2007

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Regular Paper

Orthogonal Array Experiment for Architecting a System of Systems Responding to Small Boat Attacks

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Received 12 July 2006; Revised 26 December 2006; Accepted 8 March 2007, after one or more revisions

DOI 10.1002/sys.20074

ABSTRACT

In this work we solve the problem of architecting a conceptual, near-term, cost-effective system of systems (SoS) to respond to small boats used by terrorists to attack maritime commerce traffic and critical shore infrastructures in the United States, by formulating the architecting problem as an assignment problem which is then solved using the orthogonal array experiment. Also known as the Taguchi method in quality control, the orthogonal array experiment is efficient for this class of problems. The optimality of the resulting architecture, called optimal cost-effective architecture, is validated against a heuristically developed architecture and an optimal effective architecture; the latter is obtained also with the orthogonal array experiment approach. The main purpose of this paper is an exploratory application of the Taguchi method to architecting a system of systems. The principal results of the

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Systems Engineering, Vol. 10, No. 3, 2007

orthogonal array experiment method reported herein underline this successful exploratory work in architecting a system of systems. This method can be extended to architecting other systems of systems.

Key words: maritime threat response (MTR); small boat attack (SBA); architecture; system of systems (SoS); orthogonal array experiment; Taguchi method

1. INTRODUCTION

A small boat attack (SBA) in U.S. waters and ports is an attack by a single terrorist already in the U.S. who, in an explosive small boat, blends in with recreational boaters to get close to high-value units (HVUs) and assaults them at high speed. An SBA is considered to be the most likely attack in the future, because bombing of public transportation, suicide or otherwise, is the most common form of attack by terrorists. There have been numerous terrorist attacks on transportation, but only the most recent maritime incidents are noted here. On October 12, 2000, the USS Cole was severely damaged by the detonation of a terrorist suicide boat packed with high explosives. Seventeen sailors were killed and 39 were wounded in the attack, and the cost of repairing the ship was approximately $250 million [Perl and O'Rourke, 2001]. On October 6, 2002, the French oil tanker M/V Limburg suffered a similar attack three nautical miles from the coast of Yemen. The attack caused an oil spill estimated at 90,000 barrels. Both hulls of the ship's double-hull structure were breached by the explosion. On April 24, 2004, three suicide boats attempted to damage or destroy the Khawr Al Amaya and Al Basrah Offshore Terminals, which handle 90% of Iraqi crude oil exports, and two very large crude carriers tied up alongside the terminals [Howland, 2004]. The attack was foiled, but the damage or loss of the terminals would have an enormous impact on the Iraqi economy. Finally, two separate ferry bombings in the Philippines in 2004 and 2005 killed over 100 people [Villanueva, 2004; Scotsman, 2005].

There is thus a need to develop a system of systems (SoS) to respond to such terrorist threats—threats to the U.S. that emanate from the maritime domain. We shall call it the maritime threat response (MTR) SoS. In this work, a conceptual, near-term, cost-effective system-of-systems (SoS) architecture is developed to respond specifically to small boat attacks[1] in the San Francisco Bay and to do so with minimal impact on commerce and economic cost. By a conceptual SoS we mean a concept, not an actual SoS; it is merely a concept proposed in an academic project. The cost-effectiveness measure is defined in Section 3. The near-term MTR SoS [Sage and Cuppan, 2001] will consist of systems that are currently in service, in development, and commercial-off-the-shelf technologies or systems that would be available and/or could be developed within the next five years. The systems that constitute the MTR SoS include hardware, software, and human resources, which, as will be seen in Section 2.2, account for the total SoS cost. The MTR SoS architecture is a fixed system—in the sense that the systems that form the SoS remain unchanged. It is intended to be a single, simplistic SoS architecture that will be used to counter an SBA in San Francisco Bay.

Intelligence is needed before a response is taken, and the MTR SoS needs and makes use of intelligence. Due to the limited scope of this work, we consider any intelligence system such as national, service, and/or human assets not to be a component of the MTR SoS; that is, the boundary of the MTR SoS does not enclose these intelligence systems, but intelligence produced by them can be received and used by the MTR SoS. The MTR SoS itself, however, has its own internal intelligence provided to the components within the SoS boundary; the nature of the internal intelligence will be discussed in Section 2. For practical reasons, we also assume an MTR SoS solution to be free from any political and jurisdictional issues that can potentially exist.

The San Francisco Bay area is a fitting choice for the operational environment for the small boat attack scenario. The San Francisco/Oakland major metropolitan area (MMA) has numerous features that make it an attractive target for terrorist attacks. The San Francisco Bay area is heavily populated, and it attracts millions of visitors and tourists each year. It is the second-largest container port in California and the fourth largest in the nation. The combined ports of San Francisco, Oakland, and Richmond receive an average of ten foreign merchant vessels daily, primarily crude oil tankers and container ships [Young, 2005]. There are also numerous

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[1] This focused area is a part of a major campus-wide, integrated systems engineering and analysis (SEA) project carried out at the Naval Postgraduate School by the academic year 2006 SEA class. The members of this class are USN LCDR Andy Kessler, MAJ Mike Shewfelt, LT Brian Connett, LT Chewy Chiurourman, LT Joe Oravec, ENS Shawna Wark, and Ms. Jennifer Davis.

points of critical infrastructure on or near the San Francisco Bay.

One of the most famous bridges in the world, the Golden Gate Bridge, connecting San Francisco to the Marin peninsula, is one of the nation's premiere landmarks. The San Francisco–Oakland Bay Bridge is a vital economic connection between San Francisco and Oakland. There are other large public transportation systems and hubs (as expected of any MMA), including three large airports, numerous ferries, rail lines, and three other bridges of significant size. Any action that would curtail or stop transportation in the San Francisco Bay area would have significant economic impact estimable in billions of dollars [Frittelli, 2005; Arnold et al., 2006]. In addition, a large explosion, fire, or chemical cloud at the famous, heavily visited Fisherman's Wharf waterfront tourist area has the potential for mass casualties and the "cinematic" and psychological effects that Al-Qaeda and other groups seek.

The San Francisco/Oakland MMA is also relatively isolated from large military concentration areas, particularly naval assets. The two West Coast fleet concentration areas are San Diego and Seattle. The main assets for immediate maritime defense are therefore USCG units already in the Bay area. This is not to say that USCG assets are not capable of performing MTR missions, but rather to highlight that assistance may be several days in arriving. Even USCG PACAREA and District 11 assets are spread from the Oregon to Mexican borders.

Countering a small boat attack in the San Francisco Bay with a high density of recreational and commercial traffic (a USCG estimate of 300 to 400 vessels on average in a 24-h period) is a great challenge. A successful small boat attack on a densely packed passenger ferry would certainly cause extensive casualties and make emergency response and casualty treatment much more difficult than would a similar attack on a land-based target. A significant oil spill from a large crude oil tanker damaged in a successful small boat attack could cause environmental damage in the large offshore marine sanctuary area and incur significant cleanup costs. The SBA mission[2] considered in this work involves protecting five oil tankers inbound to the San Francisco Bay area, eight ferries operating on five different routes in the Francisco Bay, and five critical infrastructures such as oil offload terminals, pipelines, power facilities, etc. from an attacker who uses a 30-foot civilian speedboat with a top speed of 40 knots, loaded with 1000 pounds of conventional explosives. The five oil tankers arrive daily at times equally spaced, while the ferries operate 12 h daily.

The focus of this paper is the orthogonal array experiment methodology employed to develop MTR SoS architectures. The use of specially constructed tables known as orthogonal arrays for designing robust products and processes was originally espoused by G. Taguchi in Japan in the 1950s and 1960s. Taguchi [1978, 1993], Taguchi and Wu [1980], and Roy [1990] contain a detailed description of the Taguchi method. It has been used increasingly in many American industries, such as AT&T, ITT, Xerox, and Ford. Emphatically, the Taguchi method has been successfully used in product quality control. Parenthetically, the orthogonal array experiment and the Taguchi method are synonymous and used interchangeably in this paper.

In Huynh [1997] the Taguchi method was extended to solving a specific assignment problem—optimal allocation of files in a distributed computer network. This novel application of the Taguchi method then continued with solving the problem of optimal allocation of bandwidth in a satellite communication network [Huynh and Gillen, 2001]. In the present work we again extend the Taguchi method to architecting an MTR SoS. Specifically, we employ the Taguchi method to generate both an optimal cost-effective SoS architecture and an optimal effective SoS architecture for the SBA mission. Optimality is ensured by the Taguchi method. The difference between a cost-effective architecture and an effective architecture is that the latter provides the best performance, irrespective of the cost, while the former takes both performance and cost into account in the manner discussed in Section 3. We also develop an SoS architecture heuristically, benefiting from the SEA class' operational experience and knowledge of systems capability.

Our goals in this paper are:

- Explain our exploratory work in applying the orthogonal array experiment (or the Taguchi method) to solve system architecting problems, which we treat as assignment problems.
- Delineate the mechanics of solving the system architecting problems or assignment problems of this kind and the procedures to process experimental results.
- Illustrate our approach with the problem of architecting an MTR SoS for the SBA mission.

The rest of the paper is organized as follows. In Section 2 we define the problem of architecting an MTR SoS for the SBA mission and formulate it as an assignment problem. In Section 3, as the scope of this paper emphasizes the mechanics of applying the Taguchi

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[2] The SBA scenario considered in this academic project and in this paper does not reflect the official view of the Naval Postgraduate School, the U.S. Navy, or the U.S. government.

method to solve the MTR SoS architecting problem, we will confine our discussion to the adaptation of the Taguchi method for the problem at hand, without delving into all the statistical background and details of the Taguchi method as it applies to the quality control problem [Taguchi, 1978, 1993; Taguchi and Wu, 1980; Roy, 1990; Bendell, Disney, and Pridmore, 1989]. We then analyze the experimental results and obtain an optimal cost-effective SoS architecture for the SBA mission. In Section 4, to verify that the resulting cost-effective SoS architecture is indeed a "best" architecture, we compare its performance and cost to those of a heuristically developed architecture and an optimal effective architecture. Finally, Section 5 contains some concluding remarks.

2. MTR SoS ARCHITECTING PROBLEM AS AN ASSIGNMENT PROBLEM

We first define the problem of architecting a system of systems to respond to small boat attacks and then formulate it as an assignment problem.

2.1. MTR SoS Architecting Problem

The MTR mission to thwart a small boat attack includes searching and detecting the threat (the attacker), neutralizing the detected threat, and supporting and maintaining the MTR SoS components. A functional analysis identifies five top-level SoS functions: (1) Command, Control, Computers, Communication, Intelligence, Surveillance, and Reconnaissance (C4ISR), (2) Prepare the Battlespace, (3) Find/Fix Threat, (4) Finish Threat, and (5) Sustain. The C4ISR function ensures that the SoS has the appropriate means to carry out a mission in terms of command and control and to have appropriate communication channels to keep the forces informed of the status of operations. The Prepare the Battlespace function ensures that the SoS has the appropriate personnel, equipment, and platforms to carry out the mission; it also renders the area of operations ready for countering a potential attack. The Find/Fix and Finish functions are executed as MTR forces actually carry out the mission; the word "Threat" has been left out for convenience. The Sustain function ensures that all units and equipment are properly supported and maintained for the duration of operations. As the system concepts for Sustain are unique, system concepts corresponding only to the first four top-level functions are identified for use in an MTR SoS. Sustain will thus not be included in the formulation of the MTR SoS architecting problem as an assignment problem. Finally, as will be seen soon, some functions may be supported by as many as four different system concepts to consider, while others by as few as two concepts. We do not suggest that the system concepts considered here encompass all possible system solutions. Rather, our research and analysis indicate that they are potential "best fit" solutions associated with the top-level SoS functions. We now briefly discuss the system concepts.

C4ISR—The C4ISR has four elements: Command and Control (C2), Communicate, Compute, and Provide Intelligence. The C4ISR system attributes are "span of control," command structure, the suite of communications, and computing tools employed, and intelligence products to be used by the SoS components. "Span of control" relates to the size of the geographic region and the number of operating units in the region under the control of a single commander. The span of control can be Area or Local. An Area commander controls the forces that search and protect approximately 20 commercial ships across the Pacific Ocean as well as within San Francisco Bay. A Local commander controls the forces that protect a single high-value unit (HVU).

A command structure can be problem-solving or objective-oriented. A problem-solving approach involves issuing directives that articulate both missions and objectives for two levels of subordinates and substantial guidance as to how the objectives are to be achieved. An objective-oriented structure allows some level of trust, creativity, and initiative in subordinate commands, but it stresses synchronization of assets and actions. In the maritime domain, the objective-oriented structure is the most appropriate C2 command structure option [Alberts and Hayes, 1995]. Incorporating the advantages of the problem solving structure, it allows increased coordination and continuous contact between superior and subordinate commands as well as among subordinate commands. The problem-solving approach is also a C2 command structure option, which, as a back-up command structure, would be used in the event of either net-centric technology failure or lack of trust in either technology or subordinates.

An MTR communications infrastructure must be near real-time and interoperable across local law enforcement, national agencies, USN systems, and USCG assets. The communications system must ensure that messages, data, voice, or images exchanged among the parties in the MTR SoS are transmitted and received efficiently with minimal delays. Communications that take place within a small group, task force, or agency rely on local area networks (LAN); communications that occur among all MTR actors use wireless networks and paging systems.

The two main computing system components are information assurance and data fusion. Information assurance refers to the "technical and managerial measures designed to ensure the confidentiality, possession or control, integrity, authenticity, availability and utility of information and information systems" [Answers.com™, 2006]. The MTR information assurance system concentrates on protecting and securing the systems and information within the MTR domain. During the entire period that information is being transmitted, received, processed, and stored within the MTR domain, the MTR system employs encryption and authentication to protect information against unauthorized access, hash the information to protect it from modification without notice, and implement system redundancy to protect the mission against the loss of information. To prevent the loss of information or services to the commanders, redundant systems are implemented for disaster recovery. The defense-in-depth security model is the guiding framework for the MTR information assurance system concept.

Data fusion must enable a high level of situational awareness while minimizing information overload. Data/information certified as authentic from the trusted external sources is then processed and correlated based on the set of rules and requirements provided by the commanders. A hybrid data fusion concept employs both rule-based and self-learned algorithms such as artificial intelligence or a neural network.

The intelligence component of C4ISR is not an external system; it is a part of the SoS. The intelligence component of C4ISR sends an entire fused common operating picture (COP) to all operating units, the entire fused COP blended with the common intelligence picture to all teams, and specific fused COPs blended with a common intelligence picture (CIP) to the appropriate teams.

In summary, the Communicate concept is a combined Local Area Network, Wireless Metropolitan Area Network, and Wide Area Paging. The Compute concept is defense in depth and hybrid data fusion. The Provide Intelligence concept is customized COP and CIP. The C2 system concepts are Area Control/Problem Solving, Area Control/Objective Oriented, Local Area/Problem Solving, and Local Objective Oriented. While the Communicate, Compute, and Provide Intelligence components are common to all C4ISR system concepts, the C2 components vary among the C4ISR system concepts. C2 thus distinguishes the C4ISR system concepts. Consequently, we need not explicitly include the Communicate, Compute, and Provide Intelligence components in the various C4ISR system concepts. The C4ISR system options are then: (1) Area Control/Problem-solving, (2) Area Control/ Objective-oriented, (3) Local Control/ Problem-solving, and (4) Local Control/Objective-oriented.

PBS—Again, the PBS function ensures that the SoS has the appropriate personnel, equipment, and platforms to carry out the mission; it also renders the area of operations ready for countering a potential attack. Four PBS system concepts are selected for the SBA mission: (1) two small escorts, (2) two medium escorts, (3) two small escorts and two medium escorts, and (4) high-value unit based escort teams. A small escort is a highly maneuverable, small boat (25–35 ft long) with a top speed of 40 knots and a crew of four or five. A medium escort is a larger craft (80–150 ft long) with inboard engines, a top speed of 35 knots, and a crew of 20. For example, the U.S. Navy 34-ft Dauntless Boat Units and the 110-ft Coast Guard cutter are, respectively, a small and a medium escort. The medium escort has a longer endurance. The small escort mounts one medium machine gun in each position. The medium escort has a medium caliber gun only in the bow position and two medium machine guns on the port and starboard positions. The team onboard the HVU consists of six 2-man teams, each armed with a light machine gun.

Find/Fix—Involving only searching for surface contacts during escort operations, Find/Fix for the SBA mission employs visual means (e.g., binoculars), radar, or both radar and visual means. Almost every modern vessel of appreciable size routinely employs both means. The distinction between the two search methods is important in the case of small craft. Small vessels with limited height of eye have a short visual detection radius. Visual search is also dependent on weather conditions. The detection capability is then based on the presence of visual detection mechanisms, radar detection mechanisms, or a combination of both. The Find/Fix options are thus: (1) visual detection and (2) visual detection with surface search radar support.

Finish—Finish for the SBA mission is considered in conjunction with the PBS function, which is focused on weapons, platforms, and combinations of platforms (escort options). The focus now shifts to the additional advantages the response team gains by employing armed helicopters and unarmed unmanned surface vehicles (USV). Parenthetically, PBS involves escort operations while Finish hostile engagement; armed helicopters are thus needed to execute it. An armed helicopter offers additional capability to challenge suspicious small boat traffic, "clear a path" for the HVU, and engage the threat. A USV physically places itself between a suspicious boat and an HVU without involving personnel. The USV can deliver challenges and warnings at large distances from the HVU and therefore offers the response team considerable time available for a lethal engagement. The USV could be outfitted with various cameras and other sensors to classify surface contacts and loudspeakers, police lights, pyrotechnics, or other low-cost measures to warn innocent boaters. The USV could also shoulder suspect vessels or ram identified targets and complicate enemy plans by forcing the threat to take action earlier than planned. Research and existing programs suggest that a USV with the described capabilities could be fielded within the required five-year timeframe. Four SBA Finish system concepts are: (1) organic weapons, (2) organic weapons and armed helicopters, (3) organic weapons and USVs, and (4) organic weapons, USVs, and armed helicopters.

Table I summarizes the four top-level SoS functions and their associated system concepts. An MTR SoS architecture is a combination of these system concepts. But which pertinent system concept is selected to perform a top-level function, so that, together, the selected system concepts constitute an optimal MTR SoS architecture, in the sense that it maximizes some objective function of performance and cost? Performance refers to the probability of mission success. Cost includes the cost of delay to commerce caused by the response to the threats and the cost associated with the SoS. We now formulate the MTR SoS architecting problem as an assignment problem.

2.2. MTR SoS Architecting as an Assignment Problem

Let F denote the set of the SoS top-level functions, F_j, $j = 1, \ldots, 4$, and S_j the set of system concepts that can perform function F_j. Let X denote a set of allocation functions defined according to

$$X_{jk} = \begin{cases} 1, & \text{if system concept } k \text{ of } S_j \\ & \quad \text{is assigned to function } F_j, \\ 0, & \text{otherwise,} \end{cases}$$

where $j = 1, \ldots, 4$, and $k = 1, \ldots, |S_j|$; $|S_j|$ denotes the number of elements (i.e., system concepts) in S_j. As shown in Table I,

$$|S_3| = 2 \text{ and } |S_1| = |S_2| = |S_4| = 4.$$

2.2.1. Probability of Mission Success

An SBA mission is declared a success if the terrorist attack boat is prevented from reaching a lethal range (50 yards) of a protected asset. If the terrorist attack boat is still alive when reaching within the lethal range of the protected asset, then the SBA mission is a failure. The SBA mission success or failure is related to the allocations of the system concepts to the top-level functions; that is, it is a function of X_{jk}. The probability of mission success, P_s, thus depends on the allocations X_{jk}. It is obtained by Monte Carlo simulation, as the Monte Carlo method is a convenient and useful method for obtaining solutions to the problem at hand. The probability of mission success, P_s, is the fraction of the number of Monte Carlo simulation runs in which the SBA mission is a success.

2.2.2. Cost

All costs are in Fiscal Year 2006 millions of US dollars (FY2006$M). The total cost of an SoS architecture depends on the allocations X_{jk}. It is contributed by the cost of procurement of both additional existing and new SoS components (platforms), the cost of operating and supporting (O&S) the SoS, and the cost associated with both time delay suffered by commerce (the ferries and the oil tankers) in the course of responding to an attack, and the cost associated with damage to the physical entities resulting from failures to neutralize the terrorist threat. Table II contains the cost estimates of the system

Table I. System Concepts for the Top-Level Functions

Function	System Concepts			
	1	2	3	4
C4ISR	Area Control/Problem-solving	Area Control/Objective-oriented	Local Control/ Problem-solving	Local Control/Objective-oriented
PBS	Small escorts	Medium escorts	Small and medium escorts	HVU-based escort teams
Find/Fix	Visual detection	Visual detection with surface search radar support		
Finish	Organic weapons	Organic weapons and armed helicopters	Organic weapons and USVs	Organic weapons, USVs, and armed helicopters

Table II. Cost Estimates*

Function	System Concepts		Total Cost ($FY2006 Million)
C4ISR	1	Area Control/ Problem-solving	12.1
	2	Area Control/ Objective-oriented	12.1
	3	Local Control/ Problem-solving	60.1
	4	Local Control/ Objective-oriented	60.1
PBS	1	Small escorts	92.6
	2	Medium escorts	1534.8
	3	Small & medium escorts	1583.9
	4	HVU-based escort team	36.1
Finish	1	Organic weapons	0.8
	2	Organic weapons & armed helicopters	13.8
	3	Organic weapons and USVs	21.3
	4	Organic weapons, USVs, & armed helicopters	35.7

*The Find/Fix system concepts incur no cost as their costs are already assessed under PBS and the radar is organic to both the small and medium escorts.

concepts. The delay and damage costs are generated by the mission-level modeling and simulation. The estimation of the remaining costs follows.

MTR O&S Costs—The annual MTR O&S costs are the product of the number of days per year the SoS would be involved in MTR-related activities and the daily O&S rate, which is the sum of the daily O&S rates for the SoS platforms and those for the personnel involved. The daily O&S rates for the selected platforms used in the MTR SoS is calculated by dividing the average annual O&S costs by 365 days. Two types of platforms constitute the SoS: Platforms for which cost data are available and platforms for which there are no cost data. The average annual O&S costs of existing platforms are obtained by adjusting data from Visibility and Management of Operating and Support Costs (VAMOSC) [Navy VAMOSC, 2006]. For the platforms for which VAMOSC data do not exist, existing analogous VAMOSC data are adopted and adjusted as needed. The daily O&S rates for the platforms are then obtained by dividing the average O&S costs by 365 days. The daily O&S rate for MTR personnel is computed, based on the most recent annual pay and allowances of all Navy and Marine Corps officers and enlisted men, the total number of full-time equivalents in both services, and a basis of 365 days per year. The number of days per year the MTR SoS is employed is now determined, based on the following assumptions: (1) a standard two-week annual training for boarding/search teams; (2) all platforms participating in one 10-day exercise per year and one actual operation per year; and (3) the SBA mission lasting for 30 days.

MTR Procurement Costs—The procurement of both additional existing platforms and new platforms accounts for MTR SoS procurement costs. Official Department of Defense budget documents [OUSD, 2006], if available, or Jane's and the original equipment manufacturer Web site are used to the maximum extent possible to obtain unit costs for the existing platforms. The costs of new systems are obtained by adjusting appropriately the costs of analogous existing systems. As an exception, program-of-record national fleet assets, such as the Littoral Combat Ship and the National Security Cutter, are assumed to be sunk costs and therefore are not included in the total cost. The procurement costs of the systems supporting the top-level SoS functions are now elaborated.

C4ISR—The main components of the C4ISR system are the Boarding Team Communications Pack (BTCP), correlation engine software, software training, headquarters workstations, shipboard combat information centers, small boat communications equipment, space-based and land-based stations, and the planning effort required to develop rules of engagement and standard operating procedures for MTR missions. All of the components are assumed to exist in an adequate form with the exception of the BTCP, correlation engine, and dedicated personnel for software and communications gear currency and readiness requirements. The detailed cost estimate for a single BTCP, based on data from manufacturers' Web sites and analogous equipment, is $15,005. The Rosetta Stone Advanced Capability Technology Demonstration is used as the analogy for correlation engine algorithm development and technology demonstration. It is assumed that Area C2 requires only one correlation engine, while Local

C2 requires an engine for each HVU escort team. An additional \$2.5 million per C2 location is assumed for hardware/software integration costs, and the software O&S cost is 20% of the RDT&E cost. Each software-installed location is assumed to require one commander, two analyst/operators, one boarding team communications expert, and one boarding team gear maintainer/storekeeper, all full time. No cost differential is identified between the problem-solving and the objective-oriented command structures. The total C4ISR cost estimates are \$12.1 M and \$60.2 M for Area C2 (Option 1 and 2) and Local C2 (3 and 4), respectively.

PBS—The PBS main components are escort boats and boarding teams. The small escort boats are Rigid Hulled Inflatable Boats (RHIBs) and other light patrol/security craft. The small boat unit cost is taken to be the average of the costs of the USCG Long Range Interceptor, the SeaArk Marine “Dauntless” craft, and Special Operations Forces combatant craft systems. The mall escort O&S cost is assumed to be 20% of the PC O&S cost. The mid-sized escorts used in Options 2 and 3 are similar to the Navy Patrol Coastal (PC) or the USCG Fast Response Cutter (FRC). The PC O&S cost and FRC procurement costs are therefore used. The total costs of the four different PBS options are roughly \$92.6 M, \$1,534.8 M, \$583.9 M, and \$36.1 M for Options 1, 2, 3, and 4, respectively.

Find/Fix—The main components of Find/Fix are the search teams and surface search radar. Because the costs associated with the teams are included under PBS and the radar is organic to both the small and medium escorts, there is no additional cost for either of these two options.

Finish—Finish employs the escort teams and platforms whose costs are already accounted for under PBS. The number of teams is consistent with PBS: 10 teams for Options 1, 2, and 3, and 27 teams for Option 4. Additionally, the Finish main components include hand-held weapons, armed helicopters, and unmanned surface vehicles (USVs). The MK-19 Grenade Launcher procurement cost is used as the standard hand-held weapon cost. The hand-held weapon O&S cost is assumed to be 25% of procurement cost. The helicopter O&S daily rate is based on that of the Navy H-60. The SeaFox USV is used as a basis for assessing the USV procurement cost. Because the SeaFox is built atop an 8-m RHIB, the SeaFox O&S cost is 20% of the PC O&S cost. The cost estimates are roughly \$0.8 M, \$13.8 M, \$21.3 M, and \$35.7 M for Options 1, 2, 3, and 4, respectively.

Sustain—Nearly all critical sustaining costs are based on the VAMOSC data. For example, food is included through the Basic Allowance for Subsistence cost in the VAMOSC personnel data. The VAMOSC database also accounts for the majority of SoS maintenance requirements. Any spares needed to meet reliability requirements are included in unit quantities. For example, although only 4 USVs are required for an HVU, a total of 92 must be procured to account for refueling, maintenance, and breakage. Training cost is based on the duration of MTR activities, which include a 10-day exercise per year per mission and a 2-week school for boarding team members on MTR mission-specific equipment and procedures.

2.2.3. Objective Function

In this work, we introduce a dimensionless objective function, z, which results from mapping the performance measure (P_s) and the total system cost (C) by means of a rule ρ according to

$$z = \rho(P_s, C).$$

The objective function z is thus a function of the allocations X_{jk}. A specific rule ρ which will result in a dimensionless objective function will be elaborated in the Taguchi data analysis (Section 3.4).

The problem of optimizing the MTR SoS architecture amounts to determining an assignment of the system concepts to the four SoS top-level functions (i.e., the allocations X_{jk}) that maximizes the objective function z. We solve this problem using the orthogonal array experiment approach employed in Huynh [1997] and Huynh and Gillen [2001].

3. THE ORTHOGONAL ARRAY EXPERIMENT

Having a mathematical foundation in linear algebra—specifically, the Galois field theory—orthogonal arrays began with Euler as Latin squares in the 18th century [Euler, 1849]. R.A. Fisher was the first to apply them extensively. Factorial design of experiments was first introduced by R. A. Fisher in the 1920s. For a full factorial design the number of possible conditions or experiments is L^m, where m is the number of factors and L is the number of levels for each factor. Taguchi’s partial factorial design requires only a smaller number of unique factor/level combinations captured in an orthogonal array. All combinations of levels occur and occur an equal number of times in every pair of columns of an orthogonal array. This combinatorial property ensures the orthogonality property [Pao, Phadke, and Sherrerd, 1989]; all columns in the array are thus orthogonal to each other.

The work discussed in this paper is focused only on the SBA mission, which is one of the MTR missions addressed in Kessler et al. [2006], in which two to four different system concepts (levels) could be assigned to seven system-level functions (factors) to account for all MTR missions. For a full factorial design the number of possible combinations of these system concepts, 3072, need be evaluated for their effectiveness, using Monte Carlo simulation. Each simulation run, taking place on an Intel Pentium (R) CPU 3.40 GHz Dell computer, takes more than 3 min. It would therefore take 704 days of continuous running of the simulation to evaluate those potential combinations (architectures), with each combination requiring 100 simulation runs. This would be impractical.

An efficient form of fractional experiment design is thus needed, which would dramatically reduce the overall number of combinations or architectural trials and simulation time. An efficient form of experiment design is known as the Taguchi method, commonly associated with measures to achieve higher levels of quality control in a manufacturing process [Roy, 1990]. The Taguchi method involves using orthogonal arrays, obtaining the so-called response from each combination or architectural trial, analyzing the effects of the different system concepts, and determining an optimal architecture from the analysis. In the Taguchi parlance, the system functions are called factors, and the various system concepts corresponding to the system functions are called levels. This method amounts to optimally assigning the levels (system concepts) to each factor (system functions) in order to achieve the best possible result for some response function. The application of the Taguchi method to the assignment problem at hand is, again, motivated by a successful extension of the Taguchi method to solve assignment problems [Huynh, 1997; Huynh and Gillen, 2001]. It must be pointed out that the Taguchi method has nothing to do with computer power. It has to do with saving costs in carrying out experiments to find ways to achieve desired product quality [Roy, 1990]. It is in the exploratory work [Huynh, 1997; Huynh and Gillen, 2001] that experimentation is carried out by computer simulation. Even with the existing computer power, in some circumstances the Taguchi method is still preferred over the full factorial design or other mathematical optimization [Huynh and Kohfeld, 1994; Huynh, 1997].

3.1. Definition of Factors and Levels

A key step in designing orthogonal array experiments is defining the factors and their levels [Pao, Phadke, and Sherrerd, 1989]. In the Taguchi parlance [Roy, 1990], factors are the causes which produce an effect, levels are the way in which the factors are changed, and the response is the result produced by the factors. In our approach, we identify the SoS top-level functions as factors; thus, C4ISR, PBS, Find/Fix, and Finish are the factors. From here on, functions and factors are used interchangeably. Care should be exercised to choose factors and levels appropriately so as to take advantage of the established orthogonal arrays. There is no systematic way to define factors and their levels for assignment problems in general [Huynh, 1997]. For the problem at hand, the levels of a function (factor) are defined as the different system concepts that can perform the function. The system concepts supporting a function are thus the levels of the function (factor).

3.2. The Orthogonal Array Experiment Design

At the outset, for the problem at hand, an experiment is a computer simulation. As mentioned above, the full factorial experiment to explore all possible factor-level combinations would impractically require performing a large number of experiments in this case. The use of orthogonal arrays reduces the number of experiments drastically.

Taguchi and Wu [1980] have tabulated a number of orthogonal arrays which can be conveniently used to construct orthogonal designs for any experimental situation. The appropriate orthogonal array for the problem at hand is a portion of the mixed orthogonal array $L_{32}(2^1,4^9)$, shown in Table III [Taguchi and Konishi, 1987]. Note that the full orthogonal array $L_{32}(2^1,4^9)$ can be used to study up to 9 factors at 4 levels per factor and 1 factor with 2 levels. The columns in the array correspond to the factors (functions). Each of the 32 rows or experiments (or conditions) corresponds to an architecture trial. The entries in the orthogonal array, ranging from 1 to 4, represent the system concepts (levels) shown in Table I. Each level in the orthogonal array is used in each factor and each appears an equal number of times. The different combinations are varied throughout the array so that each level has at least one trial with every level from every other factor.

3.3. Experiment

3.3.1. Experimental Procedure

Carrying out an experiment for each row of the orthogonal array means performing a Monte Carlo simulation of the MTR SoS response, z, to an attack of a HVU by a small boat attacker. The Monte Carlo simulation involves 2000 simulation runs of an EXTEND™ SBA mission model,[3] each of which produces success or failure of the SBA mission. Again, by success we mean the MTR forces successfully prevent the small boat attacker from hitting the HVU. By failure we mean that

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[3] EXTEND™ is a modeling and simulation tool developed by Imagine That!, Inc., San Jose, CA.

Table III. The Orthogonal Array Reduced from $L_{32}(2^1,4^9)$

TRIAL	C4ISR	PBS	Find/Fix	Finish
1	1	1	1	1
2	1	2	2	2
3	1	3	1	3
4	1	4	2	4
5	2	1	2	3
6	2	2	1	4
7	2	3	2	1
8	2	4	1	2
9	3	2	2	2
10	3	1	1	1
11	3	4	2	4
12	3	3	1	3
13	4	2	1	4
14	4	1	2	3
15	4	4	1	2
16	4	3	2	1
17	1	4	2	3
18	1	3	1	4
19	1	2	2	1
20	1	1	1	2
21	2	4	1	1
22	2	3	2	2
23	2	2	1	3
24	2	1	2	4
25	3	3	1	4
26	3	4	2	3
27	3	1	1	2
28	3	2	2	1
29	4	3	2	2
30	4	4	1	1
31	4	1	2	4
32	4	2	1	3

the small boat attacker has closed within 50 yards of the HVU. A statistical analysis of the Monte Carlo simulation results then yields the probability of mission success.

3.3.2. SBA Mission Model

Since this paper is focused on application of the Taguchi method, we will not elucidate in detail the EXTEND™ SBA mission model; instead, we will provide a cursory description of the EXTEND™ SBA mission, its input, and its output. The EXTEND™ SBA mission model represents the C4ISR, PBS, Find/Fix, and Finish functions, the kinematics of the small boat attacker, the response engagement geometry, the engagement types (i.e., warning and lethal engaging), the engagement sequence (e.g., helicopter followed by close escorts or the onboard team), and the MTR SoS responses. Constrained by the scope of the paper, we will not describe the modules (with their EXTEND™ icons) of the EXTEND™ SBA mission model; instead, for illustration purposes only, we include a representative snippet of the EXTEND™ SBA mission model, shown in Figure 1. We also hasten to add that the accuracy and fidelity of the models used in the simulation affect the response of each experiment, and, hence, the Taguchi analysis results. Care must thus be taken to ensure the models in the simulation are accurate and have a similar level of fidelity.

C4ISR is simulated through initial orders, which are issued upon receipt of intelligence that a small boat attack might occur. Some time delay, assumed to be constant, is incurred with the action of issuing the initial orders. As related to the assessment of mission success, if the small boat attack takes place before or during the course of issuing the initial orders, then the MTR SoS system will fail to stop the attack.

Find/Fix is represented through the identification and classification function. The time it takes the MTR forces to identify and classify the small boat attacker varies according to the means employed in the Find/Fix: 10 s for visual means and 5 s for both visual means and radar.

The small boat attacker's position relative to the high value target (i.e., the initial attacking distance) is initialized by adding an initial attacking distance variation to a nominal distance. The former is a function of the system concepts associated with the PBS and of Finish functions. The latter is assumed to admit a normal distribution with a mean of 500 yards and a standard deviation of 150 yards.

Engagement involves warning and engaging. Warning is carried out by non-lethal or lethal means. In this work, the terms "nonlethal" and "lethal" refer to the means by which the warning is issued, not its intended effect. For instance, the nonlethal warnings could include auditory warnings, police-type lighting, or pyrotechnics. The lethal warnings denote firing shots in front of a potential small boat attacker. During the course of engagement, engagement decisions will be made as to when nonlethal or lethal warning and nonlethal or lethal engaging are executed and by whom (the armed helicopters, the escorts, or the team onboard). The engagement decisions depend on the closing distance (i.e., the remaining distance) between the small boat attacker and the HVU. The small boat attacker's speed is assumed to be constant during its attack. As a result, this distance is linearly reduced with the elapsed time (relative to the time of the initial attacking distance).

If the closing distance is sufficient (i.e., it is greater than 50 yards), then the helicopter will give a nonlethal warning, which takes 10 s. In the absence of armed helicopters, the MTR escorts or the team onboard the HVU will give a nonlethal warning, which takes also 10 s or, if Finish uses USVs, 5 s. If the closing distance

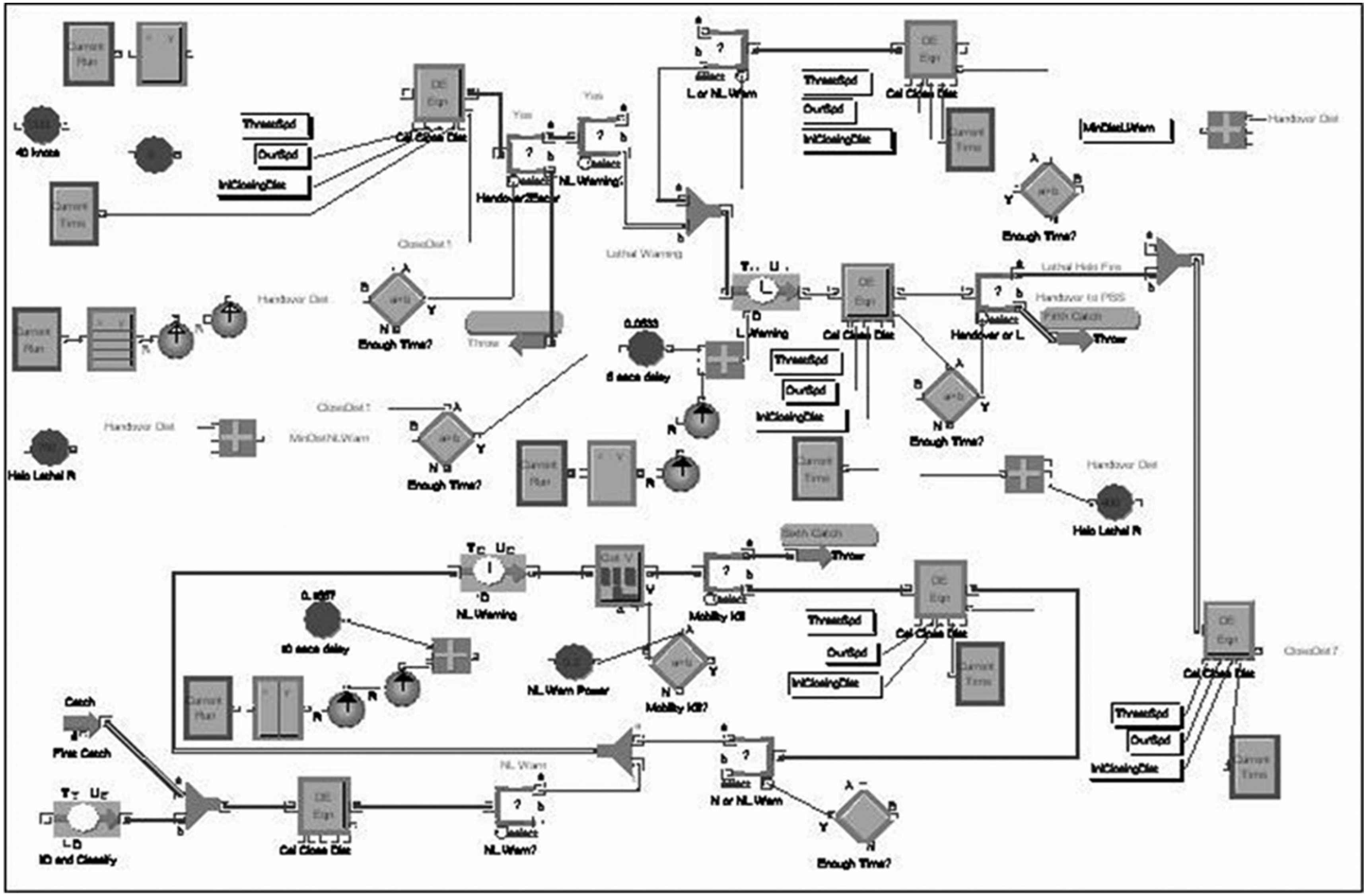

Figure 1. A snippet of the EXTEND™ SBA mission model.

is insufficient or the nonlethal warning is unheeded, the armed helicopter will fire lethal warning shots, which will take 5 s. If an armed helicopter is not present, the MTR close escorts will fire lethal warning shots, which will also take 5 s or, if the Finish alternative includes USVs, 2.5 s. If the closing distance is insufficient, the helicopter will lethally engage the small boat attacker. Otherwise, the MTR close escorts will engage the attacker. The effectiveness (i.e., probability of kill) of the helicopter is related to the closing distance.

If the nonlethal warning is unsuccessful and if the closing distance is sufficient for carrying out a nonlethal engagement on the small boat attacker, then the MTR escorts or the team onboard the HVU will spend 10 s to nonlethally engage the small boat attacker. If the closing distance is sufficient for lethal warning or if lethal warning fails, then the MTR escorts or the team onboard the HVU will lethally engage the small boat attacker once it is within 500 yards of the HVU. The probability of kill by MTR escorts or the team onboard the HVU also depends on the closing distance. If the small boat attacker is within 50 yards of the HVU, then the MTR forces do not have enough time to lethally engage the attacker and the SoS will therefore be ineffective.

As aforementioned, ferries and oil tankers traveling within the area of operations constitute commerce. The delay imposed to commerce by the MTR forces during the SBA mission is a function of the number of ferries and oil tankers to be escorted, the number of escort teams available, and the duration of the operation (measured in days). We assume daily HVU traffic consists of eight ferries operating 12 h and five oil tankers transiting for 10 h. The oil tankers arrive in a uniformly distributed fashion over the entire 24-h period. We also assume the cost of delaying an oil tanker to be greater than the cost of delaying a ferry, and priority is given to escorting oil tankers whenever a scheduling conflict arises. The architectures considered for the SBA mission are specifically designed to cause no delay to commerce.

Input to the SBA mission model includes the portion of the $L_{32}(2^1,4^9)$ orthogonal array (Table III), the SoS architecture alternatives with their components and pertinent characteristics, the initial distance of the attacker from the HVU and its variance, and all constant quantities (e.g., time to issue warnings, time of classification, and so forth).

Output from the SBA mission model is mission success or failure for each Monte Carlo run. Post-processing yields the probability of mission success for each of the 32 trials (experiments). Table IV displays the experimental results—the probability of mission success (in the second column) and the total cost (in the third column) for each of the 32 trials (in the first column)—and the dimensionless response (in the fourth column) defined in Section 3.4.

Table IV. Experimental Results

Trial	Probability of Success, P_s	Cost ($M)	Response, z (dimensionless)
1	0.5250	105.5	72.7
2	0.7595	1560.6	48.2
3	0.6935	1617.3	40.8
4	0.6785	83.8	86.5
5	0.5860	140.3	76.8
6	0.8235	1568.1	53.4
7	0.7015	1609.8	41.7
8	0.6330	49.0	83.7
9	0.7700	1616.2	47.4
10	0.5385	188.4	71.3
11	0.7055	97.1	88.4
12	0.6990	1657.9	40.0
13	0.8135	1608.7	51.3
14	0.5805	153.6	76.0
15	0.6350	131.9	81.3
16	0.6995	1665.3	39.8
17	0.3935	61.9	62.8
18	0.7745	1596.8	48.3
19	0.6215	1582.5	35.7
20	0.6065	125.9	79.0
21	0.2605	69.4	51.1
22	0.7950	1631.6	49.0
23	0.6095	1547.6	35.7
24	0.7050	118.4	87.7
25	0.7615	1679.7	44.7
26	0.3955	117.5	61.2
27	0.6310	166.5	79.9
28	0.6285	1595.7	35.9
29	0.8090	1644.9	49.8
30	0.2400	110.0	48.1
31	0.7090	174.0	86.4
32	0.6325	1630.6	35.1

3.4. Data Analysis

As in Huynh [1997] and Huynh and Gillen [2001], the data analysis performed here consists of the standard analysis outlined by Taguchi. The purpose of the data analysis is to study the main effects of each of the factors (the SoS top-level functions) in order to identify the optimal condition [Roy, 1990]. The main effects indicate the general trend of the influence of the factors; that is, the effect of a factor (function) on the objective function when it goes from one level (system concept) to another. The analysis of the main effects involves the calculation of the averages for the levels of all factors. We describe the data analysis next.

Associated with the ith experiment (row) are the probability of mission success, P_{s_i}, and the cost, C_i. The architectural trial (row in the orthogonal array) that yields the most expensive architecture is assigned a score of 0 for cost, while the trial that yields the least expensive architecture a score of 100 for cost. These two extreme data are then used in a linear function to obtain the dimensionless cost scores of the remaining trials, which vary between 0 and 100. The resulting dimensionless cost ξ_i associated with the *i*th experiment (row) is then given by

$$\xi_i = \frac{100}{\xi_{max} - \xi_{min}} (\xi_{max} - C_i),$$

where $\xi_{max} = max_{i \in N_\varepsilon} C_i$, $\xi_{min} = min_{i \in N_\varepsilon} C_i$, and N_ε and denotes the number of experiments (rows).

Likewise, the trial that yields the highest probability of success is assigned a score of 100 for effectiveness, while the trial that yields the lowest probability of success a score of 0 for effectiveness. These two extreme data are then used in a linear function to obtain the dimensionless effectiveness scores of the remaining trials, which vary between 0 and 100. The resulting dimensionless cost associated with the *i*th experiment (row) is then computed according to

$$\pi_i = \frac{100}{\pi_{max} - \pi_{min}} (P_{S_i} - \pi_{min}),$$

where $\pi_{max} = max_{i \in N_\varepsilon} P_{S_i}$ and $\pi_{min} = min_{i \in N_\varepsilon} P_{S_i}$.

In this work, the rule ρ (Section 2.2) that amalgamates the total cost C_i, and the probability of success, P_{S_i}, into the dimensionless response z_i associated with the *i*th row is simply the linear combination of the two resulting dimensionless scores,

$$z_i = \lambda_{P_S} \pi_i + \lambda_C \xi_i,$$

in which λ_{P_S} and λ_C are the weighting coefficients associated with π_i and ξ_i. The weighting coefficients λ_{P_S} and λ_C, which take values in [0, 1], are such that $\lambda_{P_S} + \lambda_C = 1$. Note that an optimal effective architecture corresponds to $\lambda_C = 0$. When both the performance and the cost are equally weighted, as done in this work, the weighting coefficients λ_{P_C} and $\lambda_C \xi_i$ are taken to be 0.5 in order for z_i to take values in [0, 100]. This formulation thus allows flexibility in adjusting the contributions of the cost and performance to the response. The response corresponding to the *i*th row is thus computed according to

$$z_i = \frac{1}{2}\left[\frac{100}{\pi_{max} - \pi_{min}} (P_{S_i} - \pi_{min}) + \frac{100}{\xi_{max} - \xi_{min}} (\xi_{max} - C_i)\right],$$

which is the average of the two resulting dimensionless scores π_i and ξ_i.

Let a_{ij} denote the level of the *j*th column (function or factor) in the *i*th row (trial, experiment, or condition), z_i the response (i.e., the objective function) corresponding to the *i*th row. Then the average performance (i.e., the objective function) of the *j*th factor (function) at the α_jth level, denoted by $\langle f_{j\alpha_j} \rangle$ is calculated according to

$$\langle f_{j\alpha_j} \rangle = \frac{1}{N_{j\alpha_j}} \sum_{i=1}^{N_\varepsilon} \delta(a_{ij} - \alpha_j) z_i, \quad \begin{pmatrix} j = 1, \cdots, 4 \\ \alpha_j = 1, \cdots, |S_j| \end{pmatrix},$$

in which $N_{j\alpha_j}$, the number of experiments (rows) the α_jth level (system function) assigned to the *j*th factor (function) is

$$N_{j\alpha_j} = \sum_{i=1}^{N_\varepsilon} \delta(a_{ij} - \alpha_j)$$

and

$$\delta(a_{ij} - \alpha_j) = \begin{cases} 1, & \text{if } a_{ij} = \alpha_j, \\ 0, & \text{otherwise.} \end{cases}$$

For the problem at hand,

$$N_{j\alpha_j} = \begin{cases} 8, & j = 1, 2, 4, \\ 16, & j = 3. \end{cases}$$

In this work it is convenient to deal with the so-called signal-to-noise ratio (SNR), which is defined as $SNR_{j\alpha_j} = 2ln\langle f_{j\alpha_j} \rangle$, rather than with $\langle f_{j\alpha_j} \rangle$. Taguchi effectively employs the concept of SNR, which originates in the electrical engineering field, in quality control. The "signal" is the change in the quality characteristics of a product under investigation in response to a factor introduced in the experimental design. The "noise" refers to external factors (or noise factors) that affect the quality characteristic under test. The signal-to-noise ratio quantifies the sensitivity of the quality characteristic to the noise [Roy, 1990]. Since the quality characteristic (in the Taguchi parlance) of the problem at hand is "the larger the better" performance (the objective function), the levels of the factors are identified according to the maximum signal-to-noise ratio. If $SNR_{jk} = max_{\alpha_j} SNR_{j\alpha_j}$, then the α_kth level (system concept) is assigned to the *j*th factor (top-level function). Reflecting the data analysis results in Table V, Figure 2 displays the graphs of the signal-to-noise ratios against the levels (system concepts) for each factor (function). It depicts the main effects of the factors (functions) on the objective function. The selected level of a factor corresponds to the largest signal-to-noise ratio.

Table V. Data Analysis Results for the Optimal Cost-effective Architecture

Function		System Concepts	$\langle f_{j\alpha_j} \rangle$	$SNR_{j\alpha_j}$
C4ISR	1	Area Control/ Problem-solving	59.2449	8.1634
	2	Area Control/ Objective-oriented	59.9036	8.1855
	3	Local Control/ Problem-solving	58.5951	8.1413
	4	Local Control/ Objective-oriented	58.4826	8.1375
PBS	1	Small escorts	78.7288	8.7320
	2	Medium escorts	42.8334	7.5146
	3	Small & medium escorts	44.2714	7.5807
	4	HVU-based escort teams	70.3925	8.5082
Find/Fix	1	Visual detection	57.28653	8.096131
	2	Visual detection with surface search radar support	60.82659	8.216054
Finish	1	Organic weapons	49.5370	7.8054
	2	Organic weapons & armed helicopters	64.7897	8.3423
	3	Organic weapons and USVs	53.5537	7.9614
	4	Organic weapons, USVs, & armed helicopters	68.3459	8.4492

3.5. Optimal, Cost-Effective MTR SoS Architecture

Both Figure 2 and Table V show that SNR_{12} is the largest value among the values $SNR_{1\alpha_1}$, SNR_{21} maximum among the values $SNR_{2\alpha_2}$, SNR_{32} the largest among the values $SNR_{3\alpha_3}$, and SNR_{44} maximum among the values $SNR_{4\alpha_4}$. In other words, the maximum signal-to-noise ratios are obtained with factor 1 at level 2, factor 2 at level 1, factor 3 at level 2, and factor 4 at level 4. This means that, as displayed in Table VI, the optimal cost-effective MTR SoS architecture consists of Area control/Objective-oriented for C4ISR, Small escorts for PBS, Visual detection with surface search radar support for Find/Fix, and Organic weapons, USVs, and armed helicopters for Finish. As shown in Tables II and V and Figure 3, this optimal cost-effective MTR SoS architecture results in a 0.72 probability of mission success and costs $188.6 M. Figure 4 shows the high-level operational concept of the optimal, cost-effective MTR SoS architecture. The operational environment is San Francisco Bay. The dashed line indicates a route (threat path) potentially taken by the attacker. The potential targets are the commercial traffic. The placement of the SoS components, which does not necessarily reflect realism, is intended to show their SoS membership, with the names of the SoS components placed as close as possible to the components. The "lightning strokes" depict the communications among the SoS elements.

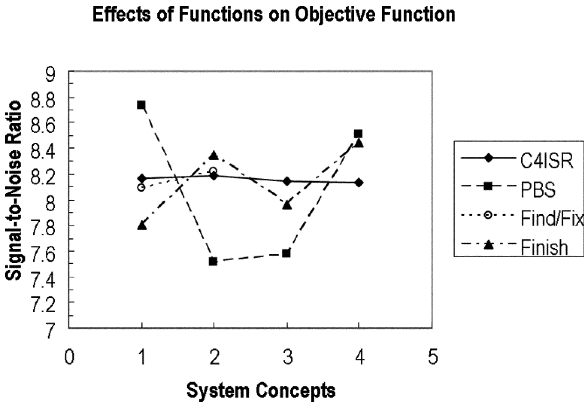

Figure 2. Effects of the SoS functions on the objective function.

Table VI. Allocation of System Concepts to Top-level Functions in the Optimal Cost-effective SBA SoS Architecture

Function	System Concepts			
	1	2	3	4
C4ISR		Area Control/ Objective-oriented		
PBS	Small escorts			
Find/Fix		Visual detection with surface search radar support		
Finish				Organic weapons, USVs, and armed helicopters

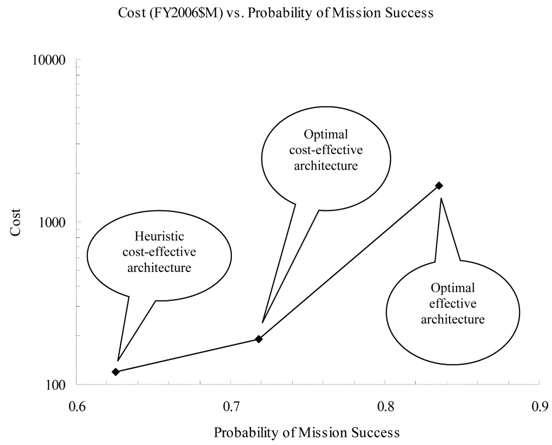

Figure 3. Cost-effectiveness of the heuristic cost-effective, optimal cost-effective, and optimal effective SBA SoS architectures.

4. COMPARISON OF RESULTS

To verify that the resulting cost-effective SoS architecture is indeed a "best" architecture, we compare its performance and cost with those of two additional architectures, namely, a optimal effective SoS architecture and a heuristic cost-effective SoS architecture. The Taguchi method is also employed to develop the optimal effective architecture, but with the objective function being the probability of mission success; the cost is not considered. The heuristic cost-effective SoS architecture is based on the collective experience of the SEA class [Kessler et al., 2006] and consists of the lowest cost system concepts that would meet system effectiveness requirements. Table VII shows the components of these two architectures along with those of the optimal cost-effective SoS architecture.

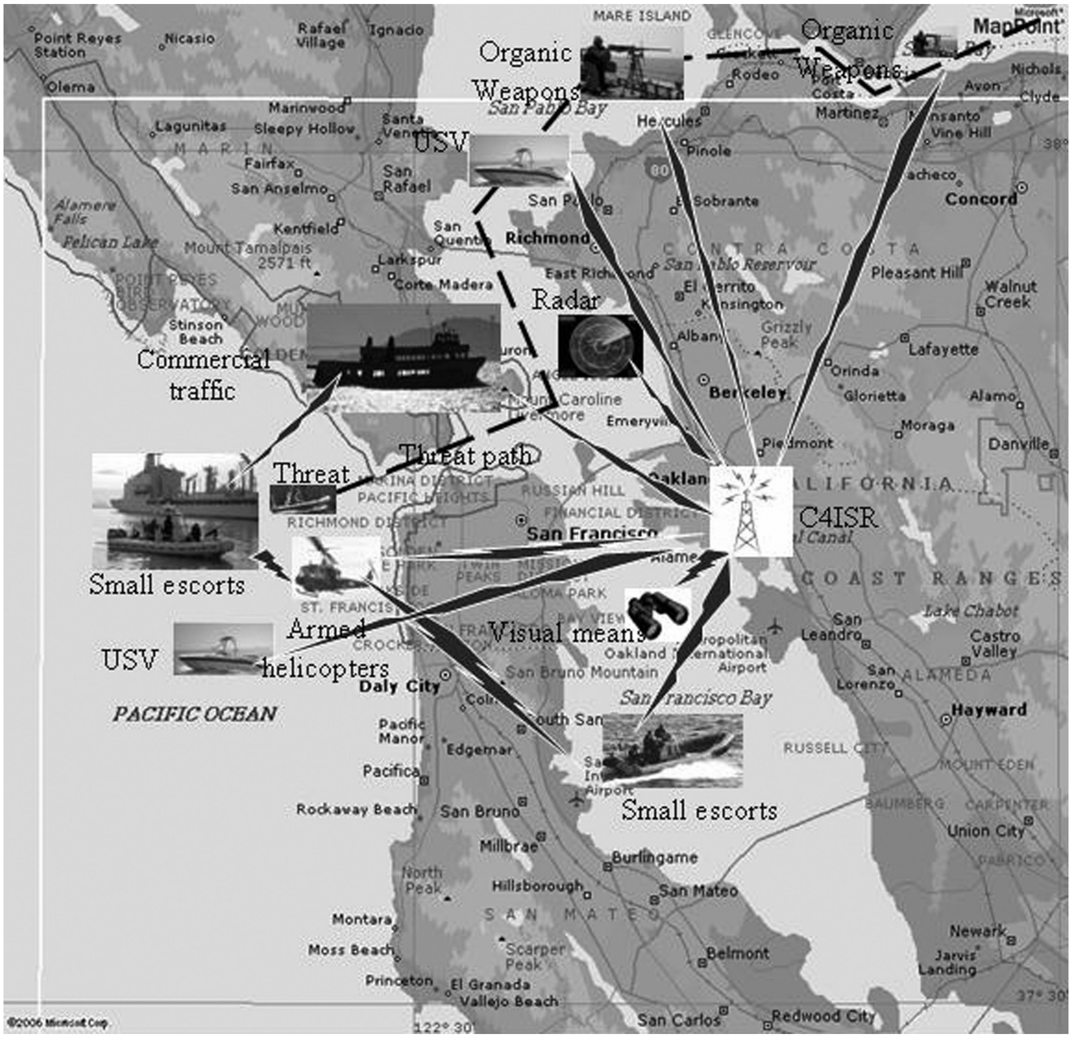

Figure 4. The high-level operational concept of the MTR SoS countering small boat attacks in the San Francisco Bay.

Table VII. Allocation of System Concepts to Top-Level Functions in the Heuristic Cost-Effective, Optimal Cost-effective, and Optimal Effective SBA SoS Architectures

Function	System Concepts		Architecture		
			Heuristic	Optimal Cost - effective	Optimal Effective
C4ISR	1	Area Control/ Problem-solving			
	2	Area Control/ Objective-oriented	X	X	
	3	Local Control/ Problem-solving			
	4	Local Control/ Objective-oriented			X
PBS	1	Small escorts	X	X	
	2	Medium escorts			
	3	Small & medium escorts			X
	4	HVU-based escort teams			
Find/Fix	1	Visual detection	X		
	2	Visual detection with surface search radar support		X	X
Finish	1	Organic weapons only			
	2	Organic weapons & armed helicopters	X		
	3	Organic weapons and USVs			
	4	Organic weapons, USVs, & armed helicopters		X	X

Figure 3 shows the cost-effectiveness curve, which depicts the cost of each architecture against the probability of success for the SBA mission. The "knee" in the cost-effectiveness curve corresponds to the optimal cost-effective architecture. The large difference between the cost of the optimal effective architecture and those of the two cost-effective architectures is caused by the cost of procurement of the requisite number of medium escorts. As shown in Table II, the cost for procurement of the combined small and medium escort force in the optimal effective architecture for the SBA mission is roughly \$1584 M; the cost for procurement of the only small escort force in the two cost-effective architectures is approximately \$93 M. A roughly 1603% increase in the SBA mission cost results in only an approximately 16% improvement in the probability of mission success over the optimal cost-effective architecture. Furthermore, the USVs in the optimal cost-effective architecture provide roughly a similar improvement in the probability of mission success over the heuristic cost-effective architecture, but at a cost of only about \$38 million, which equates to a 34% increase in cost. Also, while its performance is not significantly higher than that of the heuristic cost-effective architecture, the optimal cost-effective architecture provides an order of magnitude greater improvement per unit cost than that provided by the optimal effective architecture. The Taguchi approach does thus lead to a "best" MTR SoS architecture for the SBA mission.

5. CONCLUSION

As in Huynh [1997] and Huynh and Gillen [2001], our exploratory work here establishes the applicability of the orthogonal array experiment (or the Taguchi method) to optimizing an SoS architecture.

The crux of the MTR SoS architecting problem in this work is to develop architectures of a conceptual, cost-effective, near-term system of systems (SoS) to respond to terrorist threats to the United States that emanate from the maritime domain—in particular, to small boats used by terrorists to attack maritime commerce traffic and critical shore infrastructures. To solve this SoS architecting problem, we formulate it as an assignment problem which is then solved using the orthogonal array experiment. The orthogonal array experiment approach allows us to solve this assignment problem by carrying out the smallest possible number of experiments and determining the solution from the responses of the experiments. It is efficient and, for this class of problems, provides an optimal cost-effective architecture for the MTR SoS. The results discussed in this paper underline this successful exploratory work in architecting an SoS.

This work provides some insights into the SoS solution to the problem of maritime threat response to SBA in the 5-year timeframe. Further research is needed to provide additional insights into the following areas.

While armed helicopters appear to be useful in countering a small boat attack, it is not clear, however, whether their usefulness results from their ability to scout sea space ahead of the protected vessel and warn incoming boats, their ability to be a rapid reaction engagement platform, or both. The area in which armed helicopters add value to the overall SBA architecture thus need be isolated; this in turn could ascertain increased effectiveness of such helicopters.

Nonlethal weapons are useful in warding off innocent boats that venture too close to protected vessels in the counter SBA mission. However, an attacking boat would presumably continue to press its attack even in the face of such nonlethal weapons engagement by MTR forces. An analysis is needed to assess the effectiveness of the use of nonlethal weapons in securing prisoners possessing potential intelligence value while reducing the likelihood of civilian casualties in the case that a failed nonlethal weapons engagement necessarily precipitates lethal weapons employment.

This work considers a formation in which a protected vessel has an escort vessel in front, behind, and to each side of it. Future work needs to examine other formations and their potential benefits such as a possible reduction in the required number of escort forces. The potential difficulties associated with multiple attackers, decoy attack boats, and other concerted terrorist efforts also need be analyzed. An SBA countering concept need be developed to deal with a situation in which the terrorist attack boat en route to the protected vessel would engage the escort vessels rather than simply attempt to bypass the escort vessels

The prohibition on recreational boat traffic upon receipt of intelligence suggesting a small boat attack can be implemented effectively. However, what is the most efficient method to clear the bay of nonessential boat traffic? A study could be devoted to finding such a method.

Furthermore, a detailed analysis is needed to assess the technologies, control system capabilities, and costs of the USVs.

Finally, the SoS architecting methodology espoused in this paper can be extended to architecting other systems of systems. Such extension will require appropriate orthogonal arrays to reflect the required SoS top-level functions and the system concepts selected for these functions. In this work we deal with a small number of system-level functions (factors) and a small number of related system concepts (levels) and hence a small and readily available orthogonal array. For any SoS that has a large number of system-level functions and a large number of associated levels, a large orthogonal array is needed. Large orthogonal arrays can be generated or obtained from the American Supplier Institute [ASI].

ACKNOWLEDGMENTS

We thank Brian Connett, Chewy Chiurourman, and Mike Shewfelt for useful discussions. We also thank three anonymous reviewers for their useful comments, which helped improve the paper.

ACRONYMS

C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CIP	Common Intelligence Picture
COP	Common Operating Picture
FRC	Fast Response Cutter
HVU	High Value Unit
MDA	Maritime Domain Awareness
MMA	Major Metropolitan Area
MTR	Maritime Threat Response
NPS	Naval Postgraduate School
O&S	Operating and Support
PBS	Prepare the Battlespace
PC	Patrol Coastal
POR	Program of Record
P_s	Probability of Success
RDT&E	Research, Development, Test, and Evaluation
RHIB	Rigid Hull Inflatable Boat
SBA	Small Boat Attack
SEA	Systems Engineering and Analysis
SNR	Signal-to-Noise Ratio
SOP	Standard Operating Procedures
SoS	System of Systems
U.S.	United States
USCG	United States Coast Guard
USN	United States Navy
VAMOSC	Visibility and Management of Operating and Support Costs
PACAREA	Pacific Area

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