Cotecmar

Vol. 7 · No. 13 · July 2013

Ship Science & Technology ISSN 1909-8642

SHIP
SCIENCE & TECHNOLOGY
CIENCIA & TECNOLOGÍA DE BUQUES

ISSN 1909-8642

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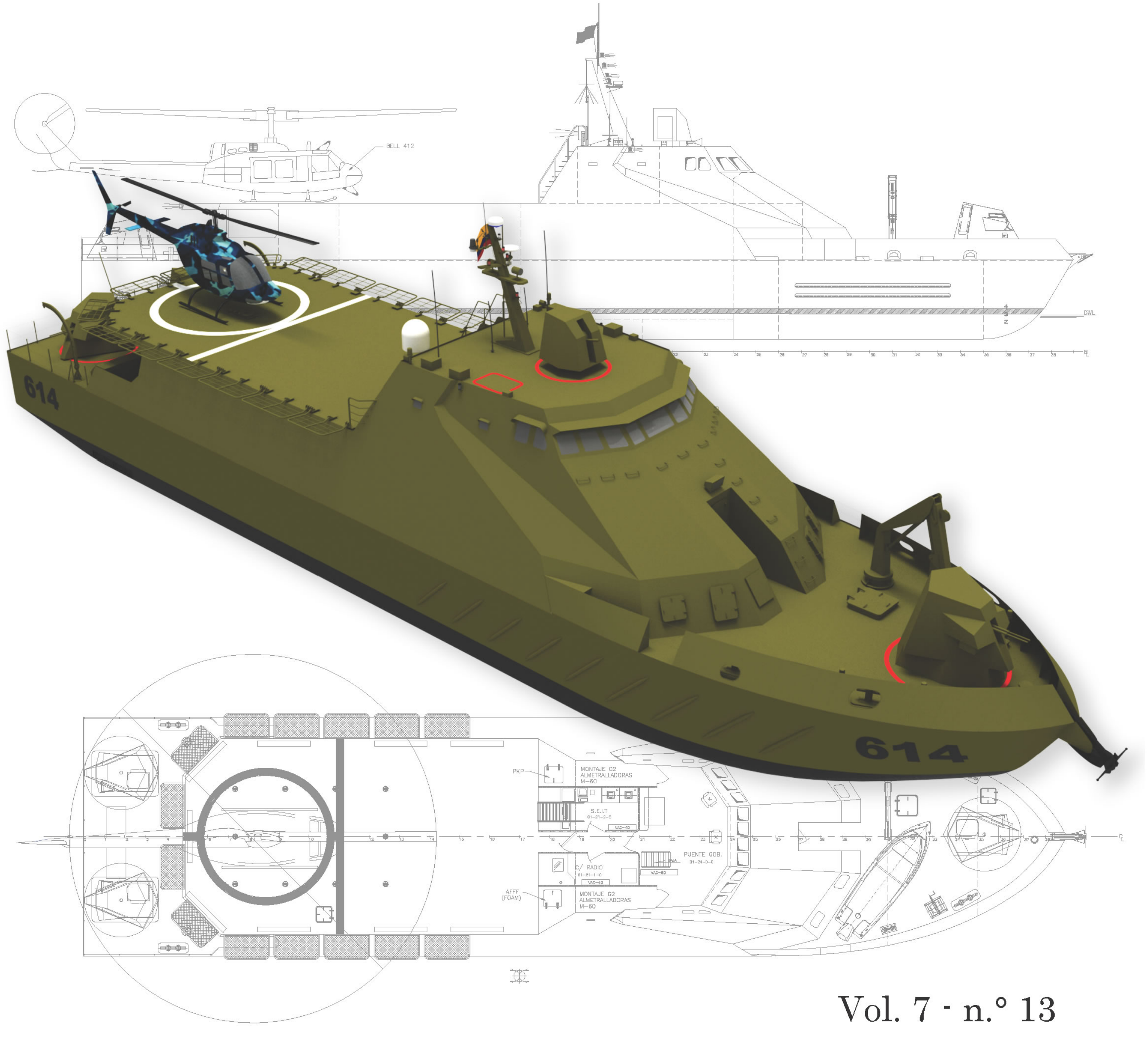

Vol. 7 - n.° 13
(1 - 80) July 2013

SHIP

SCIENCE & TECHNOLOGY

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Ship Science & Technology is a specialized journal in topics related to naval architecture, and naval, marine and ocean engineering. Every six months, the journal publishes scientific papers that constitute an original contribution in the development of the mentioned areas, resulting from research projects of the Science and Technology Corporation for the Naval, Maritime and Riverine Industries, and other institutions and researchers. It is distributed nationally and internationally by exchange or subscription.

A publication of

Corporación de Ciencia y Tecnología para el Desarrollo de la Industria Naval, Marítima y Fluvial - Cotecmar
Electronic version: www.shipjournal.co

COTECMAR
COLOMBIA

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Layout and design
Mauricio Sarmiento Barreto

Printed by
C&D Publicidad & Marketing. Bogotá, D.C.

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Editorial Note

Cartagena de Indias, 22th July 2013

Again, the Ship Science & Technology journal has begun a series of special publications with the best works presented during the International Ship Design and Naval Engineering Congress, which successfully culminated its third version in the city of Cartagena de Indias on the 13th, 14th, and 15th of March 2013 with the central theme: *"Toward enhancement of the technological capacities for the development of the national maritime power – Surface Strategy Platform (PES, for the term in Spanish)"*.

On this opportunity, the International Ship Design and Naval Engineering Congress maintains and strengthens its recognition as the first event in this specialization at the national level and as one of the main reference events of scientific divulgation for the naval, maritime, and riverine industries at the international level, compared to COPINAVAL, an event organized by the Pan-American Institute on Naval Engineering (IPIN, for the term in Spanish).

The program was comprised of three keynote conferences, 22 scientific presentations, 12 technical presentations, and three forums, with participants from Germany, Spain, Brazil, Panama, the United Kingdom, France, and Colombia. The keynote conferences were delivered by guest speakers: Alan Brown, Virginia Tech - USA, PhD in Marine Engineering from the Massachusetts Institute of Technology (MIT); Thomas Lamb, University of Michigan - USA, Naval Architect; and Luis Guarín, Colombian from the United Kingdom, PhD in Seakeeping performance. Stemming from the aforementioned, this edition gathers work related ship design and optimization, ship dynamics, hydrodynamics, 3D image generation of submerged objects, and vibration analyses in ship propeller systems.

We thank researchers, students, engineers, and the general public participating in the International Ship Design and Naval Engineering Congress and followers of the Ship Science & Technology journal who motivate us to continue with the task of sharing new knowledge related to naval engineering, naval architecture, marine engineering, and ocean engineering; areas currently on the rise in Colombia and which will be the pillars for the development of the national maritime power.

Captain OSCAR DARÍO TASCÓN MUÑOZ
Editor of the Ship Science and Technology Journal

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Nota Editorial

Cartagena de Indias, 22 de Julio de 2013.

Nuevamente, la revista Ciencia y Tecnología de Buques inicia la serie de publicaciones especiales con los mejores trabajos presentados en el Congreso Internacional de Diseño e Ingeniería Naval, el cual culminó con éxito su tercera versión en la ciudad de Cartagena de Indias los días 13, 14 y 15 de marzo de 2013, teniendo como eje temático principal *"Hacia el fortalecimiento de las capacidades tecnológicas para el desarrollo del Poder Marítimo Nacional - Plataforma Estrategia de Superficie (PES)"*.

El Congreso Internacional de Diseño e Ingeniería Naval en esta oportunidad se mantiene y afianza su reconocimiento como el primer evento de esta especialidad a nivel nacional y como uno de los principales eventos referentes de divulgación científica para la industria naval, marítima y fluvial a nivel internacional, comparándose con COPINAVAL, evento organizado por el Instituto Panamericano de Ingeniería Naval – IPIN.

El programa estuvo conformado por tres conferencias magistrales, 22 ponencias científicas, 12 ponencias técnicas y tres foros, contando con asistentes de Alemania, España, Brasil, Panamá, el Reino Unido, Francia y Colombia. Las conferencias magistrales estuvieron a cargo de los invitados: Alan Brown, de *Virginia Tech* - EEUU, PhD en Ingeniería Marina del *Massachusetts Institute of Technology* (MIT); Thomas Lamb, de Universidad de Michigan - EEUU, Arquitecto Naval; y Luis Guarín, colombiano proveniente del Reino Unido, PhD en Comportamiento en el mar. Partiendo de lo anterior, en esta edición se recopilan trabajos relacionados con diseño de buques y optimización, dinámica del buque, hidrodinámica, generación de imagen tridimensional de objetos sumergidos y análisis de vibraciones en sistemas de propulsión de buques.

Agradecemos a investigadores, estudiantes, ingenieros y público en general participante en el Congreso Internacional de Diseño e Ingeniería Naval y seguidores de la revista Ciencia y Tecnología de Buques que nos motivan a continuar con la tarea de ofrecer los recursos para compartir nuevo conocimiento relacionado con la ingeniería naval, arquitectura naval, ingeniería marina e ingeniería oceánica, áreas que actualmente se encuentran en una etapa emergente en Colombia y que serán los pilares para el desarrollo del Poder Marítimo Nacional.

Capitán de Navío OSCAR DARÍO TASCÓN MUÑOZ
Editor Revista Ciencia y Tecnología de Buques

Application of Operational Effectiveness Models in Naval Ship concept exploration and design

Aplicación del modelo de efectividad operacional en el concepto de exploración y diseño de buques navales

Alan J. Brown [1]

Abstract

Traditionally, the Concept and Requirements Exploration process is the first stage of ship design. Concept and Requirements Exploration responds to a stated mission need with early high-level assessment of a broad range of ship design options and technologies. Our design group uses a Multi-Objective Optimization approach to explore the design space and identify non-dominated designs ranked by cost, risk, and effectiveness. Our method of calculating effectiveness in this approach has, in the past, been based on expert opinion. In this study, the use of a more direct physics-based Operational Effectiveness Model approach is considered to provide greater confidence in the validity of effectiveness results and a perception that results are more unbiased and rational. This approach requires significant early investment. How much analysis is enough and is there significant payoff for this significant effort? This paper presents this approach and explores these questions.

Key words: ship design, operational effectiveness models, systems engineering

Resumen

Tradicionalmente, el proceso de concepto y requerimientos de exploración es la primera etapa del diseño de la nave. El concepto y requerimientos de exploración responden a una necesidad de la misión con una evaluación temprana de alto nivel de una amplia gama de tecnologías y opciones de la nave. Nuestro grupo de diseño utiliza un enfoque de optimización multi-objetivo para explorar el espacio de diseño e identificar los diseños no dominados por costo, riesgo y efectividad. En el pasado, nuestro método de cálculo de la eficacia de este enfoque se ha basado en el dictamen pericial. En este estudio, se considera el uso de un enfoque basado en la física más directa del modelo de eficacia operacional para proporcionar mayor confianza en la validez de los resultados de eficacia y una percepción de que los resultados son más imparciales y racionales a la vez. Este enfoque requiere una importante inversión temprana. ¿Cuánto análisis es suficiente? ¿Hay una importante recompensa significativa para este esfuerzo? Este artículo presenta este enfoque y explora estas preguntas.

Palabras claves: diseño de embarcaciones, modelos de eficacia operativa, ingeniería de sistemas

Date Received: January 16th, 2013 - *Fecha de recepción: 16 de Enero de 2013*
Date Accepted: March 1st, 2013 - *Fecha de aceptación: 1 de Marzo de 2013*

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Introduction

In the US Navy, continuous early mission operational and capabilities analysis is typically performed by naval or multi-service officers and civilians in what is (today) called the Joint Capabilities Integration and Development System, JCIDS *(DoD, 2008; DoD, 2003)*. Working from strategic guidance and after a significant effort of operational analysis, including a concept of operations, functional needs analysis, capabilities-based assessment, and consideration of high-level material and non-material solutions, an Initial Capabilities Document (ICD) is developed and passed to the acquisition community. Among other things, ICDs provide the following:

- Identification of a mission need.
- Capabilities required and their associated operational characteristics and attributes.
- Capability gaps and associated operational risks.
- Assessment of the viability of non-material solutions.
- Recommendations on type of solutions (transformational, evolutionary, or information technology) to be pursued.
-

Next, the acquisition community develops Analysis of Alternatives (AoA) guidance and an AoA is performed. The AoA brings ship designers and engineers into the process typically to identify potential technologies and assess a matrix of ship design alternatives identified by the AoA study team, acquisition executives, and operational community. An AoA begins by establishing Key Performance Parameters (KPPs) for each alternative. The KPPs help compare the operational effectiveness, suitability, and life cycle costs of alternatives to satisfy the military need.

The AoA and its associated documentation is required before any major investment decision and before each decision milestone and is, therefore, one of the most important steps in the US military acquisition process; however, the process often lacks a complete and effective systems engineering approach.

Over the last 15 years at Virginia Tech and MIT, we have called this design phase Concept and Requirements Exploration (C&RE). During C&RE we use a total systems approach, including an efficient search of the design space for non-dominated designs based on the multi-objective considerations of effectiveness, cost, and risk *(Brown and Thomas, 1998; Shahak, 1998; Brown and Salcedo, 2003; Strock and Brown, 2008; Brown, 2010)*. Our current method of calculating an Overall Measure of Effectiveness (OMOE) for the C&RE uses expert opinion and pairwise comparison. Given that we have developed this process, systems engineering has also evolved to include new Model-Based Systems Engineering (MBSE) approaches *(Buede, 2011)*, enterprise architectures including new Department of Defense architectures *(DoD, 2011)*, and naval systems analysis and effectiveness-modeling methods *(Fox, 2011; Gomez-Torres, 2010)*. We have concluded that an early structured search of the design space through the synthesis and assessment of hundreds or thousands of alternative concepts is essential for sufficient understanding of the relationship among cost, effectiveness, and risk. This is a difficult problem and requires significant upfront effort, but without this understanding, responsible specification of requirements and subsequent responsible acquisition decisions cannot be made.

Others have come to similar conclusions. Andrews *(2012)* calls his early C&RE process “Requirements Elucidation”. He proposes that requirements engineering, as often practiced without material solutions, is not appropriate for warships and that requirements engineering without material solutions is bad systems engineering. He calls his Requirements Elucidation problem the “Wicked Problem”. We heartily concur.

Jons *(2012)* presents ship design as illustrated in Fig. 1. Here, concept formulation is shown as a complex spiral interaction of operational needs and technical inputs, another “wicked problem” which becomes more wicked when performed in a large organization. Jons also points out that the ultimate success of any design must be effectiveness, not performance. This is illustrated in Fig. 2. Once the ship is designed and built, the “means” are determined. The “environment” comes with the threat and the “ways” are determined by the operator. Collectively, they determine effectiveness, but the “means” are locked in with the design – mostly, during the earliest stages of design.

Fig. 1. Design Process (Jons, 2012)

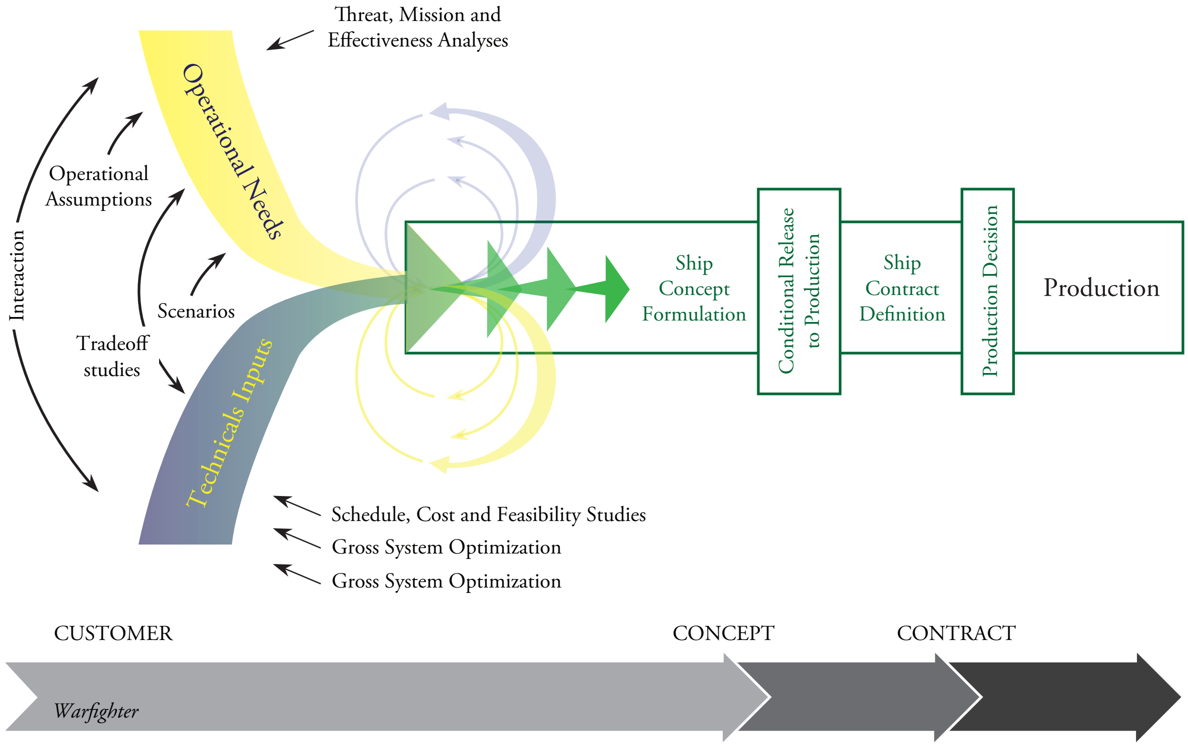
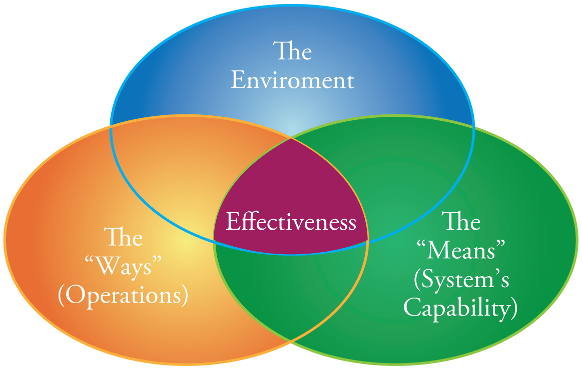


Fig. 2. Success Measured by Effectiveness (Jons, 2012)

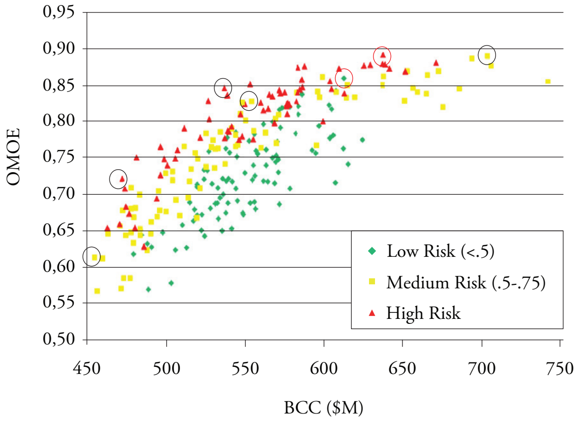


It should also be noted that the human element (“means”) in determining effectiveness is critical and very difficult to capture in a model. When we first developed our C&RE process, we developed an OMOE metric using expert opinion and pairwise comparison *(Demko, 2005)* because of this difficulty. We are now developing a methodology using Operational Effectiveness Models (OEMs) as an alternative to an expert opinion-based OMOE, and working to integrate this methodology into our current multi-objective optimization method. In this new methodology, a Design Reference Mission (DRM) composed of multiple Operational Situations (OpSits) with conditions and measures is used to develop the OEMs. An MBSE approach and a Total-Ship System Architecture are used to define and understand the relationships among various aspects of the ship design and their relationships to operational effectiveness *(Kerns, 2011).*

In our search for the design space, a non-dominated solution for cost, risk, and effectiveness is a feasible solution for which no other feasible solution exists, which is better in one objective attribute and at least as good in all others. Non-dominated concepts are typically presented in a multi-dimensional plot of cost, risk, and effectiveness where each point in the plot represents a feasible ship design. Fig. 3 is a typical 2D representation of non-dominated (Pareto) results with the color/shape of each design point representing the risk, with cost on the x axis, and effectiveness on the y axis. All the designs represented in this plot are feasible and non-dominated. The preferred design should always be a non-dominated design. The non-dominated surface with a full range of cost-risk-effectiveness possibilities can be presented to decision-makers, "knees in the curve" can be seen graphically, trade-off decisions can be made, and specific design concepts can be chosen for further analysis.

Our new C&RE process is shown in Fig. 4. The first steps in this process must develop a clear and precise mission definition including mission essential tasks, Design Reference Mission with Operational Situations, Operational Effectiveness Models, Required Operational Capabilities, and ultimately an Overall Effectiveness Model. The development of these important system elements is the primary focus of this paper.

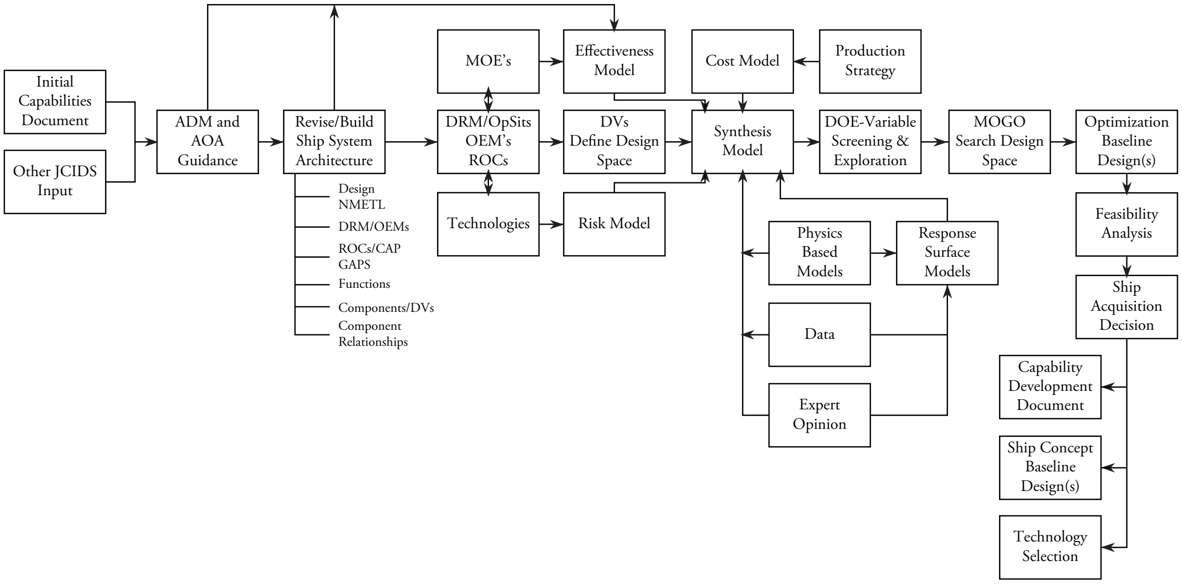
Fig. 3. Non-Dominated Frontier



System Architecture and Data

Systems Engineering (SE) addresses both engineering and management processes. It begins with a clear statement and understanding of the problem, must resolve competing trade-offs, must identify system boundaries, and most importantly, it must manage complexity. A critical tool to a successful SE approach is an effective system architecture and data model *(Vitech, 2010)*. A systems model serves as a "repository" to document important characteristics, data, and relationships

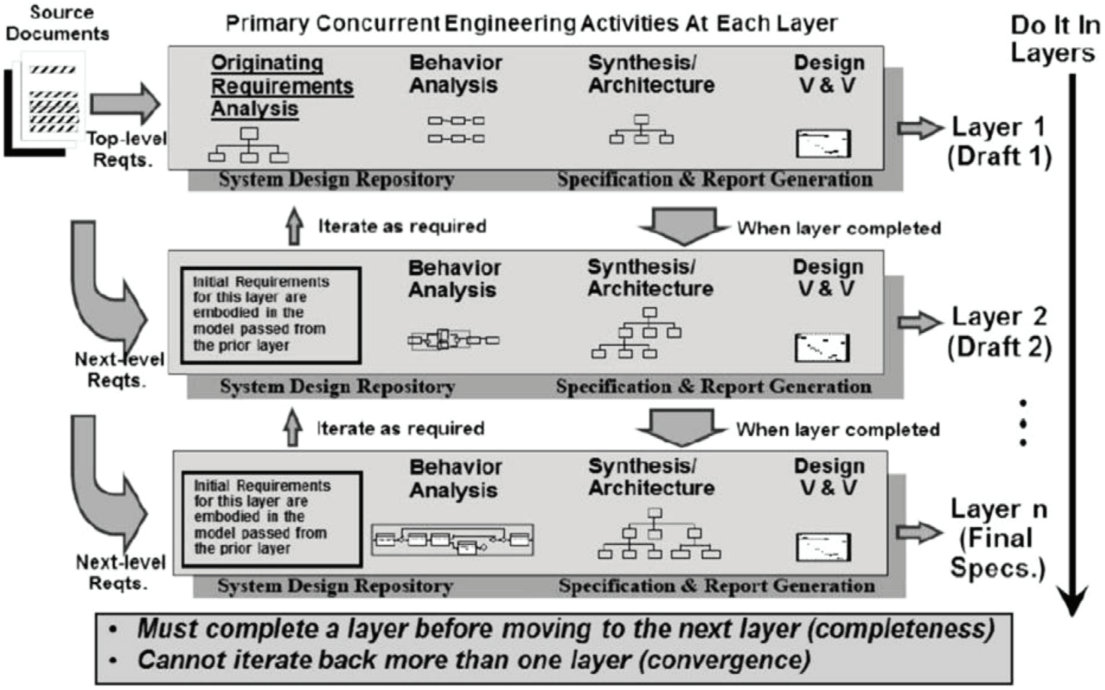
Fig. 4. Concept and Requirements Exploration Process (C&RE)



from customer requirements to function to system architecture to validation and verification. Complex Systems-of-Systems (SoS) are too large to manage without a system model. Unfortunately, the process of managing an acquisition through a large government organization with many stakeholders is often characterized by a series of "throw-it-over-the-wall" events where early assumptions, models, analyses, and results may get lost. These details may be very significant and frequently must be "reinvented" later in the process. This requires redundant work, but a greater concern is that different parts of the SoS may be inconsistent, even incompatible with one another, and not reflect the original foundation of strategic guidance and the original mission operational and capabilities analysis. Chaos ensues, the design never does what it was conceived to do and program cost skyrockets in attempts to band-aid and fix.

Fig. 5 illustrates the MBSE process and architecture as a series of layers. Each layer involves the four activities of Requirements Analysis, Behavior or Functional Analysis, Synthesis/Architecture, and Validation and Verification. Concept and Requirements Exploration deals significantly with Requirements, defining requirements in terms of missions, operational tasks, and operational scenarios and translating them into cost-effective capabilities, system functions, components and interfaces. This is represented by Layer 1.

Fig. 5. Model-Based Systems Engineering (MBSE) (Buede, 2011)

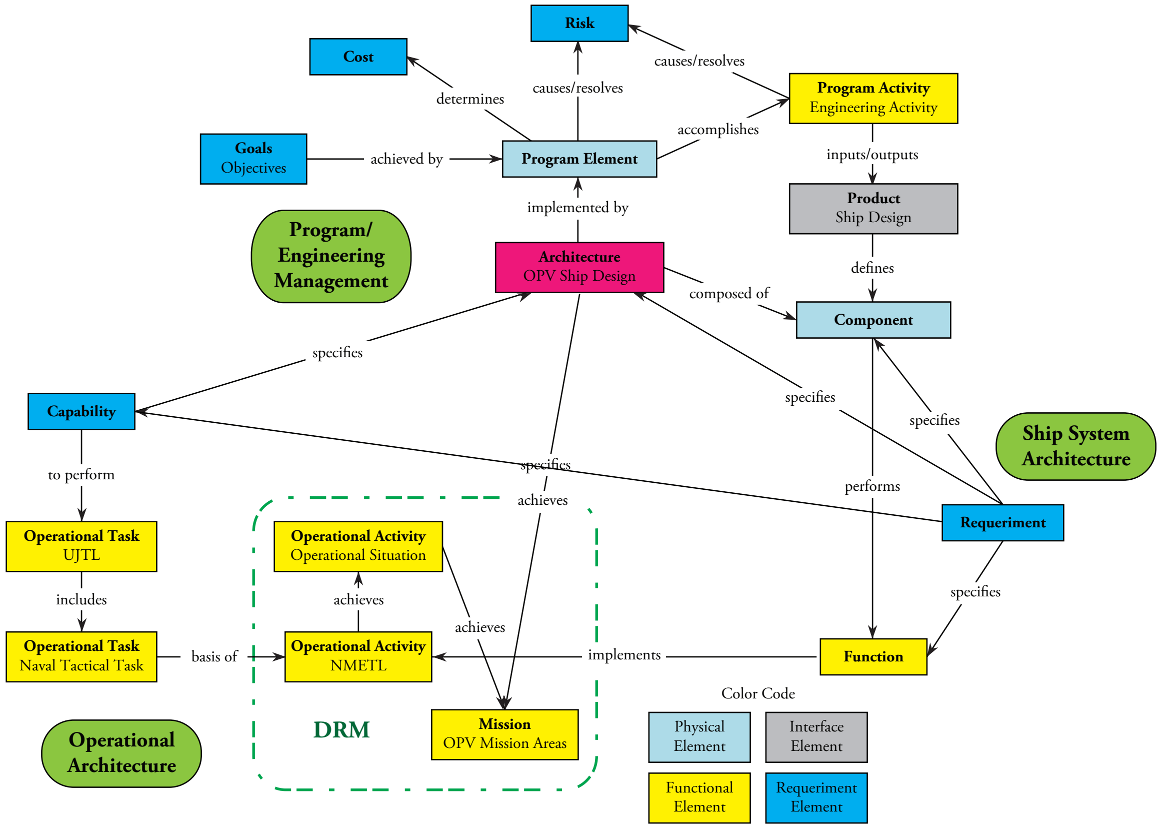


The system model database consists of elements modified by attributes and related to other elements. This structure uses an object-oriented approach. Elements are represented as objects with the attributes stored as data within the objects. The relationships then define the interaction between objects.

Our ship system design architecture includes three domains: Operational Architecture, Ship System Architecture, and Program/Engineering Management Domains with classes and relationships, as shown in Fig. 6. The individual parts of the architecture are classes including Capabilities, Functions, Components, Operational

Tasks, etc. Each class contains elements of that class. Thereby, the ship would be a component and then it would be broken down into its many physical parts with each being captured as a component system or subsystem. The Operational Architecture Domain provides necessary classes, attributes, and relationships to capture the initial operational requirements, guidance, mission, and required capabilities. The Capability class defines the qualities, abilities, features, etc., of the entire architecture that can be used or developed to achieve action goals. The Mission element includes the mission(s) that the overall architecture was designed to achieve. The Operational Task element is an action to be performed in support of a mission. An Operational Activity is an action or process needed to fulfill a mission, task, or role. The Operational Item element class is the data or physical entity required for the flow among operational activities and, thereby, among the performers.

Fig. 6. Ship Design System Architecture (adapted from Vitech, 2010)



The Ship System Architecture Domain includes Component elements and the system or system of systems with their interfaces. It includes Function elements and ultimately Requirement elements, standards, and specifications. The Components are the physical or logical elements that perform a specific function or functions. The Function elements define the functions of the components. The Requirement elements can be either an originating requirement extracted from a source document, a refinement of a higher-level requirement, a derived characteristic of the system or one of its subcomponents, or a design decision *(Vitech, 2011).*

Operational Effectiveness Models And DRMs

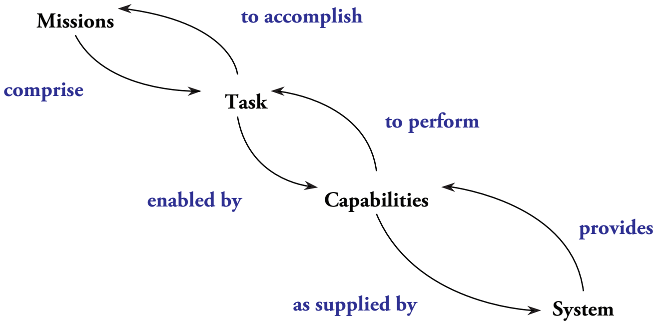
An OMOE model or function is an essential prerequisite for optimization and design trade-off. Our prior work with mission effectiveness models used multi-attribute value theory (MAVT) and the analytical hierarchy process (AHP) with expert opinion to integrate many diverse inputs, and assess the value or utility of ship performance in an OMOE function *(Belton, 1986; Saaty, 1986; Demko, 2005)*. The benefit and efficiency of this approach has been demonstrated in a study revisiting the DDG-51 design *(Stepanchick and Brown, 2007)* and in a simple experimental study comparing results obtained by using a commercial war-gaming tool for expert opinion results *(Demko, 2005)*.

Despite the results obtained using expert opinion, more direct physics-based OEMs starting with a detailed DRM may provide greater confidence in the validity of the results and results that are more unbiased and rational.

Design Reference Mission(s) define the specific projected threat and operating environment baseline for a given force element, which may range from a single-purpose weapon system to a multi-mission platform to a multi-system, multi-platform system of systems. They are primarily an engineering design tool to support systems engineering activities by identifying significant design-driving operational elements and characterizing them to the level of detail necessary to assess design impact. A DRM also includes detailed characterizations of the threat, background traffic, weather, and other factors required to assess system performance and overall platform effectiveness. OpSits are developed as part of the DRM to feature selected operational characteristics, or combinations thereof, in operationally viable combat environments and situations *(Skolnick et.al., 2000)*.

Tasks that are enabled by the required capabilities are the basic elements for accomplishing the mission or mission objective. Fig. 7 illustrates important relationships of these components.

Fig. 7. Ship Design to Mission Accomplishment Relationships (Vitech, 2010)



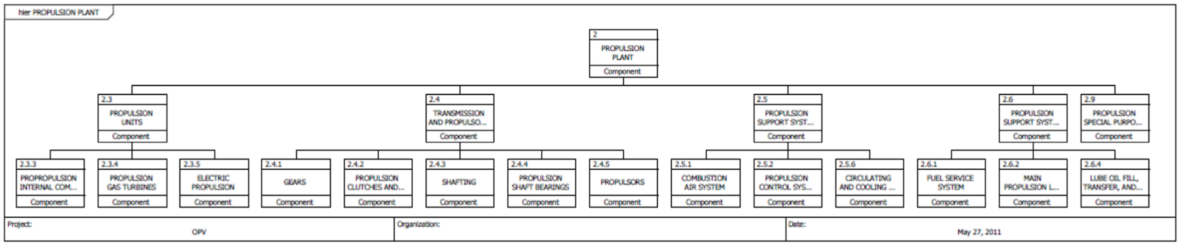
The Universal Navy Task List (UNTL) is a combined Navy, Marine Corps, and Coast Guard document that includes tasks from the UJTL and NTTL. The UNTL also includes measures for each task and a chapter of possible conditions to assign to task. The conditions list is thorough but not comprehensive as commanders may make and assign new conditions as appropriate *(NWDC, 2000)*.

In our process, Navy Mission Essential Tasks (NMETs) for a particular ship mission or ship design are selected from the UNTL with associated measures of task performance and conditions under which the task could be accomplished. The final collection of tasks is called a Naval Mission Essential Task List (NMETL), tailored for a particular design. The NMETs, properly sequenced, form a scenario that includes its own measures and conditions. The scenarios built from NMETs become the OpSits that make up the DRM.

These OpSits can be translated into a discrete-event simulation that considers the conditions and uses the identified measures of task performance to calculate a specific measure of effectiveness for a ship design in that OpSit. The family of OpSit simulations that fully encompass the mission set of the ship can be combined to calculate an OMOE for a given ship design. This is accomplished within the context of the system enterprise architecture.

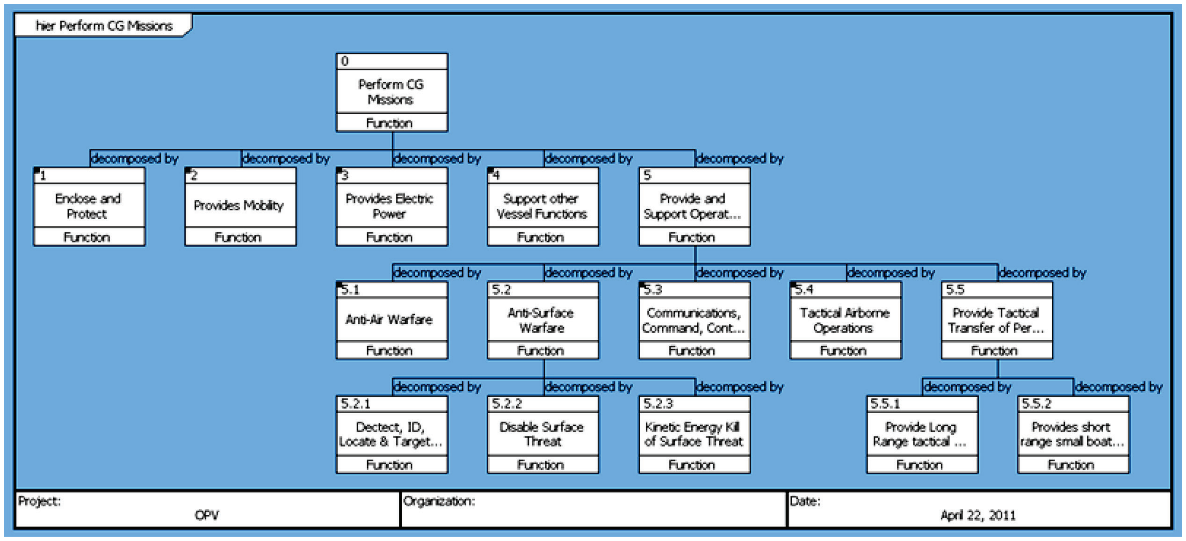
The focus of the paper, thus far, has been the Operational Architecture Domain, defined through Capabilities, Operational Tasks, Operational Activities, Operational Items, Performers, and Missions. To continue the architecture and establish the relationship between the OpSits and the ship design, the System Architecture Domain must be constructed. In our example, the first step is to build the Component class based on the components for our notional OPV. The top-level component (System of Systems) is the Offshore Patrol Vessel, and it is broken down into a hierarchical framework based on the relationship 'built from'. We use the traditional ESWBS for this hierarchy, as shown in Fig. 8.

Fig. 8. OPV Propulsion Machinery Plant (SWBS 200) Component Hierarchy



The functions for each component are entered into the Function class based on the 'performs' relationship with a particular component. The functions can also be viewed hierarchically with respect to other functions based on the 'decomposed by' relationship. The top-level function, directly related to the top-level component, Offshore Patrol Vessel, is the function "perform CG Missions". Fig. 9 is a hierarchical view of "perform CG Missions" with the Provide and Support Operational Requirements function expanded along with the sub-functions of Anti-Surface Warfare and Provide Tactical Transfer of Personnel.

Fig. 9. OPV Function Hierarchical View



The OPV functions are then related to the NMET level Operational Activities by the relationship 'implements'. The Components are also related to Performers by the same relationship. Functions are also related to the Requirement class, which includes the capability gaps, by the 'specifies' relationship. With these additions, the OPV ship design architecture has traceability between the Operational and Systems domains. The OpSits and the activities they are composed of are traceable through the Operational Architecture Domain and through the Systems Architecture Domain. The NMETs are sequenced via the OpSit scenario to accomplish the mission objectives as defined by the ICD and, thus, the CBA from the JCIDS process. The NMETs are also traceable to the design variables of the OPV via the component functions. The functions are specified by the capability gaps from the ICD and the components must provide the functionality to perform the NMETs and achieve mission objectives.

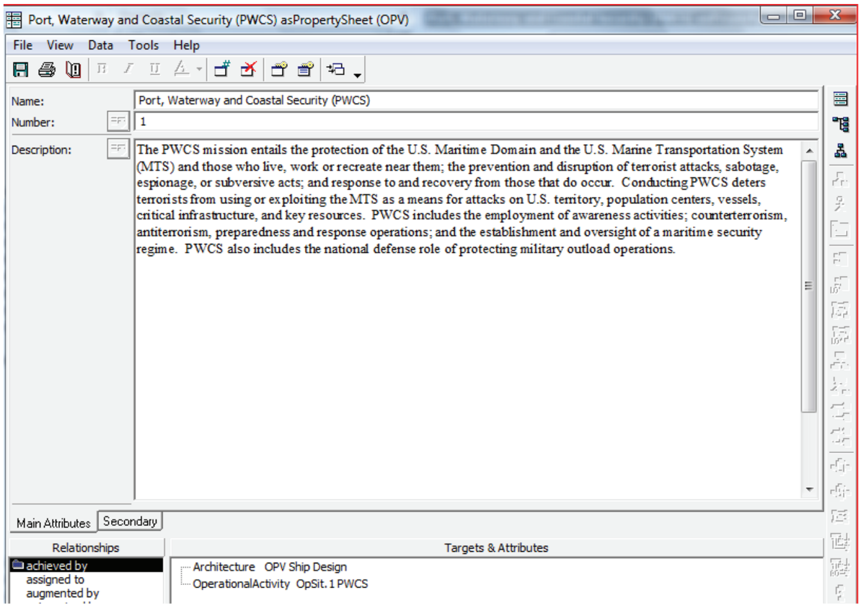
C&RE Process

The C&RE Process was presented in Figure 4. Given the JCIDS input, ICD, ADM, and AoA Guidance, the process begins by building or adapting a total-ship system enterprise architecture. This is followed by further development of the Design Reference Mission with Operational Situations, Operational Effectiveness Models, Required Operational Capabilities, and, finally, an Overall Effectiveness Model. Nothing should have to start from scratch. The system architecture and data repository must be built from the start of the JCIDS process, but even this nucleus may be adapted from earlier similar system architectures and repositories. This is the knowledge base! It should not depend on people, but stand on its own and support program continuity and consistency as people change.

Once the NMETL has been developed, it is used to assemble the DRM with the OpSits and the NMETL tasks. Here, we use a notional OPV to illustrate this process. The missions of the OPV have been defined by extracting them from the ICD. The mission objectives are described on each mission element property sheet as the element description *(Vitech, 2011).* Fig. 10 shows a Port, Waterway and Coastal Security (PWCS) mission element property sheet with the mission description.

The next step in the process is to identify the tasks that must be completed to accomplish each OpSit for each mission. Our notional OPV DRM is defined using 11 OpSits, one for each mission including the sub-missions under Defense Readiness. Once the necessary NMETs are selected, OpSit Functional Flow Block Diagrams (FFBDs) are built. When complete, OpSit elements can be expanded to show the sequenced NMETs that make up the OpSit. A DRUG Interdiction (DRUG) OpSit FFBD is

Fig. 10. PWCS Mission Element Property Sheet



Name: Port, Waterway and Coastal Security (PWCS)

Number: 1

Description: The PWCS mission entails the protection of the U.S. Maritime Domain and the U.S. Marine Transportation System (MTS) and those who live, work or recreate near them; the prevention and disruption of terrorist attacks, sabotage, espionage, or subversive acts; and response to and recovery from those that do occur. Conducting PWCS deters terrorists from using or exploiting the MTS as a means for attacks on U.S. territory, population centers, vessels, critical infrastructure, and key resources. PWCS includes the employment of awareness activities; counterterrorism, antiterrorism, preparedness and response operations; and the establishment and oversight of a maritime security regime. PWCS also includes the national defense role of protecting military outload operations.

Relationships	Targets & Attributes
achieved by	Architecture OPV Ship Design OperationalActivity OpSit. 1 PWCS
assigned to	
augmented by	

illustrated in Fig. 11. Each NMET has associated metrics and conditions, as shown in Fig. 12, and ultimately NMETs are modeled by using detailed physics-based OEMs *(Kerns, 2011)* and manning models.

Fig. 11. Drug Interdiction (DRUG) OpSit Enhanced FFBD (EFFBD)

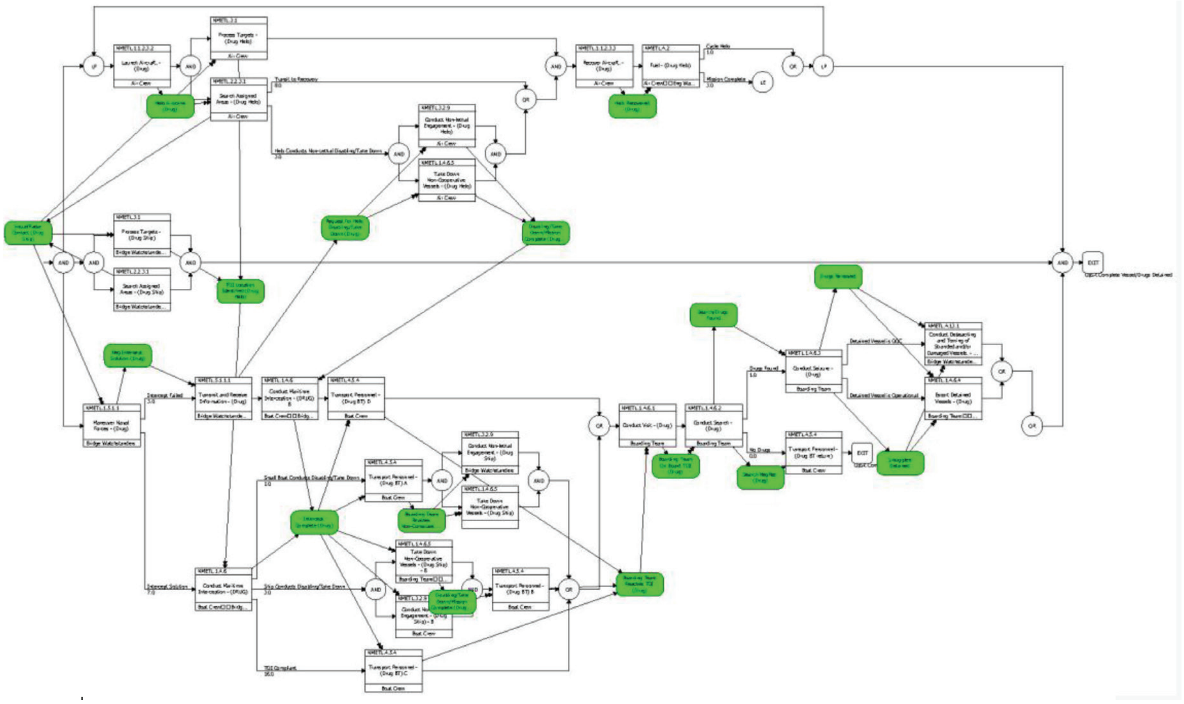
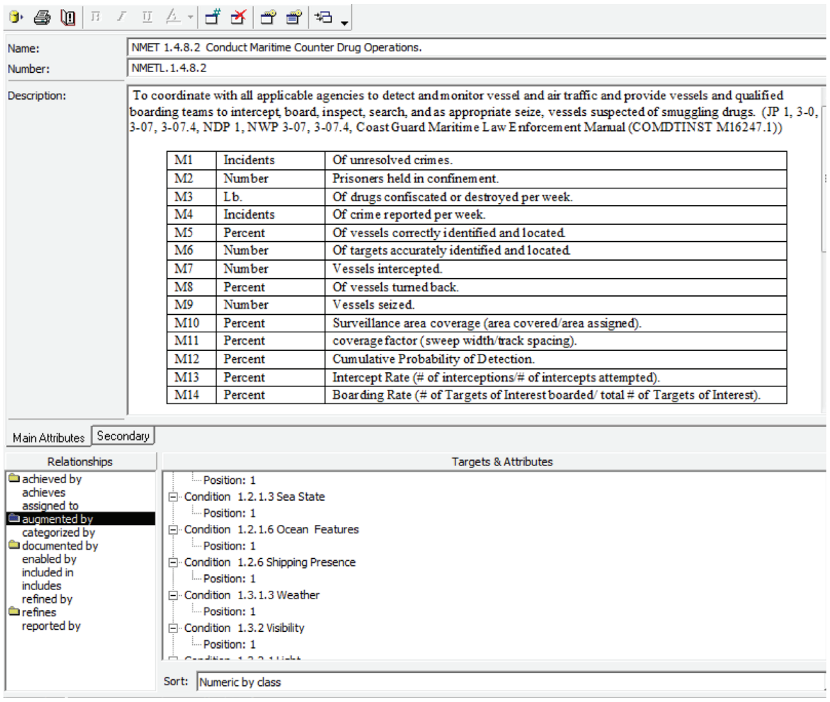


Fig. 12. NMET 1.4.8.2 Conduct Maritime Counter Drug Operations Property Sheet



Name: NMET 1.4.8.2 Conduct Maritime Counter Drug Operations.

Number: NMETL.1.4.8.2

Description: To coordinate with all applicable agencies to detect and monitor vessel and air traffic and provide vessels and qualified boarding teams to intercept, board, inspect, search, and as appropriate seize, vessels suspected of smuggling drugs. (JP 1, 3-0, 3-07, 3-07.4, NDP 1, NWP 3-07, 3-07.4, Coast Guard Maritime Law Enforcement Manual (COMDTINST M16247.1))

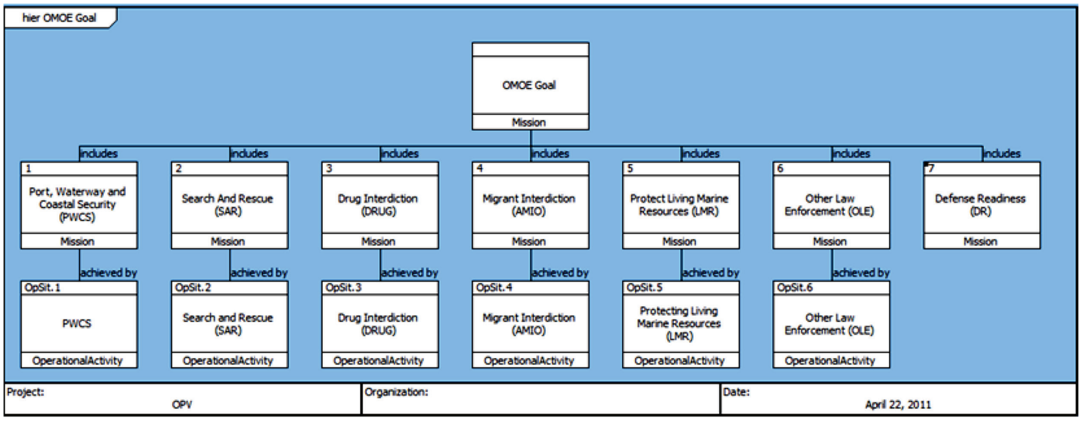
M1	Incidents	Of unresolved crimes.
M2	Number	Prisoners held in confinement.
M3	Lb.	Of drugs confiscated or destroyed per week.
M4	Incidents	Of crime reported per week.
M5	Percent	Of vessels correctly identified and located.
M6	Number	Of targets accurately identified and located.
M7	Number	Vessels intercepted.
M8	Percent	Of vessels turned back.
M9	Number	Vessels seized.
M10	Percent	Surveillance area coverage (area covered/area assigned).
M11	Percent	coverage factor (sweep width/track spacing).
M12	Percent	Cumulative Probability of Detection.
M13	Percent	Intercept Rate (# of interceptions/# of intercepts attempted).
M14	Percent	Boarding Rate (# of Targets of Interest boarded/ total # of Targets of Interest).

Position: 1
Condition 1.2.1.3 Sea State
Position: 1
Condition 1.2.1.6 Ocean Features
Position: 1
Condition 1.2.6 Shipping Presence
Position: 1
Condition 1.3.1.3 Weather
Position: 1
Condition 1.3.2 Visibility
Position: 1

Sort: Numeric by class

OEMs are developed using simulation software for multiple discrete event operational situations based on the OpSit framework from NMET sub-models. These simulations depend explicitly on ship design variable values. We are exploring ways to implement all of this through the design architecture. The scope of these OEMs is determined by the architecture. The complexity is determined primarily in the simulation software. Each mission has a measure of effectiveness (MOE) based on the measure results from its' OpSit(s) simulations. A Response Surface Model (RSM) is built in a Design of Experiments (DOE) for each MOE as a function of Design Variable (DV) values. The resulting MOE RSMs are combined to form the OMOE. The OMOE hierarchy for the OPV (with Defense Readiness not expanded for readability purposes) is shown in Fig. 13, created directly by using the system architecture.

Fig. 13. Proposed OPV OEM-based OMOE Hierarchy



Conclusions

This paper describes a framework for performing operational-effectiveness-based ship concept and requirements exploration. Important to this framework are a total ship design architecture and a structured approach to ship effectiveness using a Design Reference Mission, Operational Situations and standard Naval Mission Essential Tasks to guide the integration of Operational Effectiveness Models and calculate total ship effectiveness given the mission need, capabilities, and threat specified in an Initial Capabilities Document.

Our system architecture development focused on the Operational Architecture Domain to rationally define a DRM and its OpSits. The ability of the architecture to act as a single source repository for all data, guidance, design characteristics, functions, processes, cost, risk, effectiveness, and capture all of the relationships among these aspects makes it a potentially powerful tool.

The DRM provides rational measures of effectiveness (MOEs) based on realistic operational situations and the NMETL. The DRM is developed as an integral part of the Total-Ship System Architecture. By defining a DRM for a given ship design, the foundation is laid for using OEMs in the effectiveness model. If the Total-Ship System Architecture approach is adopted as a standard requirement for the ship design process, then OEMs become a natural choice to measure effectiveness and evolve directly from the architecture.

It takes significant effort to build the OEM simulations. Integrating the OEMs into an OMOE may also require some expert opinion. Research is continuing to determine the best balance of expert opinion and OEM-based methods. This research will include comparing the results of both methods to determine which is better or more valid for a given level of effort.

Acknowledgment

The sponsor for much of this research was Ms. Kelly Cooper, US Navy Office of Naval Research, Sea Platforms and Weapons Division, Code 333P. We are very grateful for her continued support.

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A Frigate in 10 years - Challenges and Opportunities

Una Fragata en 10 años - Desafíos y Oportunidades

Thomas Lamb [1]

Abstract

Colombia is involved in preliminary philosophies regarding the acquisition of frigates in the next 10 years. This presents many challenges as well as opportunities. This not a unique situation as many maritime countries have struggled with this matter over the past 50 years. The question that quickly arises is whether a country should design and construct new naval ships themself or follow one or a combination of the many options that have been used over this period. This presentation will review these options as both challenges and opportunities and hopefully provide a starting point for important discussions of this subject.

Key words: naval ship design, naval shipbuilding, required manning level, acquisition options, technology transfer, academic needs, national shipbuilding program

Resumen

Colombia se encuentra involucrada en filosofías preliminares en cuanto a la adquisición de fragatas en los próximos 10 años. Esto presenta muchos retos, así como oportunidades. Esta no es una situación única, debido a que muchos países marítimos han luchado con este asunto por los últimos 50 años. La pregunta que rápidamente surge es si el país debe diseñar y construir nuevas embarcaciones navales por sí mismo o seguir una o una combinación de un número de opciones que han sido utilizadas durante este periodo. Esta presentación revisará estas opciones tanto como retos como oportunidades, y espera brindar un punto de partida para entablar importantes discusiones en este tema.

Palabras claves: diseño de embarcaciones navales, construcción naval, nivel de dotación requerido, opciones de adquisición, transferencia de tecnología, necesidades académicas, programa nacional de construcción naval

Date Received: February 1st, 2013 - *Fecha de recepción: 1 de Febrero de 2013*
Date Accepted: March 1st, 2013 - *Fecha de aceptación: 1 de Marzo de 2013*

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Introduction

Since the end of WWII many maritime countries have faced the task of obtaining new naval ships such as a frigate. In the early time it was often accomplished by buying an existing frigate from one of the larger naval powers such as USA, Britain, Germany, France, Italy and Spain. Others preferred to obtain state of the art new ships from foreign sales naval shipbuilding countries, mainly France and Germany. More recently some maritime countries have decided to get involved in the design and building of their naval ships in a wide range of options as how to achieve this ranging from performing all the work themselves to varying types of partnerships with experienced naval shipbuilding company. Any approach has both challenges and opportunities for the acquiring country and, not surprisingly, there have been both successful and disastrous projects. This paper will use these past approaches, their successes and failures to provide a decision database for continuing discussion of this important factor in obtaining new naval ships today for a country that has had no previous experience in designing and building naval ships and specifically a frigate.

It is recognized that the final decision on which approach to use may be based on factors other than technical and cost such as social and political. Shipbuilding is a labor intensive industry which, for commercial ships, requires a modest financial investment and can be relatively quickly learned. Thus it is a relatively easy industry to join for countries where it can be used to offset unemployment. Japan, Korea and China are all example of this. This presentation will NOT address any of the social or political factors but will focus on the approach technical, cost, and schedule factors.

Setting the stage

When a maritime country, without a significant current naval ship design and construction capability, decides that it needs to acquire new naval combatant ships they are immediately faced with a number of important decisions: should it be designed from scratch; if so who should design it; if not how to select an existing design; who should modify the design if changes are necessary; and finally who should build the ship(s)? The initial desire is often to design from scratch and by the acquiring country's designers and to build the ship(s) in their own country. The reason why this is not often done is because the non-existing capability for both design and construction cannot support such a plan from both the cost and time that would be required to do so and even if these are acceptable the risks are great.

A number of countries have faced this problem and have developed a number of approaches to achieve the goal of having the desired naval ships for the desired cost in the desired time frame. These approaches range as follows:

1. purchasing the complete new ship(s) from an experienced foreign naval shipbuilder,
2. purchasing the complete ship(s) based on an existing design from experienced foreign naval shipbuilder,
3. contracting with an experienced foreign naval shipbuilder to either prepare a new design or to select an existing design and for them to build the first ship with the acquiring country building all remaining ships with technical assistance from the selected shipbuilder,
4. purchasing an existing design and technical assistance from a foreign shipbuilder but building all the ships in the acquiring country, and
5. finally, designing from scratch and building in the acquiring country.

Each of these approaches has challenges and opportunities for the acquiring country, and it is the understanding and evaluation of these and the cost and risks involved that is essential to reaching the right decision (compromise). The selected approach may not be one of those listed above but a combination of them. Each case is going to be unique as it depends on many external factors, such as the country's politic goals social and industrial policies and employment goals.

Current Experience

Before addressing the challenges and opportunities that the program to build frigates in 10 years offers Colombia or any other similar country, it is useful to look at some of the characteristics of the naval shipbuilding industry around the world. Table I shows the breakdown of recent naval shipbuilding for both export and own use *(Birkler et al., 2005).* From this it can be seen that the biggest own use countries (USA and Britain) are not significant players in the export of naval ships. Germany, France and Russia dominate this area. Table II shows typical cost (2009) per Lightship ton for a range of naval ships as well as a few commercial ships for comparison.

Table 1. World Naval Shipbuilding. Projected Military Ship Production, 2003-2012

	Export			**Domestic Use**		
	Number	**Value ($ millions)**	**LSW Tons**	**Number**	**Value ($ millions)**	**LSW Tons**
Germany	56	10,713	96,040	21	5,799	44,144
France	25	6,405	47,570	17	13,015	146,302
Russia	20	5,000	36,025	0	0	0
Spain	6	2,035	31,343	7	2,195	26,735
The Netherlands	9	1,780	8,500	4	1,585	24,759
United Kingdom	2	650	3,000	22	17,340	235,140
United States	2	53	174	66	56,172	776,446
South Korea	1	30	1,500	7	4,905	24,500
Japan	0	0	0	16	11,090	79,125
Italy	0	0	0	18	5,289	75,170
China	0	0	0	8	3,230	26,875
Australia	0	0	0	1	650	3,051
Sweden	0	0	0	3	375	1,431
Taiwan	0	0	0	1	320	2,769
Israel	0	0	0	11	55	550
Total	121	26,666	224,152	202	122,020	1,446,997
Not Reported	23 vessels valued at $13,225 million and displacing 86,291 tons LSW.					

Source: Source: Forecast International Naval Group (2003)

Countries such as Britain, Germany, France and Italy, even though they have quite large navies, find the cost of designing new naval ships difficult to justify and have attempted to develop joint designs such as the European Destroyer and the FREM frigate to reduce the cost by sharing resources. That this is not without problems can be seen by the demise of the destroyer program and Britain opting out of the FREM frigate program (See Fig. 1). This delayed the British Frigate program while the Type 45 Destroyer program was being *(Birkler et al., 2005)* executed but now work is underway on the Type 26 Frigate for the Royal Navy (see Fig. 2).

Table 2. Typical Ship Cost (2009)

Comparisson of Military and Commercial Ship Cost		
		Average Cost per LSW Ton ($)
Military		
SSK	Type 212A (German Navy)	346,667
	Type 214 (export)	323,529
	Scorpene (export)	141,379
	Type 209-1400 (export)	103,164
SSN	*Virginia* Class	250,000
	Astute	184,615
Aircraft Carriers	WASP LHD	69,767
	CVN 77	67,004
Destroyers	DDG 51 Class	167,644
	Project 093 (Chinese)	153,846
	Type 45	141,343
	Project Horizon	122,000
Frigattes and Corvettes	Multimission Frigate (French Navy)	70,833
	MEKO ANZAK	100,156
	La Fayette (export)	122,807
Patrol	UK OPV for Brunei	216,667
	MEKO A-100 (export)	17,625
Commercial		
World Market	Cruise Ship	10,000
	Chemical product tanker (small)	2,838
	Container ship	3,100
	Oil product carrier	1,630
	Bulk carrier (small)	1,259
	Bulk carrier (medium)	884
	Crude oil tanker (medium)	2,203
	Jones Act crude oil tanker (medium)	6,925

Source: Birkler et al., 2005

Fig. 1. FREM Frigate

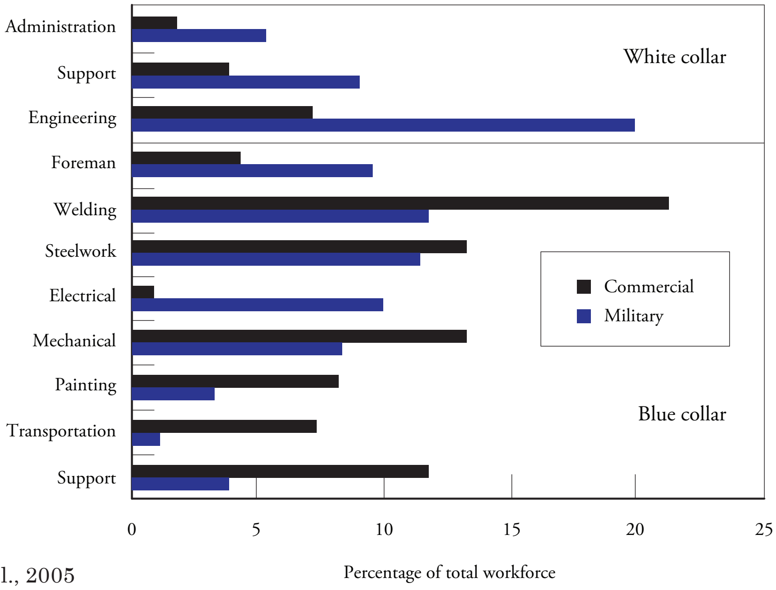
Fig. 2. British Type 26 Frigate

Many countries that want to build their own naval ships do so in the hope of establishing a shipbuilding industry within their country. They may already have a commercial shipbuilding capability or part of their plan may be to use the naval shipbuilding program (paid by the government) to jump start a commercial shipbuilding long term capability. Unfortunately, in both cases, this has not been too successful.

Some countries that have a reasonable commercial shipbuilding capability assume that this can be transferred to naval shipbuilding. Unfortunately, history has proven them wrong. Even the experience of small successful shipbuilders such as those involved in the LCS program in the USA, was not enough to enable them a successful transition into naval shipbuilding. That program ended up with the first ship costing over three times the original budget and twice as long to build. This is not a unique situation. Many naval ship design and constructions programs end up in similar straights

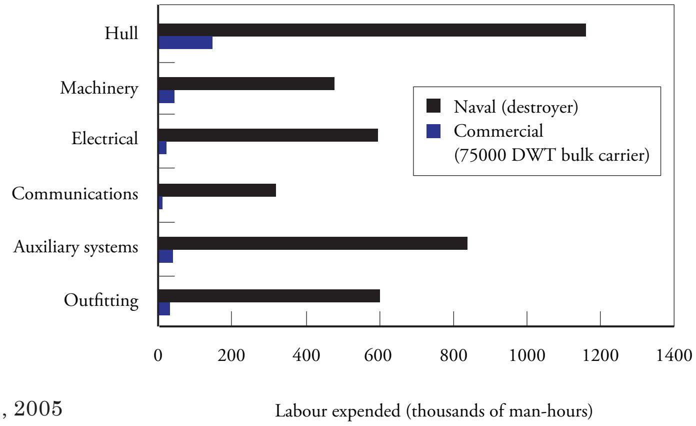
Part of the reasons for this is of the different skills required by the workers and the number of workers for naval ships compared to commercial. Fig. 3 shows the difference in worker skills for commercial and naval shipbuilding and Fig. 4 shows *(Birkler et al., 2005)* the worker man-hour breakdown for a Destroyer compared to a 75,000 t Bulk Carrier.

Fig. 3. Difference in Worker Skills for Commercial and Naval Ships



Source: Birkler et al., 2005

Fig. 4. Comparison of Shipbuilding Man-hours for Commercial and Naval Ships



Source: Birkler et al., 2005

It can be seen from Figure 3 that the big differences are 250% more for design, 200% for supervision of workers and 900% for electrical. Of course this figure can be misleading in that there are a number of disciplines where the commercial shipbuilder has a greater percentage than the naval. The true manning problem is shown in Fig. 4 where in all cases the man-hours for the naval ship are many times greater (factor of 10) than that for the commercial ship.

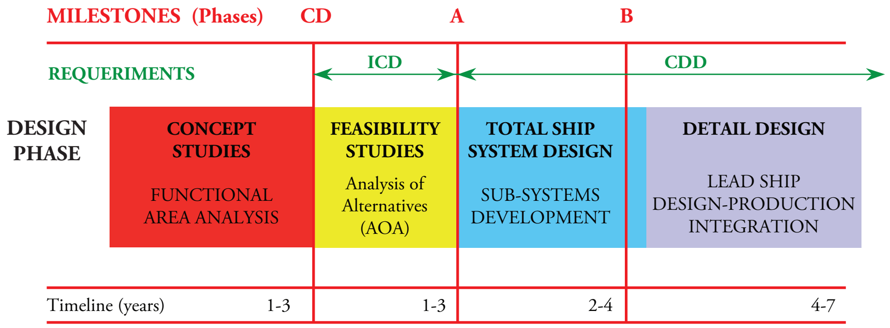
Another significant difference is the design and building schedules between commercial and naval ships. A typical schedule for a new combatant ship from Concept Initiation to completion of Detailed Design is shown in Fig. 5. It is based on experience in the USA where the design and construction capability exists (no country designs and builds as many naval ships as the USA see Fig. 6) and even with all this experience and activity the US naval shipbuilders have problems in design and construction; technical, cost and schedule.

The actual construction time that would be added to the design timeline for the first of a new frigate would be from 3 to 5 years with some overlap (start of construction before completion of design). So the total time from concept initiation to delivery of the first frigate would range from a minimum of 10 years to a maximum of 16 years.

A review of a range of recent new frigate designs show Detailed Design time from 3 to 5 years, Contract Award to Start of Fabrication of 3 years, Start of Fabrication to Launch of 3 years and launch to delivery of also 3 years.

Compare these to commercial ship design schedules of 6 to 12 months and build schedules from 6 to 9 months.

Fig. 5. Typical US Naval Ship Design Timeline

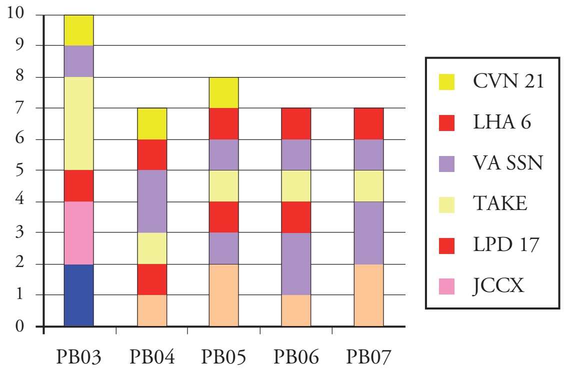


CD - Concept Decision

ICD - Initial Capabilities Document

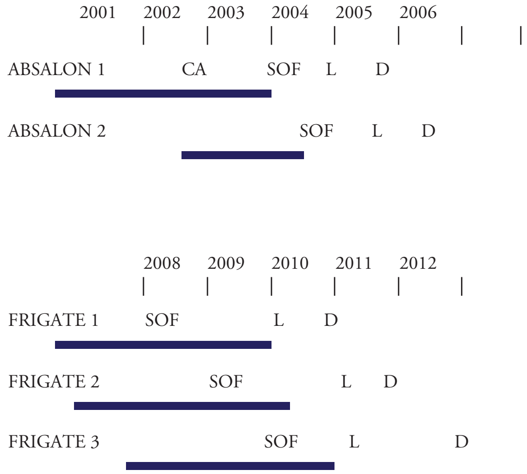
CDD - Capabilities Development Document

Fig. 6. Recent USA Naval Shipbuilding Programs



The recent accomplishment of the Danish Royal Navy and Odense Steel Shipyard is a unique and new approach. Fig. 8 shows what they were able to accomplish for the new frigate size ships of the ABSALON Class and the follow on frigate program of three ships. This was truly unique in that the build time was only a third of other programs and what is more interesting they were able to do so for 75% of the traditional frigate cost ($330M instead of $440M).

Fig. 7. Danish Naval Construction by Commercial Shipyard



Colombia is a special situation in that it has been building military ships (small) for almost a decade. Because of shipbuilding's importance it has been defined as a **strategic sector** by the Ministry of Commerce, Industry and Tourism as part of their **Productive Transformation Program**.

COTECMAR has built complex OPVs but it needs to continue to develop intermediate projects of increasing complexity in-house to acquire the capability to design and build their own frigate.

Experience has shown that it is not easy to enter shipbuilding for the first time or re-enter after a long absence. The recent Brazilian experience is an unfortunate example of this though it was for commercial ships

So now the stage is set to look at the specific focus of this paper. The rest of this presentation will look at the challenges and opportunities that each approach has in the goal to acquire a frigate in 10 years.

Challenges

For a country that has never designed or constructed a naval combatant ship (or a country that has but it is over 25 years since they designed and constructed the last one) the first and greatest challenge is to decide on the approach.

Approaches 1 and 2

The only difference between Approaches 1 and 2 are that for 1 a new design is required whereas for 2 the objective is to find a frigate already designed and constructed. As there is no in-country design or construction involved in these approaches the challenges are minimum. Though option 2 has more risk as the desired ship has not been designed and constructed. The decision making is entirely under the control of the Navy operators. An acquisition team will probably be formed and their responsibilities are to develop the design requirements based on operational needs, develop a performance specification in the case of a new design or in the case of selecting an existing design review frigate shipbuilders products and end up with a list of the two or three that meet their requirements probably involving visits to the selected frigates in service or under construction. Then with the Navy administration, budget control and contractual groups, negotiate with the short list of shipbuilders and eventually select the winning shipyard. This will obviously involve the cost, build duration, delivery schedule, shipbuilder's reputation, and any political factors. Approach 2 offers the fastest availability of the ships, lowest program cost and risk. Approach 1 will take longer, involve more risk and cost more than Approach 2. The obvious downside of both these approach are that they do not do anything for the development of an eventual self-sustained naval ship design and construction capability for the acquiring country.

Approach 3

The objective of this approach is to save cost and reduce risk by having the first ship constructed by experienced shipbuilder. This approach has been used by a number of countries that wanted to use the program (especially submarines) to build up their own capability to build such ships. The challenge for the new design and construction is for it to be successfully executed and the construction documents well prepared for the follow on ships. For using an existing design the challenge is that the existing construction drawings and documents are understandable to the in-country shipbuilder without needing any rework or additional documents just to suit the in-country shipbuilder, which would add cost and extend the schedule.

Approach 4

Here the objective is to save time by not designing the ship and reduce technical risk in that the design has been proven by construction and operation. It eliminates the need to build up a large technical capability. The challenge is to build up the workers in numbers and skills to execute the construction program and avoid the undesirable experience of other similar programs in having significant cost over-run and schedule delay.

Approach 5

The challenges of this approach are:
- how to obtain required technology?
- how to build up to the required technical manning level (150 to100 for 4 to 7 years respectively)?
- how to build up to the required worker level (300 for 7 years assuming a 4 ship program)?
- what level of infrastructure should be developed within the country?
- what are the responsibilities for government, academia and industry?
- what to do with the designers and workers AFTER the program is complete?

This approach also has the highest technical, cost and delay risks. Even though the final outcome may achieve country's shipbuilding capability goal, experience with this approach has not been good.

How to obtain required technology?
This may actually be the easiest of the listed challenges to meet. There are volumes of conference transactions and other technical forums that cover most of the technology required to design a state of the art frigate. In addition there is significant information and data available on the internet. One of my favorites is http://warships1discussionboards.yuku.com/topic/21599/Majestic-class-frigate#.URwucFbTncu. There are Naval Ship Design and Equipment Conferences held regularly in Europe and Asia. THERE IS NO NEED TO REINVENT THE WHEEL, but it is necessary to focus on acquiring the required key technologies required to achieve the country's desired capabilities. The challenge is not to find the technology but how to have new designers absorb it and mold it into an integrated ship design. This takes time and experience to be able to use it to design a successful ship.

The examples of the National Shipbuilding Research Program in the USA and the Japanese Shipbuilders Association are worthwhile examining and adapting to the new shipbuilding country's needs. Also all of the NSRP reports are available to non-US shipbuilders for a modest copying charge. Finally, the papers presented to maritime professional societies at meetings and conferences are well documented and available to all at a cost.

How to build up to the required technical manning level?
Many countries with a limited shipbuilding industry obtain the technical personnel by sending people to universities in countries recognized as being significant shipbuilders. Universities such as MIT and Michigan in the USA and Glasgow and Newcastle in Britain and a number in Europe are well known for their acceptance of foreign graduates. This approach enables the developing country to obtain a minimum level of knowledge at reasonable cost and in a timely manner.

The next step is to open naval architecture and marine engineering programs at existing universities. However this takes time (at least three learning cycles) before it has any impact on the country's ship design capability. Select graduates from the BS level are then sent to various universities around the world for graduate study. After graduation these Master degree graduates can fill the leadership role back home. Then the natural tendency is to start basic research and offer advanced degree programs. The problem with this approach is that it ignores the real immediate and near term need. When a country enters or re-enters shipbuilding there is little need for in-country developed research but rather for educated production oriented designers, production planners, supervisors and managers. Therefore the challenge is for higher education institutions to resist the move to emulate foreign universities offering all three levels of degrees and to focus on the immediate and short term need for the new shipbuilding industry and to assist the shipbuilding industry by providing access to the required key technologies (a transfer of technology) that will support the shipbuilders needs.

Another approach is to send both design and production employees to a foreign shipbuilder to serve an apprenticeship for at least 3 years. The disadvantage of this is that their labor contribution is lost for this time but it is one of the surest and fastest ways to achieve the required knowledge and experience.

How to build up to the required worker level?
The development of the required worker skills must be developed in-country. If there are enough shipyards and time it can be done by the regular apprenticeship approach. However, to reach the manning level required for a 4 ship frigate program would take 10 years.

What is needed is a different and faster approach. The involvement of shipbuilding training should start in the high schools and continue in vocational colleges and then shortened apprenticeships at the shipyards. The challenge here is where to find the lecturers/trainers for such a program?

What level of infrastructure should be developed within the country?
Shipbuilding is an assembly industry where some of the components are fabricated in the shipyard and the remainder purchased. For commercial ships the proportion of purchased material and equipment is 60%. For naval ships it is even greater with the weapons and their control systems. When a country enters or re-enters shipbuilding the in-country infrastructure does not exist and there is no choice but to utilize foreign sources. Often a country undertaking such an approach is doing so for social and political reasons and may invoke that a certain proportion of the manufacture of required components be done by new in-country small businesses. Typical "packaged" systems obtained from foreign sources are propulsion, war fighting including weapons, and electronics.

The decision on infrastructure should be part of an integrated National Shipbuilding Program. It should involve the development of a national awareness of the maritime world and its current and potential impact on the country. In some cases countries dictated that for major components, such as propulsion engines, the selected foreign engine manufacturer must set up manufacturing capability in the acquiring country.

What are the responsibilities for government, academia and industry?
The most important part of any plan involving the expansion of any industry within a country and a major success factor is how well the various

government, academic and industry players work together and also how they approach the shared responsibilities. The government must provide the overall goal for the long term plan, any funding that is required for government, academia and industry, removal of traditional obstacles, the building of a maritime interest and support by the public, programs to schools fostering the marine industry. The government should establish trade agreements with the countries that the industry needs to purchase material and equipment from. The government should also provide long term marketing at government level so the foreign competition is fair and thus future ship contracts can be won. It is also the government's responsibility to monitor that the academia is providing the number and capability of graduates to support the plan. Academia has the responsibility to provide industry with the graduates they need to meet the plan. They must be open to immediate and short term basic and practical needs and not set up programs that produce well educated theorists that do not know how to build ships. What industry needs in its early development are graduates that can design ships and manage their construction. Finally, industry must work with the government and

together establish a realistic approach to meeting the national plan, setting of milestones so that the plan can be monitored and changes made if necessary to support ultimate goal. Obviously it is the responsibility of industry to determine the numbers of designers, managers and workers needed to execute the immediate and long term program and to apply a growth plan for their shipyards (academia would use the projected numbers and needs to develop supporting programs). Industry must also design the ships and construct them

What to do with the designers and workers AFTER the program is complete?
This is perhaps one of the biggest challenges but is often ignored in the vain hope that somehow something else will come along to maintain the new shipbuilding capability after the naval ship program is completed. This must be planned for. The usual plan is that the capability built up by the naval ship program can immediately allow the country to enter the international shipbuilding market. Unfortunately that often does not occur because of the differences between commercial and naval ship design and construction mentioned above.

Opportunities

Approach 1

The advantage of this approach over Approach 1 is that it offers the county's Navy the opportunity to determine and define, in a Performance Specification, the exact requirements that it needs in the frigate for its planned operations. There would be a limited opportunity for the Navy's technical staff to learn some ship design and construction techniques from the overview of the foreign shipbuilders design and construction activities.

Approach 2

This approach offers little opportunity to improve a country's own ship design and construction. It would offer the Navy to gain experience with state of the art frigate operations and thus the potential to better define its requirements for future naval ships.

Approach 3

The process of selecting an existing ship design will offer opportunities to learn from the review process and an evaluation of the construction approach will give reviewing team some shipbuilding knowledge. It is likely that once the selection is made, technical, management and some workers will be station in the shipyard during the construction of the first ship and they will lead the technology transfer and detailed building plans to their shipyard for the construction of follow-on ships. This approach only offers limited opportunity for technology transfer and mostly the opportunity to develop the ship construction process. By not starting construction until the building of the first ship is completed offers the opportunity not to avoid the problems of starting before the design is mature (> 80% complete). This is a widely recognized productivity problem for many past new programs. Thus after completion of the frigate program it would offer a ship construction capability to construct complex ships from existing designs.

Approach 4

Here again the focus is on the ship construction capability improvement not the ship design. If an existing design is selected it would reduce cost and time before starting construction. Thus the opportunity is to get the first ship faster than if it is a new design. If it is an existing design that has been constructed the risk of starting the construction immediately is small. If a new design is obtained from a foreign ship designer all the risk of taking care of initial ship design problems remain and this is coupled with the usual first ship construction problems in the country's shipyard(s). If it is a new design there is the opportunity of the originating country to form a joint development and construction program with other countries, such as the FREM program.

Approach 5

This approach offers the greatest improvement opportunities for a country desiring to enter the shipbuilding industry, but with the greatest technology, cost and schedule risk. The opportunities are many and varied and would have the greatest and broadest benefit to the country's supporting institutions and other industries.

From the cost aspect, if the acquiring labor rate is significantly lower (say 1/3) than existing naval shipbuilders labor rate then there is a potential of 45% saving in labor cost or 25% of total ship cost. This would NOT be achieved for the first or second ships but for the follow on ships.

From the technology aspect it offers the exact matching of defined Navy requirements. This would include examining the suitability of unique hull forms such as Trimarans (Fig. 8) and SWATH (Fig. 9) forms that traditional countries seem reluctant to use (except for USA LCS 2 and the recently reported new Indian frigate program).

It also offer the opportunity to use the latest and better ship design tools than were probably used for an existing design. By designing in-country it will give the design staff as well as the education institutions the opportunity to obtain the latest design systems such as the British PARAMARINE (Fig. 10). This allows the ship to be designed from the inside out rather than to fit the required spaces into a pre-established hull form.

This approach would give great opportunity to all levels of education to establish a program that would meet the shipbuilding industry's needs. The opportunity at the university level must be focused on the needs of the next 10 years and not to copy existing universities with long histories of advanced teaching. The need in the next 10 years is for graduates that can help move from a non-existent or small ship design and shipbuilding capability to one that can design and construct modern ships, both naval and commercial. This does not need a lot of research. The need for research will grow as the long term shipbuilding industry grows. The warning given above is repeated here: THERE IS NO NEED TO REINVENT THE WHEEL.

A great opportunity exists for the schools and vocational colleges. The schools must promote the maritime world to its pupils and thus generate an interest in it. The vocational colleges must develop programs that provide the beginning of the training process for future shipbuilders.

Fig. 8. LCS 2 Trimaran

Fig. 9. SWATH Hull Forms

Fig. 10. Paramarine Frigate Design

Conclusions

Five different approaches for acquiring naval ships have been presented and the challenges and opportunities discussed with a focus on a frigate. They are summarized in Table III. However, only the technical issues have been discussed in the presentation.

Table 3. Ship acquisition source approach summary

Approach	Description	Challenges	Opportunities	Risk
1	Complete Purchase New Design	Normal new program for foreign shipbuilder	None for acquiring country not even technology transfer	Next Lowest
2	Complete Purchase Existing Design	Design may not meet requirements and thus need significant change	Same as 1 but fastest acquisition of ships	Lowest
3	Foreign Design and First Ship Build	How to develop workers with the required skills	Saving in total cost IF acquiring country's labor rate is significantly lower than experienced shipbuilder rate. Learning in foreign shipyard and time to buildup own work force	Medium
4	Foreign existing or new Design Self-Build	How to overcome lack of experienced and skilled workers	Saving in total cost IF acquiring country's labor rate is significantly lower than experienced shipbuilder rate. Long term development of shipbuilding capability	High
5	Self-Design Self-Build	Significant All challenges discussed	Saving in total cost IF acquiring country's labor rate is significantly lower than experienced shipbuilder rate. To join with other countries who need naval ship to share development cost and provide more resources. Long term development of shipbuilding capability	Highest

The important social and political factors have not and it is possible that they will be the deciding factors. The social and political factors include:

- building up technical level,
- expansion of university and technical college attendance
- providing industrial work to improve unemployment,
- generating more tax revenues, and
- reducing outflow of money for the project thus reducing the imbalance of payments.

From the cost aspect, if the acquiring labor rate is significantly lower (say 1/3) than existing naval shipbuilders' labor rate then there is a potential of 45% saving in labor cost or 25% of total ship cost. This would NOT be achieved for the first or second ships but for the follow on ships. This is a significant reason for building the naval ship in the acquiring county.

The preparing of a new ship design and engineering by the acquiring country designers offers the greatest long term capability generating opportunity but it also is a high risk approach.

Approach #4 offers the best compromise in that it has the lowest design risk (even if extensive changes are made to arrangements and weapons) and it offers the best potential for improving the acquiring country's shipbuilding capability. However, the introduction of politics will affect the final choice.

If the political goal is to establish a long term shipbuilding capability in the country then it is essential that a National Shipbuilding Policy be established covering not only the frigate program but for ships both commercial and naval beyond that, including the education of professionals both technical and management, the training of workers, the required infrastructure, financing programs, etc. its successful outcome depends on how well the plan is organized and how well all the players; government, academic and industry, work together.

So whatever approach is selected the challenges associated with that approach must be understood and actions taken to alleviate their adverse impact on the program and the opportunities that best fit with the selected approach must be put into action. The approach must be based on a broader longer term plan; it cannot be based only on a few frigates. It must include programs parallel to and after the frigates that can sustain the resulting capability and the level of designers and workers. That is the plan must balance the capability developed for the frigates with the long term shipbuilding strategy. Then stick with the decision. Follow the well-known dictum: PLAN THE WORK, WORK THE PLAN.

The presentation has deliberately been generic in that the contents apply to any country and naval combatant ship. In this conclusion I would like to end by focusing on Colombia. How does it all affect Colombia? Fortunately Colombia is NOT just entering shipbuilding. In COTECMAR it has a shipbuilding capability that has been built up over the past decade. Throughout this time it has focused on having a strong design and development capability which has tackled more complex ships such as the OPVs and continually improved its knowledge in ship design and shipbuilding processes.

It also has universities that offer naval architecture education and is currently implementing advanced graduate studies. Over the past few years Colombia has developed a national Product Transformation Program of which shipbuilding has been recognized as a strategic sector. All this obviously reduces the challenges and thus risks discussed above, but there is still a level of challenges and many opportunities for the country in expanding the shipbuilding capability and all the related support that goes with this such as university education and worker training.

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Assessment of appendage effect on forward resistance reduction

Evaluación de apéndices para disminución de la resistencia al avance

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Abstract

This paper shows experimental and numerical results of three types of appendages on forward resistance reduction of displacement and semidisplacement hulls. Forward resistance results were obtained by using Computational Fluid Dynamics and towing tank tests. The appendages evaluated are stern flaps and interceptors for displacement hulls and spray railspray rails for a semiplaning hull. The experiments are independent from each other and no research was undertaken to include the combined effect of appendages on a single hull. The predicted reduction in forward resistance in all three tested devices is around 5-10%, showing potential for fuel saving through the evaluation of hydrodynamic effects of energy saving appendages.

Key words: forward resistance, appendages, numerical tests, experimental tests, CFD, towing tank

Resumen

Este trabajo contiene resultados experimentales y numéricos del efecto de tres tipos de apéndices en la disminución de la resistencia al avance en cascos de desplazamiento y semidesplazamiento. Los resultados de resistencia al avance han sido obtenidos mediante Dinámica de Fluidos Computacional y experimentos de remolque en tanques de pruebas. Los apéndices evaluados son *flap* e interceptores de popa para cascos de desplazamiento y *spray railspray rails* para un casco de semiplaneo. Los casos estudiados son independientes entre sí y no se ha realizado un análisis que incluya el efecto combinado de ellos actuando conjuntamente en un casco. La reducción estimada de la resistencia al avance, en los tres apéndices experimentados, es alrededor de 5-10%, mostrando que existe potencial para ahorro de combustible por medio de la evaluación de los efectos hidrodinámicos de estos apéndices para ahorro de energía.

Palabras claves: resistencia al avance, apéndices, ensayos numéricos, ensayos experimentales, CFD, canal de pruebas

Date Received: January 12th, 2013 - *Fecha de recepción: 12 de Enero 2013*
Date Accepted: March 1st, 2013 - *Fecha de aceptación: 1 de Marzo de 2013*

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Introduction

Due to constantly increasing fuel costs and the growing pressure to reduce pollutant emissions, it is increasingly important to consider every means to reduce fuel consumption. Even a small reduction in the required energy could mean economic survival in the long run. Savings of 1 to 5% in fuel expenses, considered non-relevant in the past, are now crucial to the economic performance of merchant ships and fishing vessels; moreover, even military vessels are under great pressure to reduce fuel consumption due to economic and environmental reasons. A number of devices are available to reduce forward resistance; their effectiveness is not well proven and usually there is little more than a sales approach to claim savings that are sometimes unreliable and based on results from a single ship under very particular conditions. To further complicate matters, is it very difficult to evaluate the effective performance of a hydrodynamic device in real operational conditions. In effect, the variation of sailing conditions, sea state, loading, hull fouling and many other variables make it almost impossible to compare the fuel consumption of a ship with and without a fuel savings device, especially when saving margins are as narrow as 1 to 10%. Some examples of devices currently in use and their potential for resistance reduction are shown in Table 1.

Due to the difficulties encountered in full-scale evaluation of fuel saving devices, it is crucial for scientific research to undertake such an evaluation. This paper is focused on the performance evaluation in forward resistance reduction of stern appendages: flaps and interceptors, and spray railspray rails used to decrease the wet surface in planing and semiplaning hulls.

No attempt was spent on joint testing of combined devices, given that the hydrodynamic interaction of appendages is difficult to analyze and scale effects could provide confusing results. It should be warned that the potential to reduce resistance of devices, presented in Table 1, is not possible to be added directly, moreover, the combined effect of two or more of these appendages could result in a negative contribution, *i.e.*, increasing total resistance.

Stern Flaps

A stern flap is an appendage built in form of a plate that extends aft of the transom at an angle relative to the ship's buttock plane. Its interaction with the hull modifies the ship running trim, reduces propulsion resistance, and increases maximum attainable speed. The critical parameters for a stern flap geometry design are: chord length, flap angle referenced to an extension of the hull bottom, and flap span across the transom. Stern flaps have been investigated for displacement hulls, *(Cusanelli et al., 1999)*, semidisplacement hulls, *(Salas et al., 2004)*, and planing hulls. On small planing crafts, a stern flap affects the running trim angle by four to five degrees, *(Millward, 1976)*. This variation is

Table 1. Resistance reduction devices

Device or appendage	Resistance reduction potential
Stern flaps, wedges, and interceptors	5 – 10%
Pre-propeller fins	3 – 10%
Post-propeller stator, contra-rotating propellers	3 – 5%
Bulbous rudders	2 – 3%
Air bubbles over the wet hull	5 – 7%
Asymmetrical rudder	1 – 2%

the principal reason of the reduction in resistance on these types of hulls.

In contrast to the planing hull case, a stern flap affects the trim angle by 0.1 to 0.3 degrees on vessel displacements. This amount of trim change does not produce significant resistance reductions. The principal powering benefits on these vessels are attributable to the induced change in the flow field around the propeller and reduced flow separation at the stern. The flow field change reduces the drag on the stern zone and modifies the ship's wave resistance.

Assessment of Stern Flaps on a Displacement Hull

Stern flaps were evaluated on a displacement hull. Flap angles were chosen at 0, 5, and 10º; preliminary tests were also carried out for flaps with 15º, showing poor performance of this configuration. The chord length of the flaps was 1, 1.5 and 2% of LPP (DEFINE). Experimental tests of the displacement hull with stern flaps were carried out at in the towing tank at Universidad Austral in Chile. This tank is 45 m long, 3 m wide and 1.8 m deep. Details of the model, flaps tested, and the experimental setup can be found in *(Jiménez, 2009).* Computational Fluid Dynamics (CFD) was employed to obtain numerical simulations of resistance tests. The theoretical model is based on Navier-Stokes equations solved for an isothermal three dimensional flow of a viscous fluid with constant physical properties. No theoretical development of the method is given in this paper, as can be found in the technical literature, *(Ferziger and Peric, 2002)*; *(Bertram, 2011)*; *(Baos, 2011).*

The hull's main characteristics are shown in Table 2 and the stern flap mounting is shown in Fig. 1. Considering the towing tank dimensions and the maximum speed, a scale of $\lambda = 80$ was selected to build the model and flaps.

Numerical CFD simulations were carried out by using ANSYS CFX code. The meshing was allowed to be coarse in non-sensitive fluid regions far from the hull and refined in sensitive areas like the free surface, hull boundary layer, and stern flap. The stern flap and fluid mesh are shown in Fig. 2 and the virtual towing tank is shown in Fig. 3.

Table 2. Main characteristics of displacement hull

Main characteristics		
Length overall	148.20	m
Waterline Length	136.30	m
Beam	13.90	m
Draft	4.60	m
Wet surface	2086	m^2
Block Coefficient	0.51	
Displacement	4869	ton
Speed	30.00	Kn

Fig 1. 10° stern flap

Fig 2. Mesh details on stern flap, boundary layer, and free surface

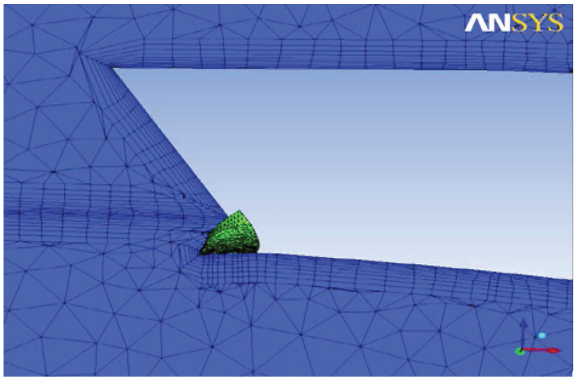
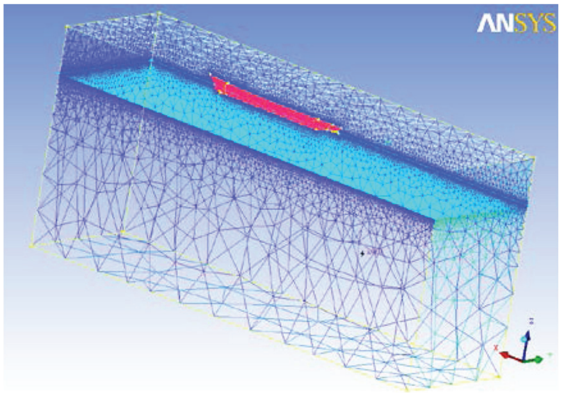


Fig 3. Hull and fluid volumes mesh



Selected experimental and CFD resistance results for model scale are shown in Figs. 4 to 7. It can be appreciated in Figs. 5 and 6 that modest, but consistent, benefits can be achieved with chord lengths 1% and 1.5% of LPP, respectively. Less efficient results can be observed in Fig. 7 for 2% chord length.

Fig 4. Experimental resistance Flap 0º; chord 1% Lpp

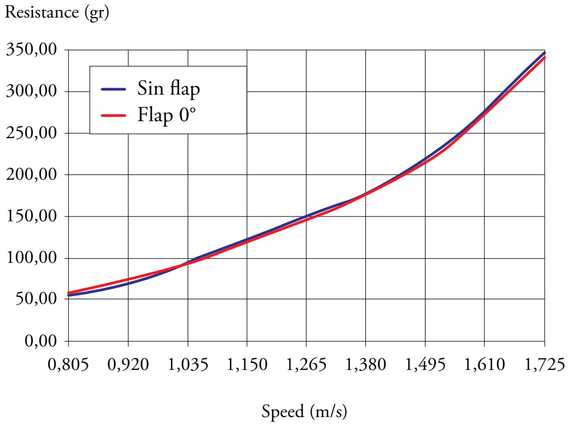


Fig 5. CFD resistance Flap 0º; chord 1% Lpp

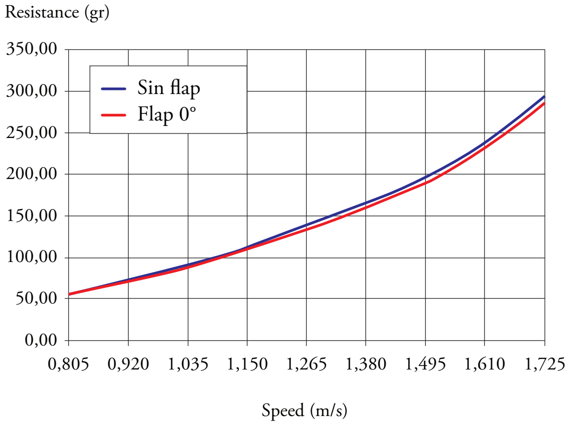


Fig 6. CFD resistance Flap 5º; chord 1.5% Lpp

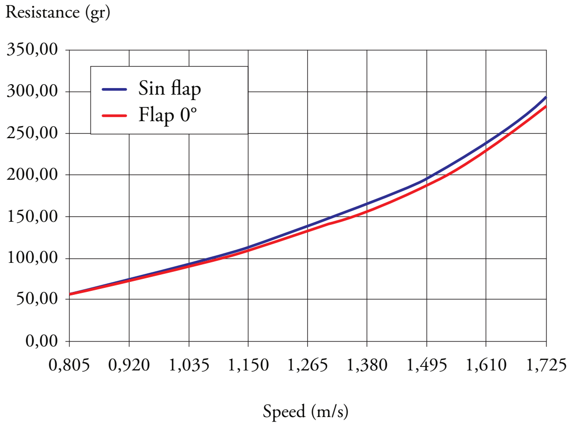
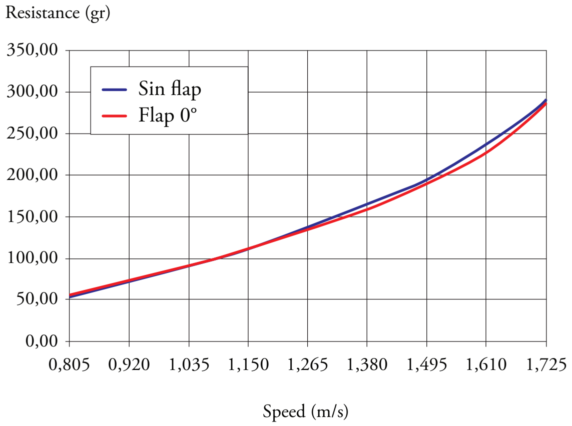


Fig 7. CFD resistance Flap 5º; chord 2% Lpp



Interceptors

An interceptor is a device designed to intercept water flow under the hull. It is usually a simple flat plate that can be built in steel or any other material. It modifies the pressure field at the stern by creating a virtual wedge, as shown in Fig. 8. An interceptor is much simpler to install compared to a flap; its length under the hull can be adjusted, so it can be adjusted to perform optimally at any particular speed.

Interceptor performance on a Fishing Vessel

To achieve a reduction of ship resistance of a fishing boat, CFD simulations of interceptors were investigated for two interceptor lengths under the hull: 5 and 10 centimeters. Numerical results were compared to towing tank results available from tests performed at ETSIN towing tank in Madrid, Spain *(see ETSIN 2002 and Sepúlveda 2006).* The main characteristics of the fishing vessel are presented in Table 3.

Fig 8. Interceptor wedge effect on the stern flow

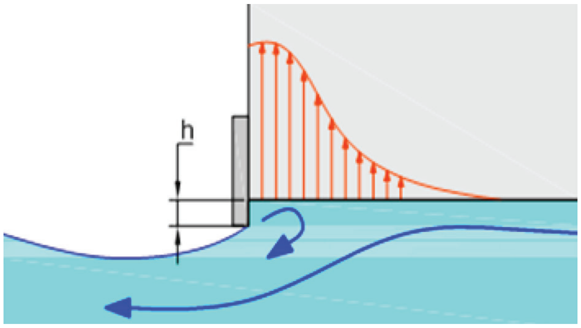


Table 3. Main characteristics

Fishing vessel main characteristics		
Length overall	25.23	m
Beam	6.60	m
Draft at the stern	2.67	m
Draft forward	1.87	m
Block Coefficient	0.41	
Wet Surface	154.99	m^2
Displacement	80.60	ton

The fishing vessel resistance tests were carried out for equivalent speeds of 10, 12, 14, and 16 knots.

The interceptors were mounted across the stern reaching a width of 4.208 m and depth under the hull of 5 and 10 centimeters in full scale.

Taking advantage of symmetry, only half of the hull and virtual towing tank were modeled in the CFD simulations. The fluid domain was created according to the Iowa University recommendations to avoid modeling fluid regions not affected by the hull movement. Local mesh refinements were created to adequately model fluid flow in relevant fluid regions like the boundary layer, free surface, and interceptor vicinity, as shown in Fig. 9. The total amount of fluid cells created was about 3.5 million, as detailed in Table 4.

Fig 9. Fishing vessel CFD mesh

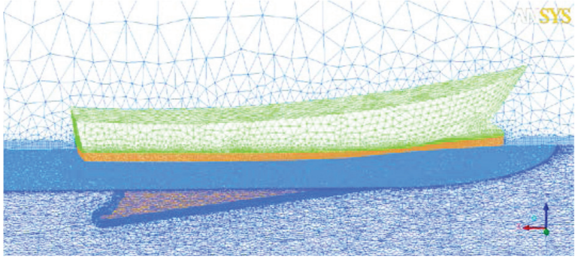


Table 4. Mesh distribution

CFD Mesh elements	
Water volume	2328874
Air volume	1077318
Wet hull	84810
Dry hull	4818
Total	**3495820**

Interceptors results

CFD simulations were able to predict the interceptor effect on smoothing stern wave patterns at all speeds, as an example the wave pattern behind the stern at 12 knots is shown in Fig. 10. Regarding total resistance, there is some discrepancy with the towing tank results in the predicted resistance of the hull, no interceptor fitted, for higher speeds, as presented in Fig. 11; however, the predicted trend is similar in both approaches, both predicting significant benefit in the resistance reduction at higher speed, given interceptor effects, as noted in the experimental and CFD results shown in Figs. 12 and 13.

Fig 10. Wave pattern at 12 knots for: no interceptor (above centerline) and 5 cm interceptor (below centerline)

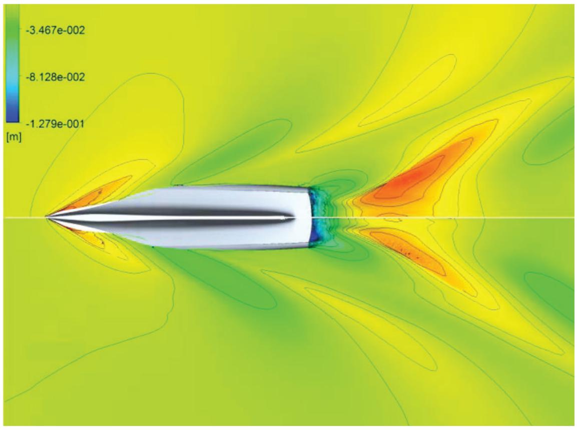
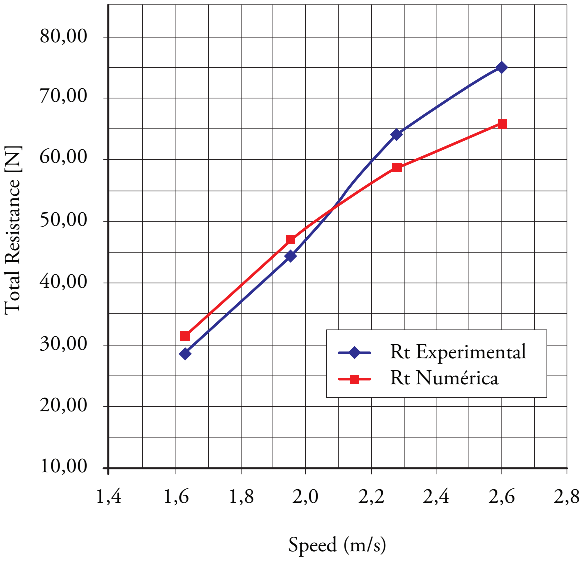


Fig. 11. Total resistance curves for experimental (blue curve) and numerical (red curve) tests. No interceptor fitted



Interceptor efficiency

Both, towing tank and CFD, results predict a significant reduction of resistance at higher speeds, despite differences in the reduction shape, as seen in Figs. 12 and 13, there is agreement in the resistance reduction potential of about 10% at higher speeds for the 5 cm interceptor. The 10 cm interceptor was predicted to be slightly less efficient.

Fig 12. Efficiency according to experimental results

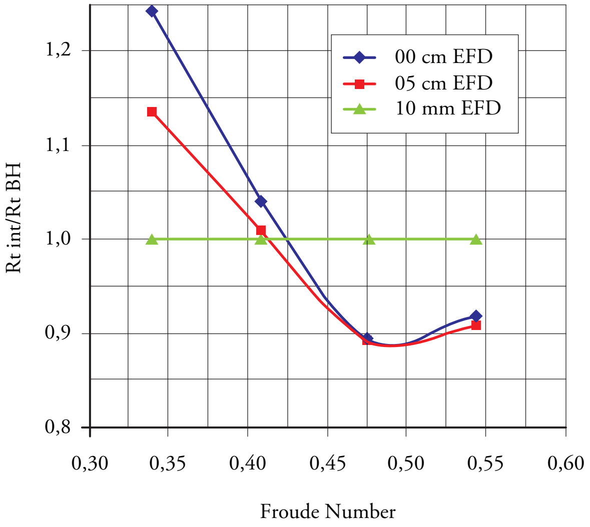
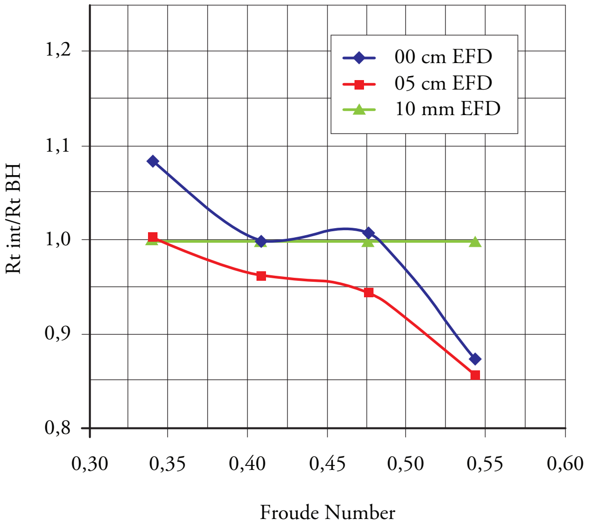


Fig 13. Efficiency according to numerical (CFD) results



Spray railSpray Rails

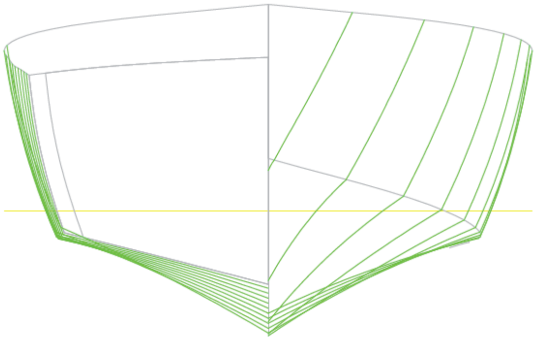
The Spray railSpray rails main function of spray rails is to separate the spray that characteristically builds-up at the bow of planing and semiplaning crafts. The purpose is to reduce the associated resistance and improve operational conditions, given that sometimes the spray becomes so large that it comes over the deck and may affect visibility. Spray railSpray rails are usually avoided by incorporating discontinuities into the hull shape; hard chines also serve that purpose. Sometimes these geometric discontinuities are insufficient to detach the spray from the hull; in these cases, a spray rail can be pre-designed or retrofitted without major difficulty.

Spray railSpray rails were numerically simulated to evaluate their effect on the dynamic wet hull and the forward resistance. The hull chosen was a hard chine planing hull with maximum speed of 28 knots. The hull's main characteristics are presented in Table 5 and cross sections are shown in Fig. 14.

Table 5. Fast craft main particulars

Main characteristics of planing hull		
Length overall	19.5	m
Waterline Length	17.7	m
Maximum Beam	5.1	m
Static Draft	1.2	m
Displacement	36.0	ton
Maximum speed	28	knots

Fig 14. Hull cross sections



Spray rail results

As expected, at lower speeds the effect of the spray rail is negative because the added wet surface increases frictional resistance. This adverse effect is not really a problem for these types of boats, which very seldom operate at low speeds. As speed increases, the spray rail pays off and there is noticeable resistance reduction (Fig. 15), which improves at high speeds. Undoubtedly, this positive outcome is the result of the spray being detached from the hull at the bow, as appreciated in Fig. 16, where spray railspray rails effects are displayed for 24 knots.

It must be warned, however, that the beneficial influence of the spray rail is not guaranteed. Initial simulations with other spray rail locations and shapes proved useful to detach the spray from the bow, but very disappointing in their resistance performance, *(Díaz, 2012)*.

Fig 15. Naked hull resistance and with spray railSpray rails

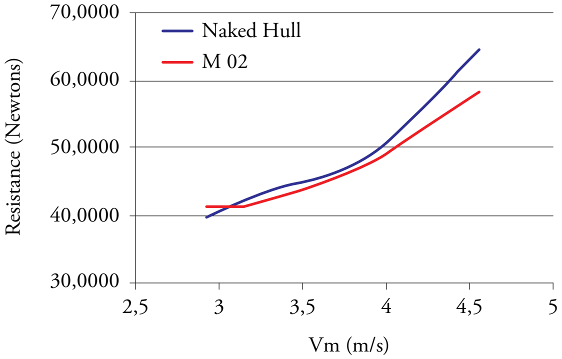
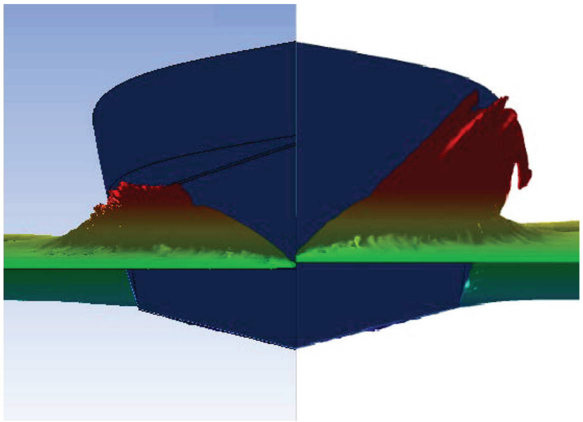


Fig 16. Spray rail effect at 24 knots (left of centerline) and naked hull spray (right) from CFD simulations.



Conclusions

It has been shown that simple appendages like stern flaps, interceptors, and spray rails can produce hydrodynamic effects resulting in reduced forward resistance. For stern flaps and interceptors, the gains arise from the change of the pressure field at the stern; for the spray rail, the reason is evidently the significant reduction of the dynamic wet surface.

Towing tank and CFD results showed good agreement in predicting the potential benefits of the appendages tested; however, some quantitative discrepancy is present in the estimated total resistance, especially at higher speeds.

CFD was proven useful in estimating forward resistance and it was also possible to visualize wave patterns for the stern flaps and interceptor cases, moreover, the spray from the semiplaning hull was also well simulated.

The predicted reduction in forward resistance in all three devices tested is around 5-10%, this is a major potential for fuel saving and in itself merits a careful evaluation of hydrodynamic effects of energy-saving appendages in any prototype being designed.

The scope for improvement is open for large displacement hulls as for small planing hulls, however, due care has to be exercised in selecting the right size and positioning of a hydrodynamic appendage because the wrong size or inconvenient location could result in actually increasing resistance and powering.

A cautious analysis should be performed on the combined use of energy-saving devices; the total result is by no means the addition of each device acting independently. It should be expected that several devices operating simultaneously will surely be interdependent and the total result could be, at the very least, lower than the addition of individual contributions, or plainly detrimental to the overall resistance performance.

Acknowledgements

The stern flap research was sponsored by the Chilean Navy; the author is grateful for the technical and financial support. Several Naval Architecture students from Universidad Austral in Chile collaborated at different stages of the research presented in this paper, namely: Patricio Jimenez, Miguel Ahumada, César del Rio, Jorge Díaz, and Rodrigo Baos were all involved either in the experimental tests or CFD simulations.

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Design based on reliability of naval multilayer fiber composite panels using evolutionary algorithms and stochastic structural mechanics

Diseño basado en confiabilidad de paneles navales fabricados en compuestos reforzados con fibras utilizando algoritmos evolutivos y mecánica estructural estocástica

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Abstract

The complexity of sea wave loads and the number of design variables involved in the design of laminated composites for naval applications makes this a challenging problem. Traditional methodologies for engineering design and analysis are not suitable to deal with these kinds of design problems. This work presents a methodology based on evolutionary algorithms and stochastic structural mechanics to design high-reliability naval multilayer composite structural panels.. The mechanical response of structural panels was modeled by using the Multilayer First Order Shear Deformable Plate Theory and the Finite Element Method. Sea wave loads were modeled as stochastic dynamic loads by using the Simulation Based Reliability Analysis approach. The structural reliability of the panel, as a function of the composite ply's fiber direction, was considered a design variable. In order to maximize the structural reliability, an optimization methodology based on Genetic Algorithms was proposed. For the design process, a computational code using FORTRAN® and the OpenMP® library for parallel computing was developed. The proposed methodology was applied to the design of composite naval panels and results were compared to those obtained through traditional design methodologies. The results show increased reliability of the panels in all cases analyzed. The proposed methodology is, thus, shown as a reliable engineering tool to optimize the structural performance of existing designs.

Key words: naval composite panels, reliability design, simulation-based reliability analysis, genetic algorithms, optimization, finite element method.

Resumen

La complejidad de las cargas de las olas del mar y el número de variables de diseño que intervienen en el diseño de compuestos laminados para aplicaciones navales hacen de éste un problema difícil. Las metodologías tradicionales de ingeniería de diseño y análisis no son adecuadas para tratar este tipo de problemas de diseño. En este trabajo, una metodología basada en algoritmos evolutivos y mecánica estructural estocástica para el diseño de paneles estructurales navales compuestos multicapa de alta confiabilidad, es presentada. La respuesta mecánica de paneles estructurales se modeló usando la teoría de Placa Multicapa Flexible a Cortante de Primer Orden y el Método de los Elementos Finitos. Cargas de las olas de mar se modelaron como cargas dinámicas estocásticas utilizando el enfoque de simulación basado en análisis de confiabilidad. La confiabilidad estructural del panel, en función de la dirección de las fibras de las capas de material compuesto, se consideró como variable de diseño. Con el fin de maximizar la confiabilidad estructural, una metodología de optimización basada en algoritmos genéticos, se propuso. Para el proceso de diseño, un código computacional usando FORTRAN ® y la biblioteca ® OpenMP para la computación paralela se ha desarrollado. La metodología propuesta se aplicó al diseño de los paneles compuestos navales y los resultados se compararon con los obtenidos a través de metodologías de diseño tradicionales. Los resultados muestran un aumento en la confiabilidad de los paneles en todos los casos analizados. El método propuesto se muestra así como una herramienta de ingeniería confiable para optimizar el comportamiento estructural de los diseños existentes.

Palabras claves: indicadores, medición del desempeño, cadena de suministros, lógica difusa, *Balanced Scorecard*, astilleros.

Date Received: October 3rd, 2012 - *Fecha de recepción: 3 de Octubre de 2012*
Date Accepted: March 4th, 2013 - *Fecha de aceptación: 4 de Marzo de 2013*

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Introduction

In recent years, stochastic methods applied to structural design and optimization have gained space because of their robustness and their ability in the search for solutions in complex configuration spaces. This is the case of sea wave loads over naval structures. Likewise, the stochastic nature of mechanical and physical properties of composites require, in many instances, considering them in the design phase.

Composites are increasingly present in naval structural applications. Although their high strength-to-weight ratio represents a very attractive aspect, one of their biggest disadvantages lies on the required ability of the designer to direct the strength and rigidity of the material following the structure's load condition, in such a way that it avails of their mechanical properties *(Soremekin, 1997)*. Thus, by orienting the fibers in each layer of the laminate, a specific design is obtained for a given load set. Thus, performance is not constant along the whole structure, because the areas with higher exposure to high load conditions have better strength and stiffness mechanical properties.

Similarly, the advantages obtained by using composite materials in naval applications are compensated by requiring much more complex structural analysis, where the use of traditional optimization techniques turns out expensive, and in many cases prohibitive, from the point of view of computational costs. Evolutive algorithms are more adequate than traditional optimization techniques for these types of problems because their computational implementation is much simpler.

The present work is framed within the field of structural design, specifically in the determination of the optimal direction of the fibers in a composite laminate plate for naval application, considering in the process the stochastic nature of the sea wave loads. The laminate composite panels are structural elements of broad practical utilization in the design of naval structures, although the complexity of their behavior makes analytical model approximations poorly applicable in practical cases of structural analysis. Thus, to guarantee the safety and functionality of the structures it is necessary to use high design factors. Those design practices tend to yield, as a result, relatively heavy structures.

Using computational tools for structural analysis allows us to overcome this difficulty, but the inclusion of the merit criteria and optimization allow us to go one step further in the quality of the system developed. But impractical tools are equally useless, in spite of how "powerful" they seem to be. Thereby, from the set of possible techniques for simulation and optimization, those considered to allow practical and direct implementation within the context of a design office have been selected.

There are many options at the moment of choosing the merit measurement for a structural design. Among them, the most commonly chosen are minimum weight design, maximum stiffness, or maximum strength. Other alternatives are also possible, like minimization of manufacturing costs, minimization of aero or hydrodynamic resistance, natural resonation frequencies, among others.

This is how the pursuit of the highest strength in a composite laminate panel as a merit criterion in a naval structure is justified by the big impact it has on cargo capacity and optimal strength against sea loads.

Structural Optimization

Formulating the optimal structural design problem is built in terms of numerical optimization. Under these terms, the minimization problem can be stated as follows:

$$\textit{Given a set of parameters } x = \{x_i\} \tag{1}$$

$$\textit{Minimize the function } f(x) \in R \tag{2}$$

$$\textit{Subject to the restrictions } g_j \leq 0 \tag{3}$$

That is, search for the set of parameters x^* which minimizes the objective function $f(x)$. The set of restrictions, as expressed in the form 1c, is the most general because a restriction in the form $g_j \geq 0$ can be expressed as $-g_j \leq 0$, and an equality restriction $g_j = 0$ can be expressed as the pair of restrictions $g_j \leq 0$ and $g_j \geq 0$.

The way in which restrictions are included in the search method seems to be very relevant for its performance. A very elegant and direct way to accomplish this task is the method of the penalty function, as exposed by Parsopoulos and Vrahatis. In this technique, the objective function is augmented with a "penalty" factor $H(x)$, which contains the information from the restriction:

$$F(x) = f(x) + H(x) \tag{4}$$

$$H(x) = \sum \theta(q_i(x)) q_i(x)^{\gamma(q_i(x))} \tag{5}$$

$$q_i(x) = \max\{g_i(x), 0\} \tag{6}$$

The term $q_i(x)$ is known as the relative violation of the restriction i: for a not violated restriction, $q_i=0$, and there is no input to the penalty factor; for a violated restriction $q_i=g_i$ constitutes a "measurement" of the violation and, in this sense, the task of the functions $\theta(q_i)$ and $\gamma(q_i)$ is to control the input from the violation to the penalty factor.

Particle Swarm Optimization

The particle swarm optimization method, introduced by Kennedy and Eberhart (1995), is an optimization technique that can be (weakly) categorized am evolutive strategies and, hence, metaheuristics. The technique was originally conceived to simulate the behavior of bird flocks or fish shoals in their search for food. Given that the distance between each individual and the food position is modeled through a function, it was quickly noticed that any function could be minimized by using the technique.

The idea behind the method is the fact that individuals from the population share certain information, which would be the best position found so far (in general terms, the best merit). Each individual uses this information along with the knowledge of its own best position found to guide its search. If the position of an individual i in the search space is x_i, the best position found so far by the entire population is x^g and the best position found by the individual is x^p_i, the search rule is:

$$v_{ij}^{k+1} = (\omega v_{ij}^{k} + c_1 r_1 (x_j^g - x_{ij}^k) + c_2 r_2 (x_{ij}^p - x_{ij}^k)) \tag{7}$$

$$x_{ij}^{k+1} = x_{ij}^{k} + v_{ij}^{k+1} \tag{8}$$

The vector v_i, from the same class tan the position x_i, is known as the velocity. The parameters ω, c_1 and c_2 are known as inertia, cognition, and confidence because they establish the influence of the current velocity, the distance from the global best, and the distance from the particle best, respectively, over the search rule. Factor x is known as the constriction and its job is to prevent the swarm from exploding by the unbound increment of the velocity. Numbers r_1 and r_2 are randomly chosen from the interval $[0,1]$, each time rule 3 is applied. Index i runs over each individual and index j runs over each dimension in the search space. Superindex k runs on each iteration of the search in which x^g and x^p_i are updated based on the merit given by the objective function.

The search rule is applied iteratively until a convergence criterion is met, the desired optimum is found, or we run out of time.

Structural mechanics reliability analysis

Uncertainty in the analysis and design of naval composite structures has always been recognized. However, traditional approaches simplified the problem by considering the uncertain parameters as deterministic and accounted for the uncertainties by using empirical safety factors. Safety factors are derived based on past experience, but do not absolutely guarantee safety of satisfactory performance *(Haldar and Mahadevan, 2000).* An alternative way to look at the problem is to consider the stochastic nature of the variables involved in the problem, such as strength, geometrical dimensions, etc. In this case, one might measure the probability of failure to satisfy some performance criterion and the corresponding term would be risk and/or failure probability *(Haldar and Mahadevan, 2000).* For this reason, naval design guidelines have recently been revised to incorporate probabilistic analysis (Ayyub et al., 2000). On the other hand, finite element analysis is a very powerful tool commonly used to analyze complicated structures. It yields good results for a set of assumed values of the variables while ignoring the uncertainty in them. However, the reliability methods currently available can still be used if uncertainty in the response can be tracked in terms of the variation of the basic variables at every step of the deterministic analysis. This concept forms the basis of the stochastic finite element method *(Haldar and Mahadevan, 2000)*.

Several methods with various degrees of complexity have been proposed to estimate the probability of failure *(Ditlevsen and Madsen, 2007)*. In any case, estimating the probability of failure using these techniques requires a background in probability and statistics. But with a simple simulation technique, it is possible to calculate the probability of failure without knowing these analytical techniques *(Haldar and Mahadevan, 2000)*.

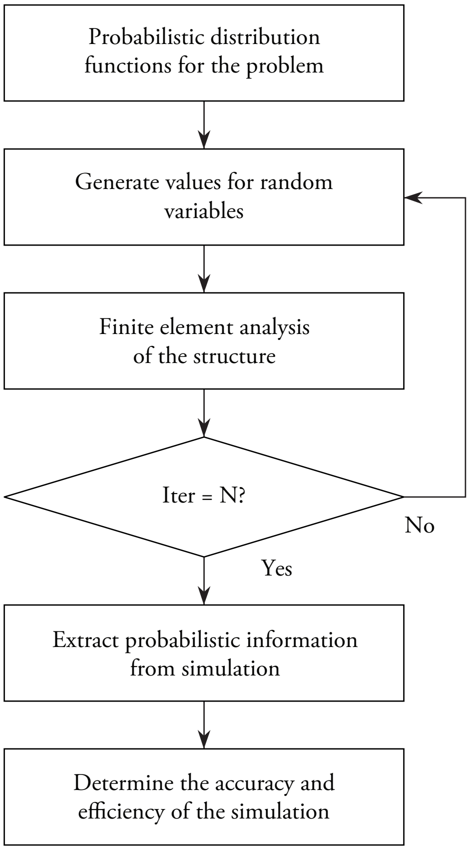
The method commonly used for this purpose is called the Monte Carlo Simulation Technique. This technique has six essential elements: (1) Defining the problem in terms of all the random variables; (2) quantifying the probabilistic characteristics of all the random variables in terms of their probability density functions and the corresponding parameters; (3) generating value for these random variables; (4) evaluating the problem deterministically for each set of generalizations of all the random variables, or simply numerical experimentation: (5) extracting probabilistic information from N such realizations; and (6) determining the accuracy and efficiency of the simulation *(Haldar and Mahadevan, 2000)*. Fig. 1 presents the general procedure used in the finite element stochastic structure.

Composite materials and failure theory

Composites have one or more discontinuous phases (fibers) embedded in a continuous phase (matrix). The basic element is a composite layer, which coupled to the other forms a laminated structure. Each layer is reinforced by fibers having a given unidirectional orientation (composites) or may have random orientations (random composites). Compared to isotropic materials, composite materials have a much more complex mechanical behaviour due to their anisotropic nature, which means that a greater number of elastic constants for characterizing their behaviour is required *(Kollár, 2003)*.

The First-Order Shear Deformation theory–(FSDT) is an extension of the Kirchhoff-Love theory of laminated plates, where the shear strain is considered in the transverse lamina *(Reedy, 2004)*. This allows taking into account failure by delaminating at the panel.

Fig. 1. Stochastic finite element analysis flowchart



Moreover, one of the most commonly used criteria for failure is the Tsai-Hill composites criterion, based on the failure criteria for anisotropic materials proposed and adapted for failure analysis composites.

This criterion establishes that the orthotropic sheet subjected to plane strain state occurs when:

$$f = \frac{\sigma_{11}^2}{X^2} + \frac{\sigma_{22}^2}{Y^2} + \frac{\sigma_{11}\sigma_{22}}{XY} + \frac{\tau_{12}^2}{S^2} + \frac{\tau_{13}^2}{S^2} + \frac{\tau_{23}^2}{T^2} \quad (9)$$

Where f is known as failure index, σ_{11}, σ_{22}, τ_{12}, τ_{32} and τ_{13} represents components of the normal stresses and shear in the plane 1-2, with respect to the material principal axes; X, Y and S and T represent the normal, transverse and shear failure stress, respectively.

Stochastic optimization methodology

The pressure distribution on the panel is a function that depends on the space and time variables. This pressure distribution can be obtained directly from experimental data, such as those achieved by the Orca type boat *(Useche et al., 2010)* or through computer models. In general, pressure distribution on the panel can be expressed mathematically through a function of the type:

$$P(x,y,t) = H(t)\, X(x,y) \quad (10)$$

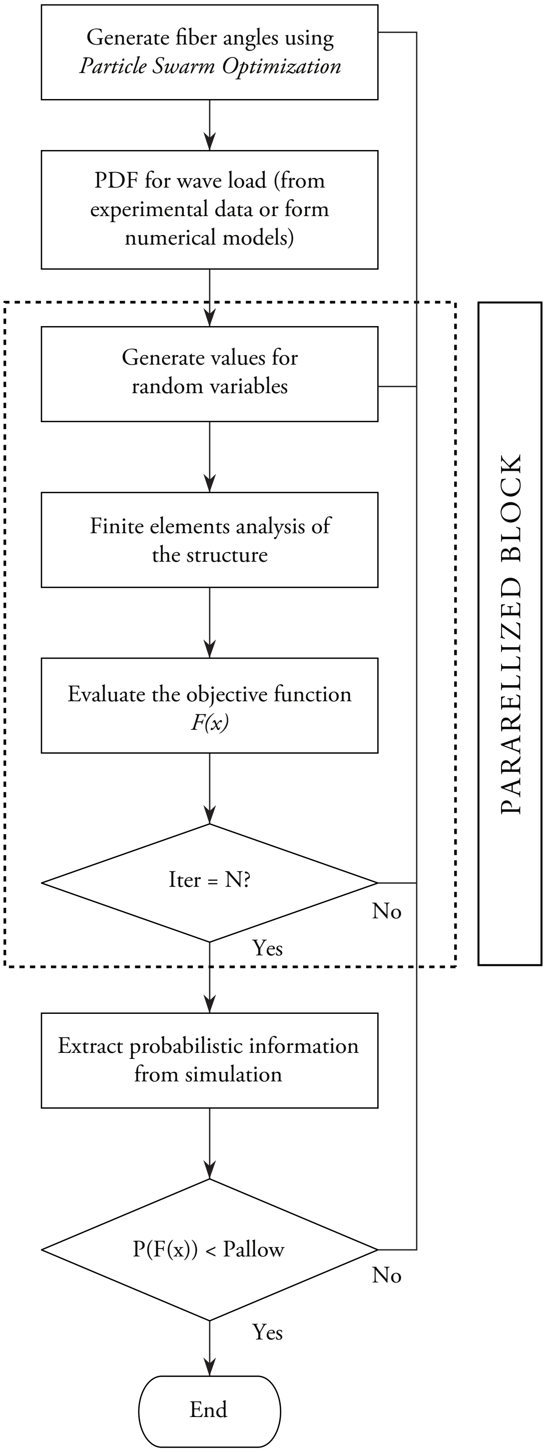
Where $H(t)$ is a time-dependent function and $X(x,y)$ a function that represents the spatial distribution of the pressure. In this paper, function $H(t)$ is described as:

$$H(t) = P_{max}(t/\alpha)^n e^{-\frac{t}{\theta}} \quad (11)$$

Where P_{max} represents the maximum pressure and α, θ, n are fitting constants determined experimentally.

The Stochastic design methodology used is presented in the flowchart shown in Fig. 2. The finite element model was developed by using the software for static and dynamic analysis of structures (FEASY/STD v4.0®) *(Useche, 2008)*. This program was incorporated as an external subroutine in a more general program developed in Python® language programming. This methodology was implemented by using parallel programming through Message Passing Interface (MPI). The module that implements the optimization methodology was developed by Giraldo (2010). Finally, the models were run at the High-Performance Computing Laboratory (HPCLAB) at Universidad Tecnológica de Bolívar.

Fig. 2. Stochastic optimization methodology flowchart



Conclusions

A methodology was presented to optimize laminated composite naval panels made by using genetic algorithms, stochastic mechanics, and the finite element method. Through minimizing the probabilistic failure criteria of the panel in function of the direction of the fibers in the laminate, it is possible to find designs with high resistance to sea loads for a given system.

Acknowledgements

The authors are grateful to the High Performance Computing Lab of the Universidad Tecnológica de Bolívar for supporting this research work.

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Generation of Three-Dimensional Image of Objects Submerged in Murky Water

Generación de imagen tridimensional de objetos sumergidos en aguas turbias

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Abstract

This article presents the design and implementation of a novel method to generate 3D coordinates from the projection of a laser line over a solid object and the processing of the images obtained during scanning. The result obtained is a 3D model of an isometric view that provides the possibility of being seen from different perspectives under a virtual environment. The methodology is applied in the capture and reconstruction of 3D images of objects submerged in murky waters.

Key words: three-dimensional digitizing, triangulation, thresholding, skelotonization, rendering

Resumen

Este artículo presenta el diseño e implementación de un novedoso método para generar coordenadas tridimensionales a partir de la proyección de una línea láser sobre un objeto sólido y el procesamiento de las imágenes obtenidas durante el escaneo. El resultado obtenido es un modelo tridimensional de una vista isométrica que brinda la posibilidad de ser visto desde diferentes perspectivas bajo un ambiente virtual. La metodología es aplicada en la captura y reconstrucción de imágenes tridimensionales de objetos sumergidos en aguas turbias.

Palabras claves: digitalización tridimensional, triangulación, umbralización, esqueletización, renderización.

Date Received: December 13th, 2012 - *Fecha de recepción: 13 de Diciembre de 2012*
Date Accepted: March 4th, 2013 - *Fecha de aceptación: 4 de Marzo de 2013*

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Introduction

One of the main objectives of underwater vehicles is to navigate and inspect underwater environments autonomously. To improve the performance of those tasks, the vehicle must have efficient systems to collect and process information from the environment, which it receives through different types of sensors. Sonar is fundamental in this process and provides high-resolution images of the submarine scene; however, those images are not easy to process automatically and are generally accompanied by significant levels of noise.

Some underwater vehicles used for ship hull inspection, like the Hovering Autonomous Underwater Vehicles (HAUV), have Doppler Velocity Log (DVL) recorders to accomplish adequate control and navigation parallel to the hull; however, the DVL cannot be used to navigate and inspect in complex regions, like the propellers or rudder, which require the use of sonar and which is also used to construct 3D images from the data collected *(Dema, 2006)*.

One of the most important developments worldwide has been the HAUV, which was designed and constructed jointly by Bluefin Robotics and MIT *(Vaganay, 2006a; 2006b)*. The HAUV employs a Doppler velocity log-type sensor for control and navigation parallel to the hull line that also permits maintaining the sonar within the estimated operation range without external aid and without the need to previously prepare the ship's surface.

Seebyte Ltd., located in Edinburgh, Scotland, made an important modification to the HAUV by adding a Dual Frequency Identification Sonar (DIDSON) *(Reed et al., 2006)*. The fusion of the information from the DVL and the DIDSON permitted, through complex algorithms, reconstructing 3D images from complex zones like the propeller and rudder.

Another important development has been the ship hull automatic inspection system designed and constructed by Desert Star Systems, which it has denominated AquaMap (2006) and consists of an acoustic positioning system that generates a two dimensional image of the ship's hull. The AquaMap does not have an automatic positioning system; rather, it requires for its operation four guide lines placed on the ship's lowest side to serve as reference points.

To generate 3D images of the ship's hull, information from consecutive sonar needs to be processed through complex algorithms that permit eliminating errors due to image noise. Other techniques do not use sonar and focus on maintaining the camera viewing angle parallel to the surface of the ship hull by using laser pointers, controlled inclination platforms, and Cartesian platforms. These use laser triangulation techniques to improve precision *(Caccia, 2007; Zainal, 2007)*.

Digitizing 3D Images

The fundamental aspect of implementing digitizing systems lies on the possibility of reproducing geometries of existing objects. This is especially useful in complex objects in terms of their shapes, contours, and profiles.

Distinct 3D digitizing systems exist, which can be mainly divided into two big groups: digitizing through contact and digitizing without contact. The main advantage of 3D digitizers without contact is that they have a higher rate of data acquisition than digitizers with contact. We can divide the digitizing techniques without contact into two: the stereoscopic or passive vision methods, where the scene being analyzed is not interfered; and active vision methods, where some type of action is undertaken on the scene, whether it is through its illumination or by sending an energy beam *(Montalvo, 2010)*.

The active vision technique was selected because these systems only require a light emitter (laser) and a receptor (camera) to obtain x, y, and z coordinates of each point of the object to reconstruct. The technique consists in that knowing the direction of the beam emitted and that of the beam received, the dimensions of the triangle are obtained and, hence, the depth of the point inspected. The following elements were used to apply the technique elected:

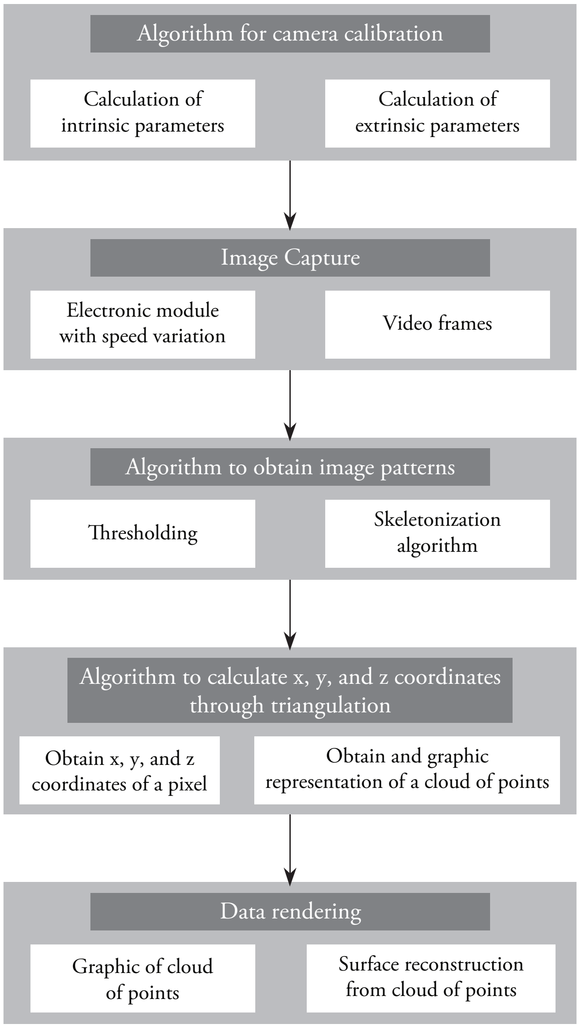
- High-resolution color TV submarine camera (600 TVL): 600-line horizontal resolution; effective pixels: PAL 795x596; minimum illumination of 0.00035 lux; 66° angle coverage; power: 12 Vdc/80 mA; video connection: 1 BNC 1Vp-p (75 ohm); operational depth: 200 m.
- Line generating laser: 532-nm wavelength; A/R coated crystal lens (adjustable focus); 1.4-mrad divergence; 65-mm length; 16-mm diameter.

Using a line generating laser permitted obtaining a large amount of pixels representative of the profile to reconstruct in a single take. If a pointer laser had been used, it would have to be projected a great many times to obtain this same information. This technique used permitted the calculation of the position (x, y, and z coordinates) of each pixel to be processed in parallel manner for a single image, thus, reducing image processing times.

Reconstruction of 3D Images

The following describes the steps taken for reconstruction of 3D images in murky waters (see Fig. 1.)

Fig. 1. Steps for reconstruction of 3D images in murky waters



Camera calibration

It is a procedure that permits determining how a camera projects an object from the real world on the image plane to, thus, extract length information from that image. Calibrating a camera consists in obtaining its intrinsic and extrinsic parameters by using photographs or video frames taken by said camera. These parameters define the image formation conditions. The intrinsic parameters are those related to the camera (internal and optical geometry), these are: Focal distance, Coordinates of the center of the image or principal point, pixel-millimeter conversion factor, effective size of the pixel in horizontal and vertical direction (in millimeters), lens distortion coefficients. Extrinsic parameters relate the real-world reference systems and the camera describing the position and orientation of the camera in the real world's coordinate system; these are: Translation Vector and Rotation Matrix.

For the camera calibration the Python open-code interpreted programming language and the OpenCV Artificial Vision library were used. This library has defined functions that permit calibrating the cameras by using the Pin-hole calibration model.

The vast majority of the calibration procedures are based on this model (pin-hole camera model), which is the simplest model that can be obtained from a camera; hence, it needs the least number of parameters to be represented. It is based on that the projection of a point from the scene is obtained from the intersection of a line passing through this point and the center of projection (focus) with the image plane. Basically, this model applies a projection matrix to transform the 3D coordinates of the points of the object in 2D coordinates of the image:

$$\lambda m = P^{*}M \qquad (1)$$

Where $M=[Xw,Yw,Zw,1]^t$ is the vector containing the coordinates of the point in the reference system external to the camera, P is a 3x4 matrix denominated projection matrix, $m=[u,v,1]^t$ is the vector of the coordinates of the point projected on the image and transformed into pixels. Term λ is a scaling factor that indicates that the elements of both sides are equivalent except for a proportionality factor.

In OpenCV this model is represented mathematically, as shown by the following:

$$sm' = A[R|t]M' \qquad (2)$$

or

$$\begin{bmatrix} u \\ v \\ i \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \qquad (3)$$

Where the $[X,Y,Z,1]$ vector contains the coordinates of the point in the reference system external to the camera (real world), the $[u,v,1]$ vector contains the coordinates of the point projected on the image and transformed into pixels. A is called the matrix of intrinsic parameters, (c_x,c_y) is the principal point (which is usually the center of the image), (f_x,f_y) are the focal distances expressed in pixel- unit. $[R|t|]$ is called the matrix of extrinsic parameters. It is used to describe the movement of a camera around a static scene or to describe the movement of a rigid object around a fixed camera.

The function used for the camera calibration is called CalibrateCamera. This function receives as input parameters the object's real-world points, the points from the image (which are the points from the object projected on the camera view), the number of points in each particular view, and the image size. It receives as output parameters an initialized 3x3 matrix that will store the values corresponding to the camera's intrinsic parameters, an initialized vector to store the values corresponding to distortion coefficients, an initialized matrix that will store the values corresponding to the rotation extrinsic parameters, and an initialized vector that will store the values corresponding to the translation extrinsic parameters.

The following steps were carried out for the calibration:

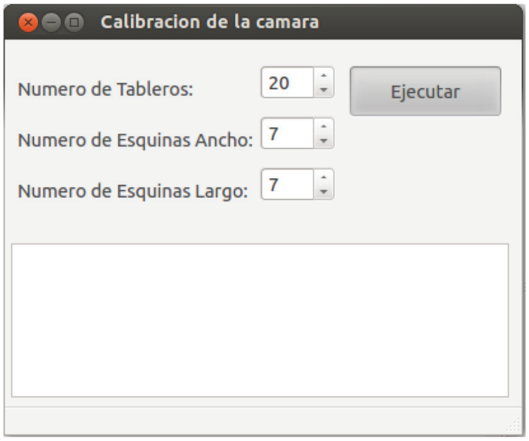
- A black and white, 8x8 square chess board was elaborated. More precise values will be obtained by increasing the size of these squares. It must be guaranteed that the corners of these squares are well-defined to avoid erroneous values.
- The code was created (in this case in Python), which permits using the chess board as system input and the camera's intrinsic and extrinsic parameters as output. The following steps were taken to create the code:
- The variables were defined for the width and length of the chess board. The board size is the width by the length.
- The OpenCV function was used, called FindChessboardCorners() that passes as parameters, image (chess board), size of the image, and the number of internal corners of the chess board, will permit finding the values of the coordinates of said corners and return those values in a vector.
- With that returned by the FindChessboardCorners() function the DrawChessboardCorners() function was used. This function should be used because it permits drawing on the screen the coordinates of the internal corners of the chess board and, thus verify graphically that said coordinates have been correctly calculated. To carry out a good calibration, it is necessary to use several photographs of the camera's video frame.

- With the matrix full of the values that represent the coordinates of the internal corners of the chess board the CalibrateCamera2() function was used. This function returns the values of the camera's intrinsic and extrinsic parameters.

Upon obtaining the intrinsic and extrinsic parameters (camera is calibrated) we can represent any point from the real world on the 2D plane of a camera, which turns out quite useful for vision applications like "augmented reality".

For the calibration process to be more dynamic, a single interface was generated – as shown by the following:

Fig. 2. Interface generated for camera calibration



Numero de Tableros: 20
Numero de Esquinas Ancho: 7
Numero de Esquinas Largo: 7

The number of boards defines the amount of images to take from the chess board to use in the calibration process. A value above 15 images is recommended.

The number of corner widths is defined by the number of squares from the first row-1, which is because the board's internal corners are counted.

The number of corner widths is defined by the number of squares from the first column-1, which is because the board's internal corners are counted.

Image capture

An algorithm was created to obtain a set of images of object to reconstruct. The number of captures will depend on the time it takes the underwater vehicle to rove the object. It is fundamental for the speed to be constant to obtain the same amount of images over time, a variation of speed will cause acquiring more or less photographs of the laser's deformation over the object at some moment, which is why upon reconstructing the images we would have sections with a higher or lower level of pixels. Another condition that must also be guaranteed is that the scan is always done at the same distance (distance between the object to reconstruct and the mechanism that displaces the laser camera system), given that a variation of the scanning system will cause a detection of a change in the depth of the object, obtaining erroneous results.

Obtaining image patterns

This is one of the most complex and important activities within the project. It starts from the frames obtained in the previous activity and image processing is carried out to only show the laser's deformed line over the image, to then manage – through another algorithm – to slim down the line until it is one-pixel wide; the importance lies in that the pixels remaining must be the most representative of the image to avoid losing image details.

Thresholding

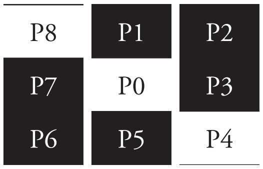
This is a simple process performed over the image with an already designed OpenCv function. It simply consists in leaving the pixels of the image that have luminosity above a threshold; this permits filtering noise and background images.

Skeletonization algorithm

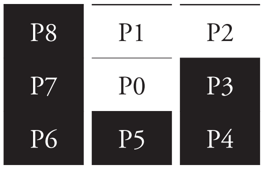
Skeletonization seeks to obtain from the image a continuous pattern that contains the least possible amount of data, but which still contains a trait of the original object. For this, algorithms exist that operate in general manner by eliminating pixels under pre-defined rules, and stopping when no other changes need to be made. It must be considered that processing time is often high, but it generally depends on the type of algorithm and on the size of the photograph (*Calyecac, 2009)*. To develop this algorithm the Zhang – Suen technique was used. This algorithm uses the eight-neighbor technique. For this, we must consider a 3x3 mask and preferably number the internal pixels in the following manner:

P8	P1	P2
P7	P0	P3
P6	P5	P4

The conditions mentioned initially require defining two basic functions. We have function *A(p)*, which represents the number of times pattern *0,1* is repeated in the sequence of matrix points, taken from point *p2* to *p2* itself, in hourly manner. In other words, we would have to count the number of times the pattern *0,1* is repeated in *p1, p2, p3, p4, p5, p6, p7, p8, p1*. Additionally, we have function *B(p)*, which is defined as the number of pixels 1 around the central pixel. The following example will permit better conceiving the functions.



B(p0)=2, A(p0)=2



B(p0)=2, A(p0)=1

Upon determining the functions mentioned, the mask must be passed throughout the image, and the central pixel below the mask will be changed to the background color, if it complies with the following conditions:

For the first sub-iteration	For the second sub-iteration
1. 2 <= B(p0) <= 6	5. 2 <= B(p0) <= 6
2. A(p0) = 1	6. A(p0) = 1
3. p1.p3.p5=0	7. p1.p3.p7=0
4. p3.p5.p7=0	8. p1.p5.p7=0

To better understand the algorithm, it is necessary to understand the meaning of the conditions mentioned.

Condition 1: 2 <= B(p1) <= 6

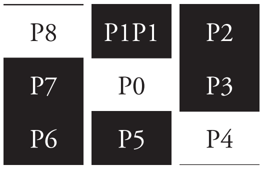
This condition combines two sub-conditions; first, the number of *p0* neighbors different from zero is higher or equal to two, and secondly that this amount is lower or equal to six. The first condition ensures that no final pixel point, which is not isolated, is eliminated. A final pixel point is any pixel that has as neighbor a pixel in the color of the object. The second condition ensures that said pixel is a pixel on the border. The following shed clarity on this matter.

B(p1)=1 B(P1)=0 B(p1)=7

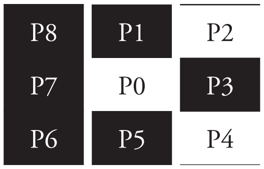
Herein, we can appreciate that if *B(p0) = 1*, then *p0* is a final point pixel, and it is additionally a point of the skeleton; thereby, it should not be erased. The following block shows that since *B(p0) = 0*, the point is an isolated point, which represents a type of noise, but this algorithm is not in charge of eliminating it. In the third block, shows that because *B(p0) = 7*, *p0* is not a border pixel; hence, it should not be eliminated.

Condition 2: A(p1)=1

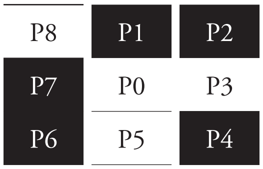
This condition represents a connectivity test. In fact, if we consider the following figures where *A(p0) > 1*, it can be noted that if pixel *p0* is eliminated, the skeleton would be disconnected.



A(p1) = 2



A(p1) = 2



A(p1) = 3

Condition 3, 4, 5, 6:

Through these conditions, we ensure that the points to be erased belong to the southeast border and on the northwest corner, for the first iteration; and for the second those of the northeast borders and south east corner, thus, validating that said points will not belong to the skeleton.

		North		
	P8	P1	P2	
West	P7	P0	P3	East
	P6	P5	P4	
		South		

Algorithm to calculate the x, y, and z coordinates through triangulation

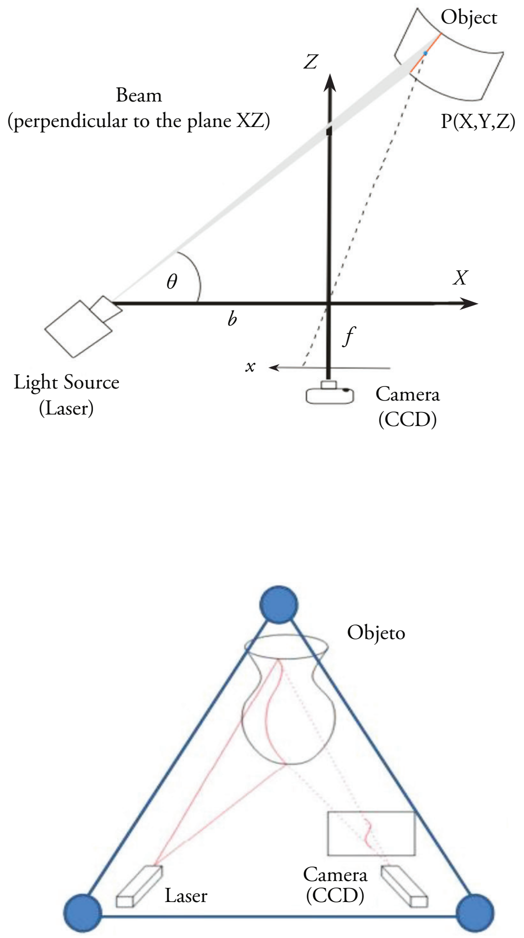
Upon obtaining all the skeletonized images with the algorithm designed, we proceeded to calculate the location of each pixel in space. To accomplish this, it was necessary to develop an algorithm that based on the triangulation theory would obtain the values of each *(x, y, z)* coordinate. To apply the triangulation technique, data from the camera calibration must be used, along with data from the motion in taking each image, the angle of the laser location to form the triangle, and the distance between the camera and the laser.

Triangulation algorithm

When all the images were skeletonized, we proceeded to calculate the location of each pixel in space. To accomplish this, it was necessary to develop an algorithm that based on the triangulation theory would obtain the values of each *(x, y, z)* coordinate. To apply the triangulation technique, data from the camera calibration must be used, along with data from the motion in taking each image, the angle of the laser location to form the triangle, and the distance between the camera and the laser.

The method used in this project determines the *(x, y, z)* coordinates of a point of the object (pixel) by using the position of the point obtained in the perspectives of two projections given, as observed in Fig. 3. This method seeks to calculate the distance from the camera to each pixel from the known angles *(θ)* that determines the laser inclination, the distance *(b)* between the laser and the camera, and the camera's lens focal length *(f)* found with the camera calibration *(Calyecac, 2009)*.

Fig. 3. Triangulation principle



By applying trigonometric properties described elsewhere (*Calyecac, 2009*), and from known parameters, positions *[X, Y, Z]* can be determined for each pixel (positions in space) of the skeletonized image through the following equation:

$$\begin{bmatrix}X\\Y\\Z\end{bmatrix} = \frac{b}{f(\cot\theta)\,x}\begin{bmatrix}x\\y\\f\end{bmatrix} \qquad (4)$$

Thus, the algorithm should run each white pixel and find its spatial coordinates based on the previous equation. However, imagine the amount of pixels per image multiplied by the number of frames; this would be a figure in the thousands or millions of pixels. For this reason, it was necessary to optimize the algorithm so that it works with parallel processes, managing to reduce the time in a 10:1 scale.

Obtaining and graphic representation of the cloud of points

A cloud of points is formed by a set of vertices in a 3D coordinate system. To obtain the cloud of points a list of three parameters *(N x 3)* was created for each image, where *N* is the number of pixels the skeletonized image contains and *3* the values corresponding to the *x, y,* and *z* coordinates, that is, there will be as many lists as the number of image captures made.

These lists must have a format that can be understood by the tool in which the points will be visualized; this project used the Meshlab tool. MeshLab is an open-code, free-access tool to process and edit clouds of points in two and three dimensions. It permits rotating the image to see the depth of the points and the position in space.

The system is mainly based on the VCG library developed in the ISTI-CNR Visual Computational Laboratory in Italy, available for Windows, MacOSX, and Linux. This tool loads the clouds of points from flat files with .py extension, which is why the algorithm constructed delivers the clouds of points of each graphic in this format and the tool permits loading simultaneously the .py files from all the images.

Graphic of cloud of points

It is the fundamental part of the reconstruction and seeks to convert a set of given points into a consistent polygonal model (meshes). Input data are always a set of pixels *P* in *R 3*. This set of input data is also called disorganized cloud point.

To conduct rendering, it was first necessary to obtain the cloud of points, as explained in section and load these images onto the Meshlab tool; this document omits the procedure because it is aimed at results.

Surface reconstruction from a cloud of points

The goal of surface reconstruction is described in the following manner; given a set of points *P* supported on or near an unknown surface *S*, the model is created of surface *S'* approaching *S*. A surface reconstruction procedure does not guarantee exact recovery of *S*, given that we have information of *S* only through a finite set of points. Whenever the density of the set of points is higher, output *S'* will be more topologically correct and closer to the original *S* surface.

Surface reconstruction is a difficult task; in principle, because the points measured from the sample set can have noise by the laser reflecting on another point of the image. Also, the surface can be arbitrary with unknown topological types and punctual traits.

Reconstruction of 3D Image

For specific application in murky waters, tests were performed in the facilities of the *Escuela Naval Almirante Padilla (ENAP)*, creating conditions of poor visibility similar to those in the bay of Cartagena. Fig. 4 illustrates the ROV in the laboratory and Fig. 5 shows it in tests in the pool.

Fig. 4. ROV in the Automatic Control laboratory at the ENAP

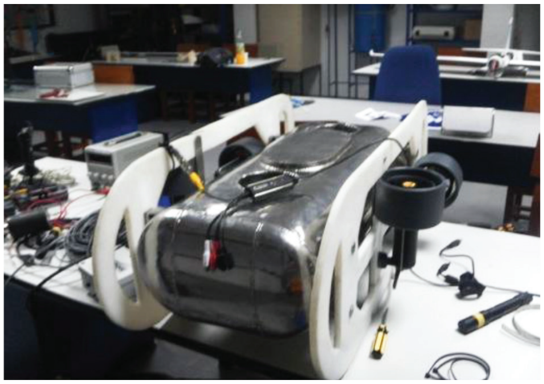


Fig. 5. ROV navigation tests in the pool at the ENAP

Fig. 6. Prototype of original ship

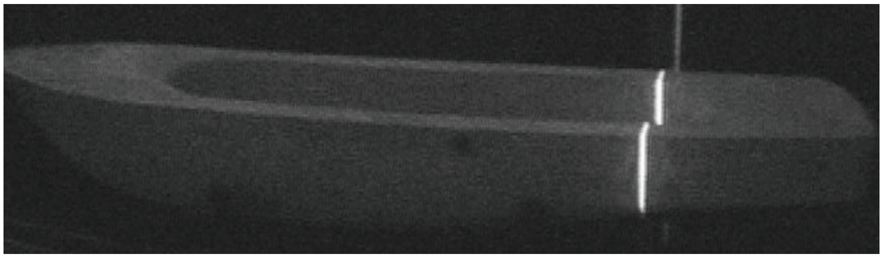
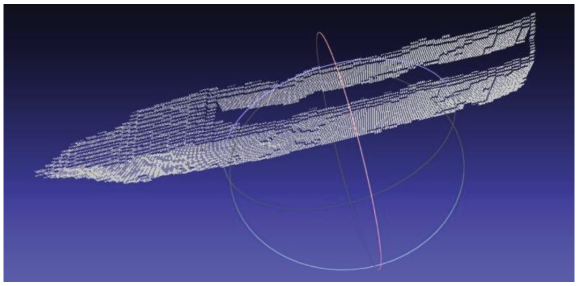


Fig. 7. Frames of the prototype ship of the ship from the naval school

Fig. 6 illustrates a ship scale model used to perform the image reconstruction tests.

As observed in Fig. 8, the ship scale is reconstructed with all its details, results that constitute a big accomplishment because it is a low-cost method without contact that permits obtaining a 3D reconstruction of an isometric view of the object, under conditions of limited visibility.

Fig. 8. Ship scale model reconstructed and changing position in Meshlab



Figs. 9 and 10 show the skeletonization process of the hull of a ship model shown in Fig. 6.

Fig. 9. Hull of a ship scale model

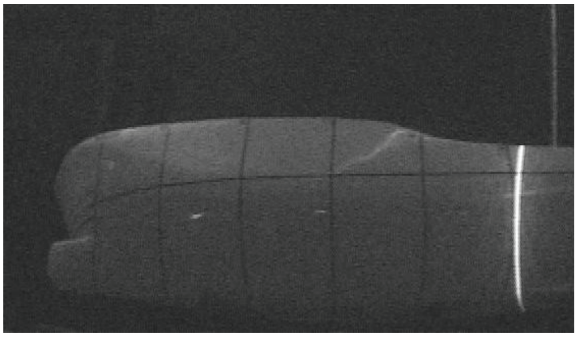


Fig. 10. Skeletonization process of the ship's hull shown in Fig. 9

Conclusions

A methodology was presented for reconstruction of 3D images in murky waters or of poor visibility employing a high-resolution submarine camera and line laser. The method presents five steps: camera calibration, image capture, obtaining image patterns, triangulation and rendering. The methodology was applied to reconstruct a ship scale model, obtaining good results.

The methodology presents two important requirements for its effective application: constant speed and distance of the vehicle transporting the camera with respect to the object sought to capture and reconstruct its 3D image.

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Analysis of most frequent cases of vibration in propulsion systems

Análisis de casos más frecuentes de vibraciones en sistemas de propulsión

Franklin Jhonny Domínguez Ruíz [1]

Abstract

This study is a review of cases of propulsion systems in which noise, vibration, or fracture problems have existed. Case studies are presented on passenger vessels, tugboats, tankers, and ferry boats. Each case is addressed based on lateral, torsional, axial vibration analysis, as well as the case analysis of the possible coupling of frequencies or possible defect or deterioration of a component. Based on the cases, a summary is presented of inertial masses of each system analyzed to establish possible problems and benchmark statistical considerations when selecting the components of a propulsion system. Calculations were performed using the ShaftDesigner software from Machine Support, Holland and Torcal software from Tecnavin S. A.

Key words: vibration, torsional, lateral, noise, fracture, propulsion

Resumen

El presente estudio constituye una revisión de casos de Sistemas de Propulsión, en los que se han presentado problemas de ruido, vibraciones, fracturas. Los casos de estudio son presentados en naves de pasajeros, remolcadores, tanqueros, lanchas ferry. El abordaje de cada caso se presenta basado en el análisis de vibraciones, laterales, torsionales, axiales, según sea el caso, análisis del posible acoplamiento de frecuencias o posible defecto o deterioro de algún componente o defecto de construcción. En base a los casos presentados, se presenta un resumen de masas inerciales de cada sistema analizado, para establecer, estadística referencial de problemas y posibles consideraciones al momento de seleccionar los componentes de un Sistema de Propulsión. Los cálculos son realizados usando el software ShaftDesigner de Machine Support, Holanda y Torcal de Tecnavin S. A.

Palabras claves: vibración, torsional, lateral, ruido, fractura, propulsión

Date Received: October 20th, 2012 - *Fecha de recepción: 20 de Octubre de 2012*
Date Accepted: April 2nd, 2013 - *Fecha de aceptación: 2 de Abril de 2013*

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Introduction

Frequently, noise and vibration problems occur in propulsion systems. Because of this, this study presents analyses of cases of problems that have been solved, as well as the example of a propulsion system without any type of inconvenience.

At the end, we present a statistical analysis of the percentage of principal inertial masses that participate in each model to have as reference when defining a propulsion system.

This study does not seek to become a publication with formulations; rather, it seeks to share experience developed in propulsion systems.

General components of a propulsion system

The main components of a propulsion system to be considered in this analysis are as as shown in Fig. 1.

Lateral vibrations in the propulsion system

Lateral vibrations in a propulsion line can be caused by: the gyroscopic effect of the propeller, thrust imbalance, inadequate distance between supports or lack of rigidity in bedplates and/or buttresses.

When these vibrations occur in a propulsion system, they can cause fracture, failure in system components or on the ship's structure, producing:

- Complete destruction of the propulsion system;
- Reduction of the service life of shafts and/or their components;
- Fatigue fracture on support brackets and/or engine mountings;
- Increased seal wear and damage;
- Excessive noise, vibrations on the hull and superstructure.

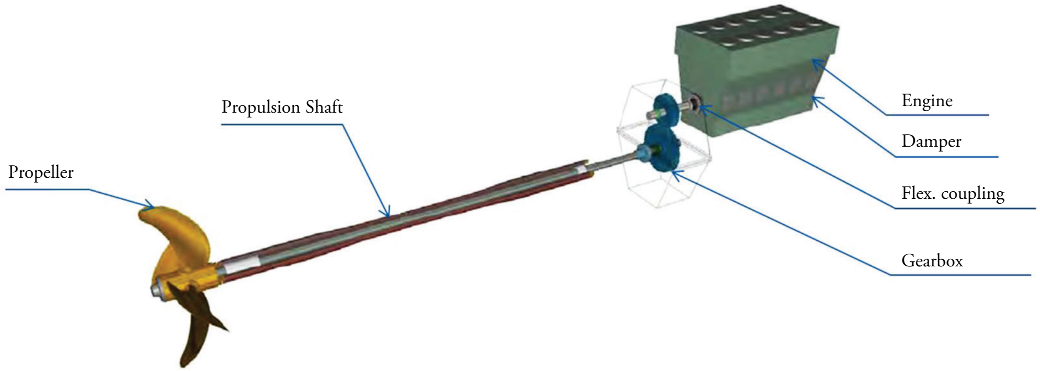
The natural frequency of lateral vibrations and critical frequencies of the system were calculated through the Finite Elements method, considering the following terms of reference:

- The bocin support center close to the propeller, taken from a distance of one shaft diameter, measured from the aft end of the bocin support, close to the propeller;
- The center of support for the other bearings was taken at the center of the length of the bocin support;
- The propeller inertial mass was calculated through integration of radial sections;
- The propeller added mass was estimated using the methodology proposed by Parsons M.G. et al., (1980) and with the aid of the PRAMAD software.
- Modeling of the line was considered up to include the thrust bearing.

Torsional vibration in a propulsion line

Torsional vibrations in a propulsion system can be produced by any of these possible causes:

Fig. 1. Typical Propulsion System - Shafdesigner



- Aging of the frontal damper,
- Misfiring of a cylinder,
- Inadequate flexible coupling,
- Excess diameter in the propulsion line, among others.

The excitations most frequently used in torsional analysis are generated by the propeller and the internal combustion engine.

- For propeller excitations, the Classification Societies recommend values in percentages of propeller torque.
- For propeller engine excitations; normally, this information is provided by engine manufacturers. If this information is missing, we may use the harmonic tangential components provided by Lloyd's Register.

Torsional vibrations occurring in a propulsion system can cause fracture, failure in system components, gear damage, premature destruction of flexible couplings.

Frequently, fractures in shafts or crankshafts, due to torsional effect, occur in 45° direction.

The methodology to model a propeller system for torsional analysis is based on the equation:

$$[I]\ddot{\theta} + [C]\dot{\theta} + [K]\theta = [F(t)] \qquad (1)$$

Where *[I], [C], [K], [F (t)]*, are the inertial mass matrices, damping, stiffness, and excitation, respectively.

The natural frequencies of torsional vibrations and the responses of the forced analysis of the system were calculated through the matrix solution method, considering the following terms of reference:

- Include the frontal damper with its inertia, stiffness, and relative damping;
- Include inertial mass and cylinder absolute damper, crankshaft stiffness;
- Include the flexible coupling with its inertial mass, stiffness, relative damping, and energy dissipation limit;
- Include the gearbox with its inertial mass, stiffness, diameters, stiffness of gear teeth. Avoid synthesizing the gearbox branches;
- Propulsion shafts: Add as much inertial mass as necessary in case of section changes.

The precision of the calculations of system response will depend on the reliability of the input data, which is why it is recommended to request information on inertial mass, stiffness, and damping from the equipment manufacturers.

For the added mass and the propeller damping, the methodology proposed by Parsons M.G. et al., (1980) and the PRAMAD software were used.

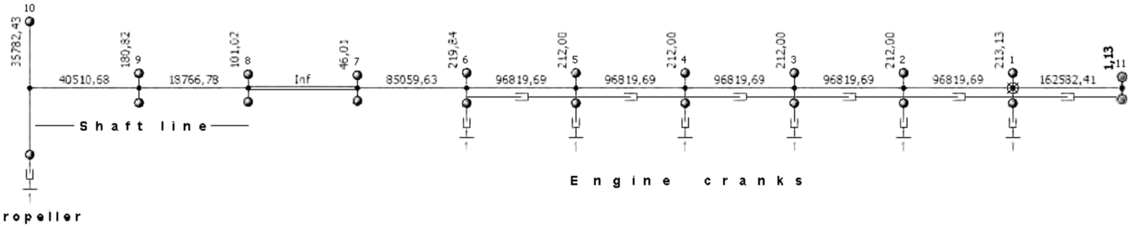
Fig. 2 presents a model example of inertial mass without branches.

Vibration analysis in a propulsion line

The vibrations in a propulsion system can be caused by lateral, torsional, axial effect or by its possible frequency couplings.

Adequate configuration of elements of a propulsion system, separation of supports, stiffness of

Fig. 2. Propulsion System Torsional Mass diagram



supports and/or struts must be conducted taking into consideration the recommendations of Classification Societies and the manufacturers of the system's components.

In the cases shown ahead, frequencies were calculated in the three orientations: lateral, torsional, and axial, to after that verify the possible coupling of frequencies of the system with the structure.

The case studies analyzed in this study are as indicated:

1. Inadequate selection of the flexible coupling on a tanker
2. Change of propeller on a tanker
3. Inadequate separation of supports on a passenger ship
4. Alteration of the distance between supports on a tugboat
5. Restriction in the operation range on a yacht
6. Inadequate stiffness in struts and inadequate separation of supports
7. Inadequate selection of flexible coupling and diameter of propeller shaft in fishing vessel
8. Example of a propulsion system without vibration problems

Case study 1: Inadequate selection of flexible coupling on a tanker

Type: Tanker
Length: 103.35 m
Engine: 1300 KW MCR
RPM: 500
Propeller: CPP

This case was analyzed by request of re-engining. Frequency analysis was carried out for lateral and torsional vibrations.

Through analysis, it was found that the flexible coupling is sub-dimensioned, which is why we recommend:

- Changing the flexible coupling according to the system's needs;
- Operating the system in restricted manner until the flexible coupling mentioned can be replaced.
- Diminish the power developed by the controllable pitch propeller, under conditions of misfiring.

Fig. 3. Tanker 1. Propulsion System Representation

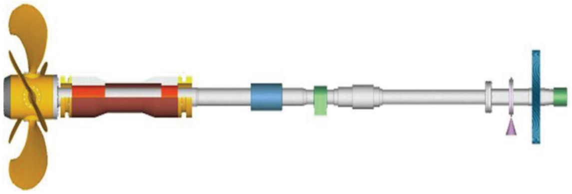
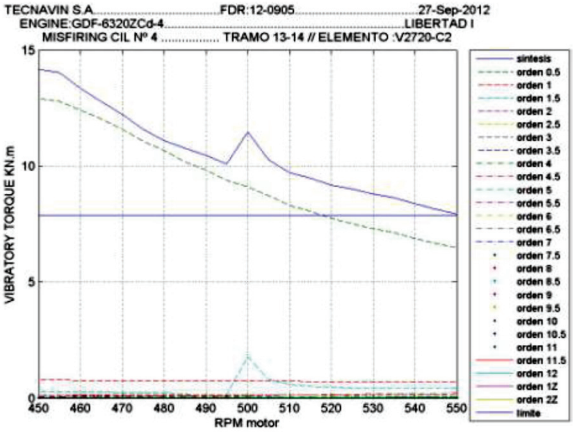


Fig. 4. Tanker 1. coupling vibratory torque graph at missfiring of cylinder Nº4



Case study 2: Change propeller on a tanker

Type: Tanker
Length: 120.55 m
Engine: 2574 KW MCR
RPM: 200 - 620
Propeller: FPP

This case was analyzed by request of change of heavier propeller.

The original propeller presented cracks and section detachment in several blades.

Frequency analysis was carried out for lateral and torsional vibrations.

Analysis revealed that by maintaining the system's original components, with the new propeller, the range of operation under conditions of misfiring of a cylinder would be restricted from 200 to 417 rpm.

Fig. 5. Tanker 1, Propulsion system torsional mass diagram

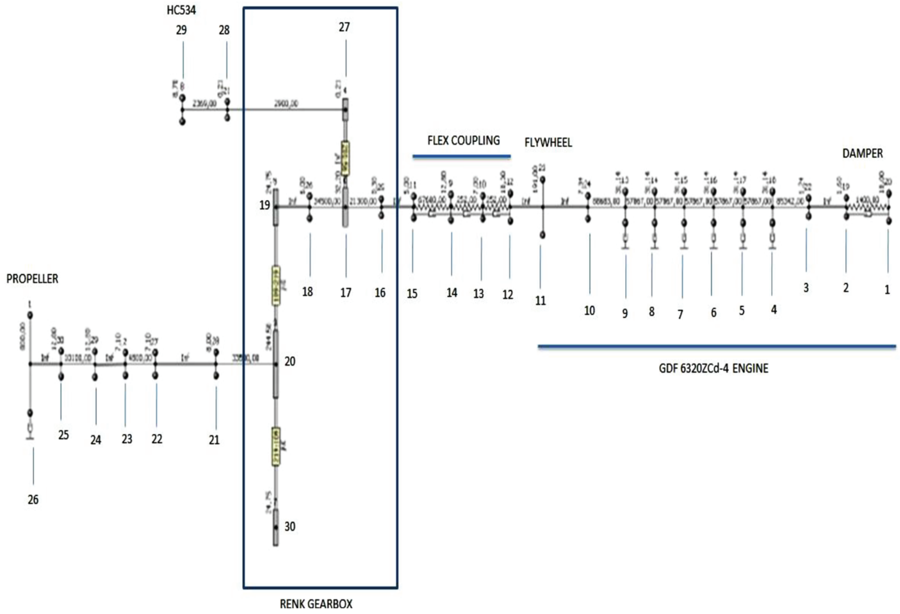


Fig. 6. Tanker 2, propulsion system

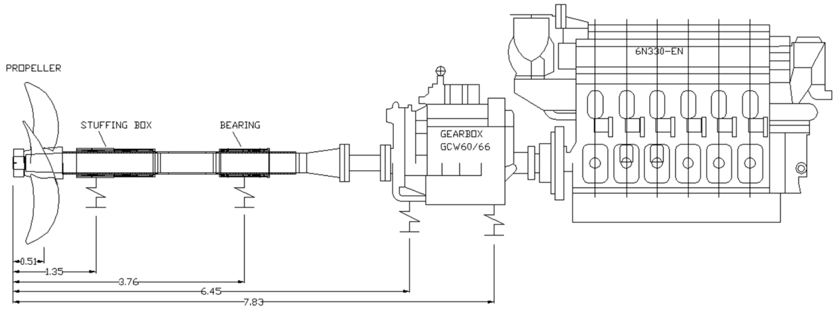
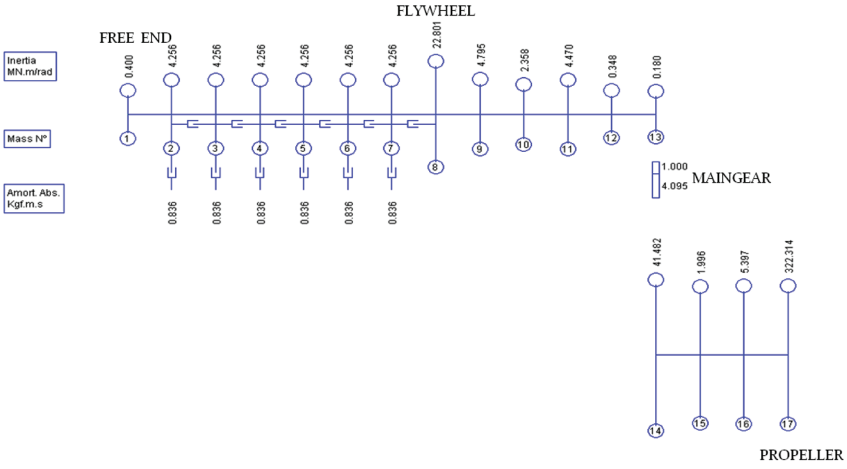


Fig. 7. Tanker 2, propulsion system torsional mass diagram



Case study 3: Inadequate separation of supports on a passenger ship

Type: Passenger Ship
Length: 78.40 m
Engine: 782 KW MCR
RPM: 600 -1800
Propeller: FPP

This case was analyzed by request of re-engining and because vibrations are being noticed on the first support of the prop shaft from the gearbox. Frequency analysis was carried out for lateral and torsional vibrations.

Lateral analysis shows that the system's natural frequencies and critical frequencies are within the working range.

Based on this analysis, the support structure for the first suport was inspected, finding that the structure was corroded.

It was recommended to relocate the supports to minimize the system's frequencies from being within the working range.

Fig. 8. Passenger ship propulsion system drawing

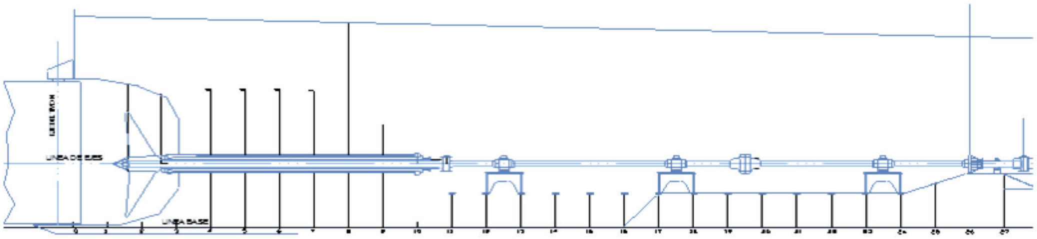


Fig. 9. Passenger ship, shaftdesigner propulsion system representation

Tabla 1. Passenger ship natural frequencies and resonances

MODE	Natural Frecuency		Resonance (RPM Motor)			
	HZ	CPM	1Z	2Z	1Z+1	1Z-1
MODE 1	12,455	747,3	2616	1308	448	747
MODE 2	23,73	1423,8	4983	2492	854	1424

Case study 4: Alteration of the distance between supports on a tugboat

Type: Tugboat
Length: 34.90 m
Engine: 1566 KW MCR
RPM: 600 – 1800
Propeller: FPP + Fixed Nozzle

This case was analyzed because of the presence of persistent noise in the propulsion system within the interval of 650 to 700 rpm.
Vibration measurements were made with a triaxial accelerometer.

With these vibration readings, wear was detected on gears of the gearbox (excessive backlash).

Frequency analysis was made for lateral and torsional vibrations, taking into consideration the wear of the gear teeth and the possible relocation of the stuffing box support.

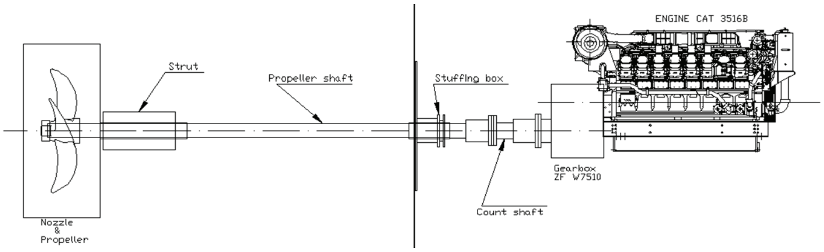
Through a sensitivity analysis, increased wear was found on the gear teeth, a possible relocation of this support in 300 mm would offer the possibility of resonance of the lateral frequency with the torsional frequency.

Lateral analysis shows that the system's natural frequencies and critical frequencies are within the working range.

Based on this analysis, the support structure for the first break was revised, finding that the structure was corroded.

It was recommended to relocate the supports to minimize the system's frequencies from being within the working range.

Fig. 10. Tugboat, propulsion system drawing



Result of the analysis of possible coupling between lateral and torsional vibrations of the system assumed:

Tabla 2. Possible coupling between lateral and torsional vibrations - assumed system

Torsional Mode and Order	IV - 4		IV - 2,5	IV - 2	
RPM Tensional	706	-	1130	1431	-
Lateral Mode and Order	I - 2Z+1	I - 2Z-1	I - 1Z+1	II - 2Z+1	I - 1Z
RPM Lateral	679	873	1222	1491	1527

Repair recommendation

- Inspect the stuffing box and restore the bearing to its original position.
- Inspect the structural condition of the nozzle.
- By relocating the stuffing box bearing, as suggested, we expect to increase the system's lateral frequency from 1527 rpm (mode 1 order 1Z) to 1580 rpm (mode 2 order 2Z+1), expecting slight vibration at speeds close to 1600 rpm.

Case study 5: Alteration of the distance between supports on a tugboat

Type: Yacht
Length: 35.40 m
Engine: 2 x 328 KW MCR
RPM: 600 – 1800
Propeller: FPP

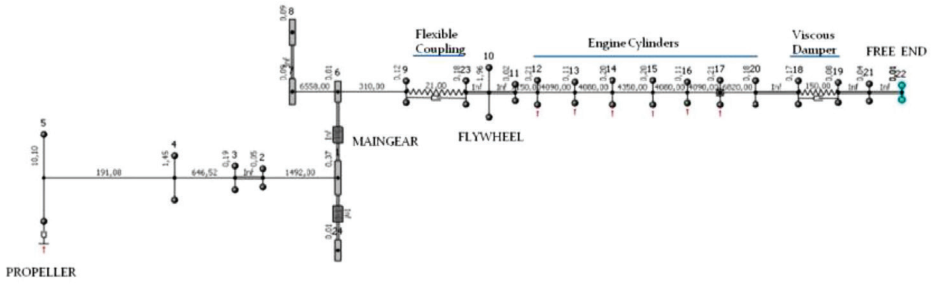
This case was analyzed due to a propulsion counter shaft fracture.

Frequency analysis was conducted for lateral and torsional vibrations.

Inspecting the system, it was found that the countershaft presents abrupt section change, close to the gearbox flange, which causes stress concentration, increasing the of the countershaft fracture risk.

From vibration analysis, we found that within the range of operation close to 900 rpm, there is increased vibratory torque in the flexible coupling; thereby, we recommend restricting operations in this rpm range until changing the flexible coupling.

Fig. 11. Yacht 1, propulsion system torsional mass diagram



Case study 6: Lack of stiffness on struts and inadequate separation of supports

Type: Yacht
Length: 39.07 m
Engine: 2 x 255 KW MCR
RPM: 600 – 1800
Propeller: FPP

This case was analyzed because of noise and vibrations in the range of 850 to 950 rpm, in both bands.

Frequency analysis was performed for lateral and torsional vibrations. Frequencies were estimated on the struts by using the finite elements method.

Fig. 12. Yacht 2. Propulsion system drawing

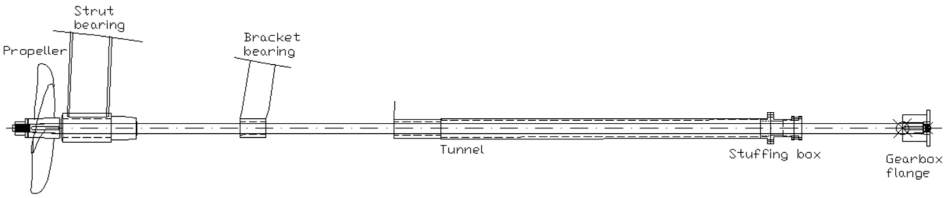
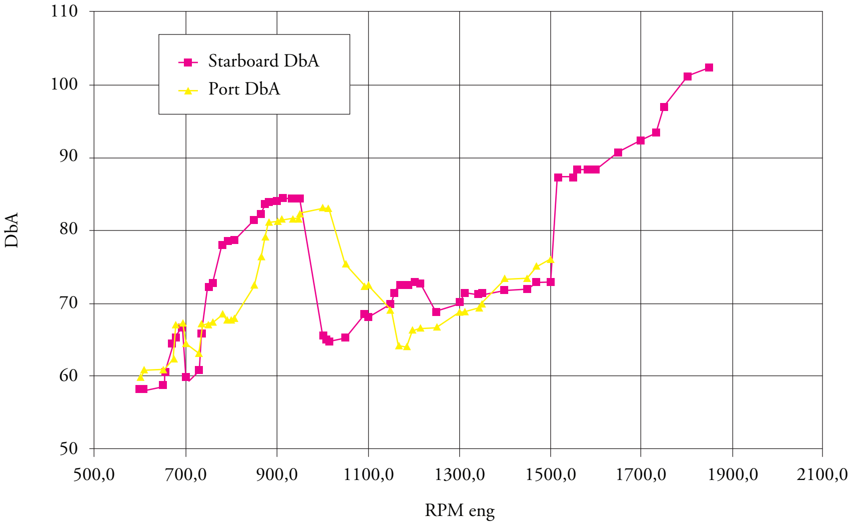


Fig. 13. Yacht 2. Noise readings over the propeller



From these analyses, it was concluded that due to the likelihood of frequency coupling:

- The structure of the struts is not sufficiently stiff,
- Inadequate separation of supports.

Case study 7: Inadequate selection of flexible coupling and diameter of propeller shaft on fishing vessel:

Type: Fishing Vessel
Length: 19.21 m
Engine: 2 x 317 KW MCR
RPM: 450 – 1225
Propeller: FPP

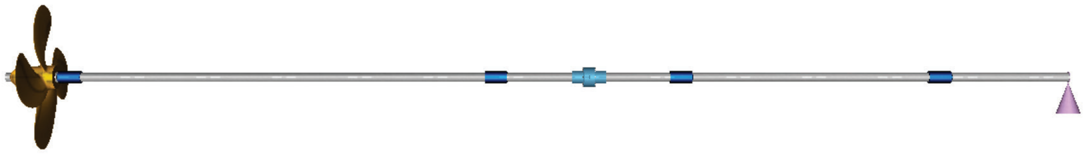
This case was analyzed due to excessive vibrations on the vessel.

Frequency analysis was conducted for lateral and torsional vibrations.

From the analysis, it was concluded:

- The flexible coupling has excess stiffness (original rubber blocks). We recommend acquiring another less stiff coupling.
- The original propulsion shaft with a diameter of 4 pl. SAE C1018 is producing frequencies within the working range. We recommend changing the propeller shaft for one with a smaller diameter of 3.5 pl. of Aqualoy material.

Fig. 14. Fishing vessel, shaftdesigner propulsion system representation



Summary of Inertial Masses for Systems analyzed

To summarize the case studies presented, Table 3 includes the inertial mass of each equipment / component, to statistically relate the percentage of inertial masses that should be considered before definitely selecting equipment or components.

Table 3. Case studies summary

STUDY CASE	Engine Inertia		Gearbox Inertia		Propeller Inertia		PTO Inertia		Total	Remark
	Kg.m^2	% total	Kg.m^2	% total	Kg.m^2	% total	Kg.m^2	% total	Kg.m^2	
CASE 1	424.3	26%	348	21%	843	26%	33.88	2%	1649	Flexible coupling change
CASE 2	478	11%	546	13%	3214	26%			4237	Propeller change and misfiring restriction
CASE 3	8.97	48%	1.08	6%	8.47	26%			18.51	Supports separation change
CASE 4	39.62	5%	89.82	11%	661	26%	0.61	0%	791	Supports separation change
CASE 5	3.7	27%	0.93	7%	9.29	26%			13.92	Flexible coupling change and countershaft fracture
CASE 6	3.16	66%	0.36	7%	1.24	26%			4.75	Check strut stiffness and supports separation
CASE 7	1.04	65%	0.19	12%	0.36	26%			1.6	Excessive shaft diameter and flexible coupling change
CASE 8	10.52	22%	5.20	11%	31.81	26%	0.27	1%	47.80	Flexible coupling and propulsion shaft diameter change
CASE 9	3.67	40%	0.94	10%	4.52	26%	0.1	1%	9.23	No remarks

Acknowledgments

We express our gratitude to all the companies which have entrusted us with the solution to noise and vibration problems. Special thanks go to the personnel from:

- Tecnavin S. A. for developing the TORCAL software, dedicated analysis of torsional vibrations;
- Machine Support, Holland, for allowing us to use the SHAFTDESIGNER software;
- Vulkan, Germany, for the technical support provided.

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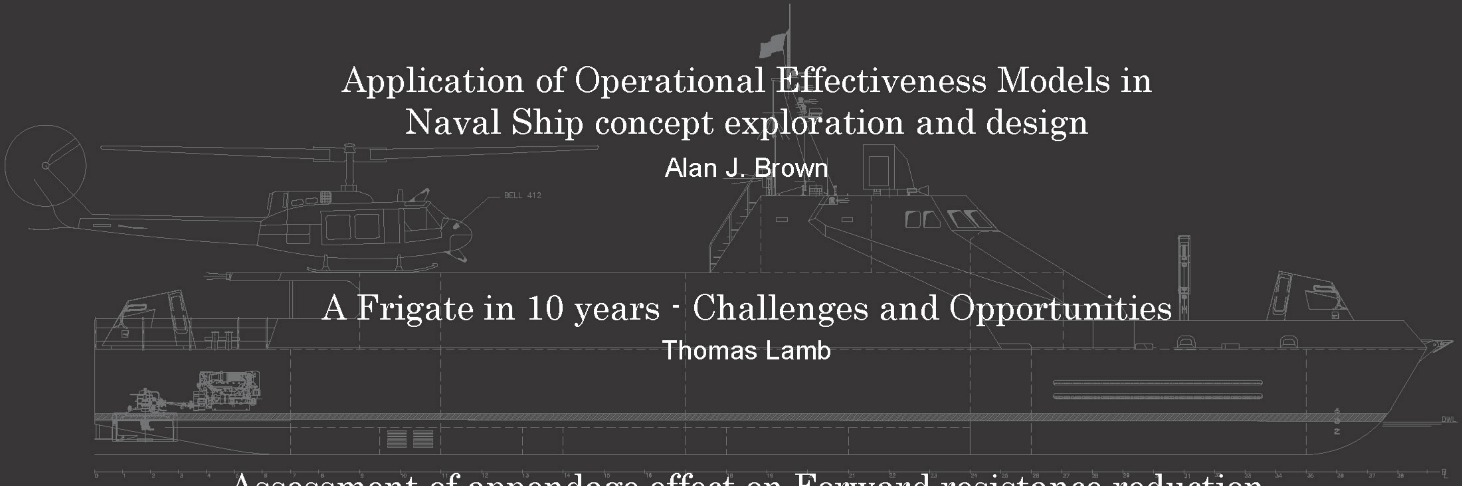

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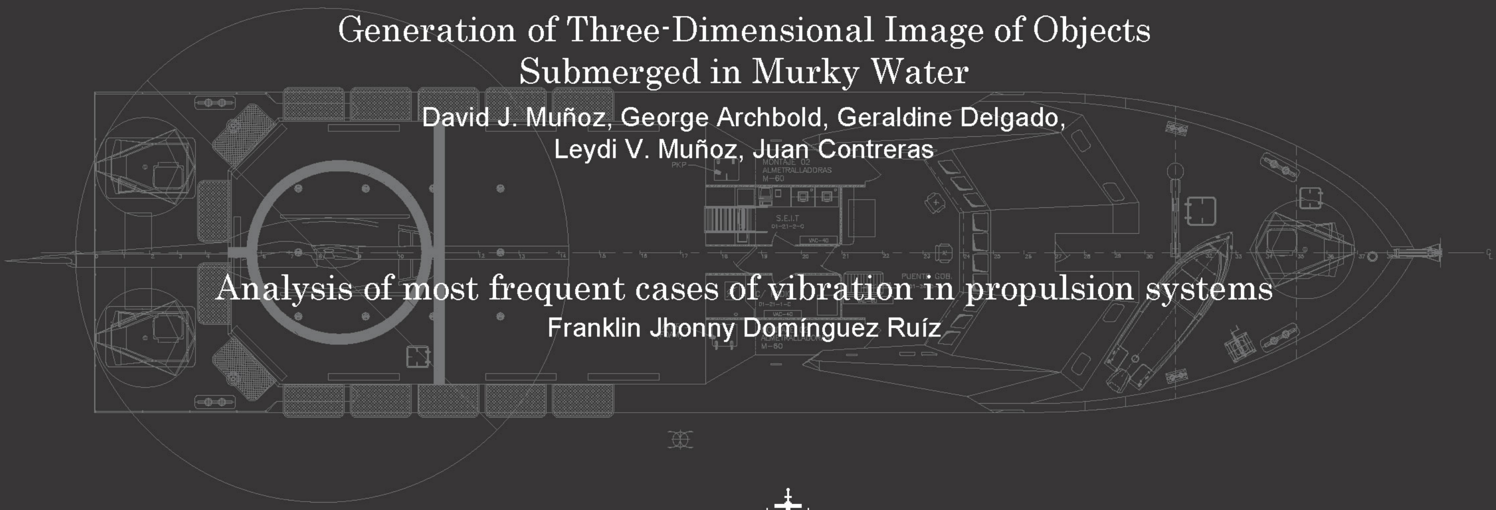

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