey an impression of the nature of the various constraints involved. Other chapters of this publication present details of the more important sources of constraints.

Section 5 concerns the basic design of manned submersibles, focusing primarily on their conceptual design. The development of conceptual design alternatives and the bases for selecting the optimum alternative, *technical feasibility* and *cost-effectiveness*, are discussed. The *empirical* and *systematic parametric analysis* approaches to conceptual design are considered. The empirical approach is modelled by the *design spiral*, and the parametric approach is illustrated with an example of a design optimization program contained in the Appendix to this chapter.

Submersible design-related references are given at the end of the chapter. It should be noted that *Manned Submersibles*, by R. Frank Busby, is considered by the author to be a companion piece to this and other chapters. It is an excellent source of general and detailed information and data on these vehicles.

2. An Overall Perspective

2.1 Overview of Mission and Submersible Systems

A system is any object or process, or group of objects or processes, created to serve some useful purpose or mission, the mission being defined by a set of mission requirements. Such a system may be called a *mission system* to differentiate it from other system categories to be discussed presently. It is often convenient to picture a system as isolated from its surroundings by a boundary for the purpose of studying its internal behavior and interaction with its surroundings. Figure 1 provides such a diagram, in this instance showing a mission system designed to serve one or more underwater missions. Note that the mission system boundary encloses *M individual* or (I) *systems*, each enclosed by its own boundary, illustrating the aforementioned fact that the mission is accomplished by a submersible supported by other systems. The mission system diagram in Fig. 1 provides an example of these (I) systems in which it is assumed that mission requirements dictate the needs, among others, for the submersible's transportation by air and on the surface of the sea as well as for its launching, recovery and support while submerged. As shown, (I_1) is the submersible, (I_2) a transport aircraft, (I_3) a surface support ship, and so forth—the last individual system, whatever it may be, is designated (I_M).

The design of many mission systems begins with most of the potential (I) systems already existing and some nonexisting. In the foregoing example, for instance, the aircraft and surface ship may already exist while the submersible does not exist. Existing systems require from no to extensive alterations to convert them to (I) systems, within a particular mission system, with commensurate amounts of design effort, construction and costs involved. Obviously, the extent of alterations required is a primary consideration in choosing between candidate (I) systems. Nonexisting (I) systems, of course, must be designed and constructed "from scratch" and are often the most costly of these systems.

Fig. 1 shows the manned submersible system isolated from the mission system. Again, note that the submersible's boundary encloses *N individual* or (S) *systems*. Examples of (S) systems shown in the figure include (S_1) hull structure, (S_2) propulsion plant, (S_3) electrical plant systems, and so forth—the last system being (S_N). The "*N*" term can be any relatively small number depending on the accounting system used by the design organization. The U.S. Navy's SWBS is used herein in which *N* is either 6 or 7 as indicated. Note also that in the submersible system shown in Fig. 1 the (S) system boundaries enclose "*i*" (SS) *subsystems*. For example, the (S_1) hull structure system would enclose the (S_1S_1) shell plating (the pressure hull), (S_1S_2) longitudinal and transverse framing (the exostructure), and so forth according to the SWBS. Although not shown in the figure, subsystems in turn can be broken down into yet smaller systems. One can visualize this "boxes within boxes" procedure extended until every last nut and bolt of every (S) system is isolated, itself, as a system. It will suffice to say here that systems breakdown becomes increasingly fine as the design process advances.

The design of any (I), (S), or smaller system also begins with at least some of its individual systems existing. These existing systems, requiring no or

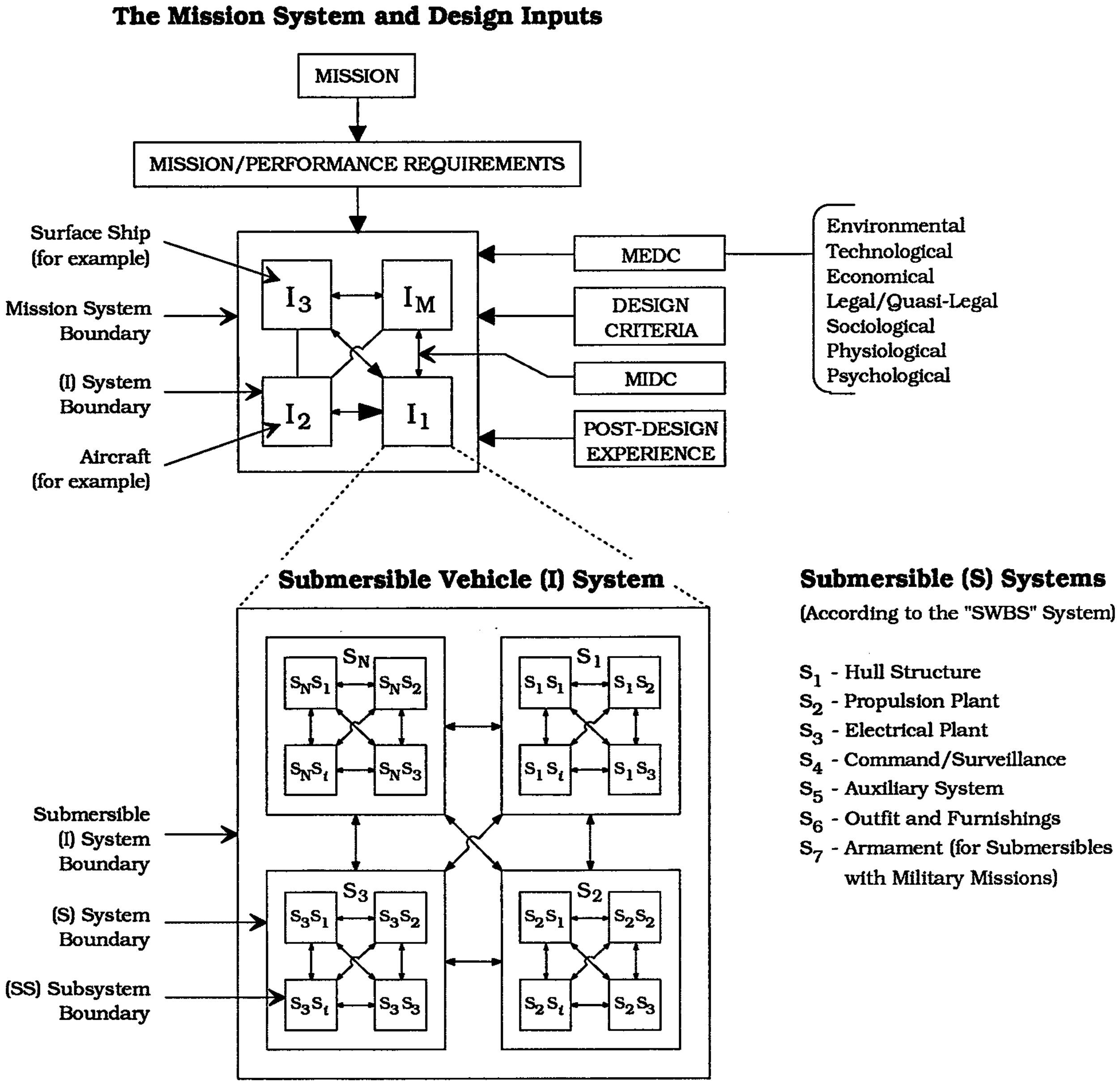

Fig. 1 The mission system and its subsystems

small modifications, are often referred to as "off the shelf" items. Their use significantly reduces costs.

2.2 The Design Goal

It is the mission system, and not necessarily any of its individual (I) systems, which should achieve the design goal of *satisfying a given set of mission requirements in as optimal a manner as possible considering the design constraints acting.* This statement introduces the topics of *design optimization* and *design constraints* which are discussed briefly in the following paragraphs.

2.3 Design Optimization

Optimizing a mission system's design is usually based on maximizing its *cost-effectiveness* (*CE*) to the extent possible given the constraints acting. This process may vary from relatively simple to complex depending on the nature of the mission system. In general, it requires extensive economics and experiential data and the use of sophisticated techniques, the descriptions of which are beyond the scope of this presentation. The purpose here is to convey an appreciation for what this process involves and for some of the major design considerations entering into it.