Defence Science Journal, Vol. 64, No. 4, July 2014, pp. 366-370, DOI : 10.14429/dsj.64.4486

Requirements Analysis of an Integrated Sonar Suite for Surface Ships : Systems Engineering Perspective

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ABSTRACT

Modern day combat warships are an integration of a large number of subsystems and components. Each of these systems communicates to a common combat management system. Anti-submarine warfare systems being an integral part of the combat management system, integration of multiple types of sonar systems or integrated sonar suite (ISS) offer complete solutions and tactical advantage against a potential threat. The operational requirements, the environment, the functional requirements and physical configuration of ISS are all discussed in this paper from the systems engineering point of view. Innovative methods are presented to capture the user requirements of ISS without compromising the classified nature of the subject.

Keywords: Anti-submarine warfare, sonar, requirements analysis, active sonar, passive sonar, classification, torpedo decoy, validation

1. INTRODUCTION

A centralized command centre is the heart of combat management in any naval warship. Typically known as combat management system (CMS), it is a complex system that involves multiple elements that integrates different types of sensors, weapons, decoys, machines, communication, operational commanders, operators and also real-time tactical intelligence[1]. CMS systems have over the years improved steadily in their functionality and effectiveness when compared with the earlier systems like CAIO, BIUS, IPN-10, etc. Typical configuration of CMS for a modern war ship includes integration of electronic warfare, navigation, anti-submarine warfare (ASW), air-to-surface defense, air-to-air defence, helicopter/fighter aircraft control systems, etc. Sonar systems which are primarily responsible for all ASW operations form an important arm in the CMS configuration. Integrated sonar suite (ISS) is an integrated system of more than one type of sonar(s), all communicating and operating under a single display and control station and forms part of the ASW system[2].

The defence services release out quality requirements (QRs) to Defence Research & Development Organisation and companies for design and supply of new systems. QRs are in the form of specifications which include operational, functional, maintenance and physical requirements. A preliminary solution design is already proposed by the user itself at this stage which may not meet the user requirement completely. The requirements arising out from other stake holders namely, the production partners and maintainers, etc are also to be considered[3].

The focus of this paper is to highlight the importance of ISS and suggest solutions from systems engineering discipline to capture the actual user requirements without compromising the classified nature of the subject.

Systems engineering is an interdisciplinary approach that integrates various disciplines and functional groups into a team effort forming a structured development process for complex systems[4,5]. It is holistic and stresses the importance of requirements study and analysis as one of the most important tasks to be carried out prior to undertaking any system development.

In the paper, an outline introduction to ASW and CMS is followed by the basic capability requirements envisaged for an integrated Sonar suite. A brief description of the concept of operations (CONOPS) as applicable to ASW operations is given. A compliance matrix is generated to verify whether the requirement analysis study and the concept abstraction is complete and it meets the requirements of IEEE P 1220 standard.

2. INTEGRATED SONAR SUITE CONCEPT

Concept of integrated sonar suite (ISS) is new and not common among navies of the world. ISS systems work primarily on data association and fusion thereby giving an integrated ASW picture. ISS is perceived to be fully automatic in operation for detection, classification and localization of different types of targets. Fire control solutions (FCS) work on passive and active sonar data to accurately find out the target range, course and speed and also classify the type of target. Data fusion and track correlation helps in track assignment in the case of crossing targets. ISS is aided by an integrated sonar

Received 11 April 2013, revised 18 March 2014, online published 21 July 2014

prediction model which helps in prediction of expected sonar range from real time bathymetric data.

The need for development of an integrated sonar suite for surface ships was necessitated by the focus of ASW on littoral warfare. The thrust of surface ship ASW missions are mainly two fold. The first and foremost requirement is to sanitize the littoral waters[6] and secondly undertake cooperative engagement against any possible torpedo/weapon threat. The integrated sonar suite shall be inducted in surface ships of naval forces undertaking ASW missions.

The following objectives are to be essentially met by the ISS.

- Active detection, tracking, classification and target motion analysis (TMA) of submerged targets
- Passive detection, tracking, classification and TMA of submerged targets
- Torpedo detection, classification using sonars and soft kill decoying using expendable decoys.

3. REQUIREMENTS ANALYSIS OF ISS FROM THE SYSTEMS ENGINEERING PERSPECTIVE

Requirements analysis and engineering represents a series of engineering decisions that lead from recognition and detailed specification of that problem[7]. Continuous interaction and detailed discussions with the user shall be held in the requirements engineering phase. Systems engineering advocates three perspective views to elicit and not merely gathering the requirements[8]. A brief study on the CONOPS is mandatory at this stage. CONOPS focuses on the system operation in the intended environment rather than the functional specifications of the system. CONOPS can identify a few scenarios to describe how the intended goals or user requirements are to be met[9]. These scenarios shall form the basis for future validation of performance of the system.

3.1 Anti-Submarine Warfare CONOPS

For successful ASW, naval fleets usually combine all its surface, air and subsurface assets and use them tactically[10]. The scouting of a submarine and ASW engagements happens in three distinct phases. They are detection, localization and targeting of the contact.

ASW screens are formed in career fleet groups to protect a high value unit (HVU). Area ASW is the first level and carried outside the ASW outer screen. This is generally performed by units with high endurance and potency. Maritime patrol craft and also ships with long passive towed array sonar systems are typically used for this purpose. Local ASW operation is carried out within the outer screen i.e. at roughly 12 to 25 nautical miles from the main unit.

4. REQUIREMENTS ANALYSIS - OPERATIONAL VIEW

The operational view addresses how the integrated sonar suite system shall serve the ASW requirement of surface ships of Navy. The following operational concept matrix[11] (as shown in Table 1) shall detail the operational specific requirements such as need definition, operational sequence, operational constraints, basic mission requirements, typical operational environments, etc.

5. REQUIREMENTS ANALYSIS - FUNCTIONAL VIEW

Processing of sonar sensor data for useful information is known as Sonics. The functional view[11] focuses on the functional specifications in the staff QRs and includes the input requirements, the outputs expected from the system in both qualitative and quantitative terms. The evaluation methodology and acceptance criteria for each of the performance parameters also should be specified. Some of the technologies of interest in ASW are given below.

5.1 Low Frequency Active Acoustics

The active sensors in use have achieved only short detection ranges because of high/medium frequencies employed. Tyler[12], suggest frequency ranges of the order of 1.5 kHz - 3 kHz to be optimum for active sonar performance.

5.2 Broad Band Active Transmission

Effective ASW requires multi-band transmission frequencies. Hence the transducer differential spread should be large extending upto 10 kHz. Flex tensional transducer technologies and new high energy transduction materials (PMN, Lead magnesium niobate) are promising.

5.3 Sonar Signal Processing

Some of the signal processing techniques of interest include,

(a) Adaptive beam-former minimum variance distortion less response (MVDR) is used for both passive and active sonar detection processing[13]. It provides a narrow beam width and low side lobe levels compared to conventional beam-former as shown in Fig.1.

(b) Transmit wave form control for active detection can incorporate selectable band widths and time frequency characteristics.

(c) Using non-uniformly spaced multi-octave towed array.

(d) Net worked towed array sends the data from the array to onboard as ethernet packets. This enhances the signal

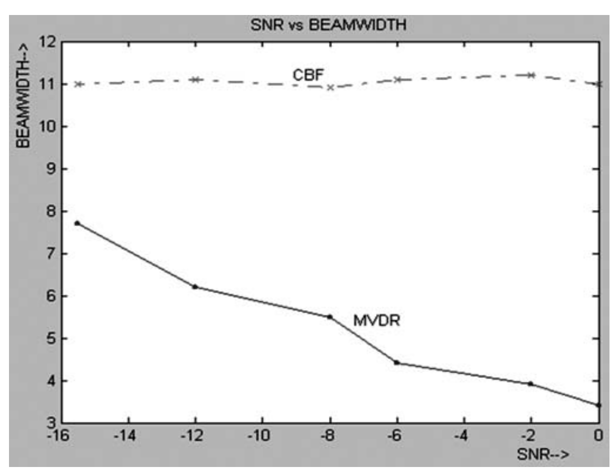

Figure 1. Comparison of beam width- conventional and adaptive beam former (MVDR).

Table 1. Operational concept matrix for integrated sonar suite for surface ships

Parameter	Requirements	Remarks
Operational need definition	• To insonify the above layer conditions. • Long range passive and active detection of targets • Multi-static or bi-static operation • To detect and characterize active transmissions from other sonars • Perform required active and passive TMA • Interface and network with existing sensor networks within the platform like RADAR, AIS and possibly carryout multi-sensor data fusion.	The following sonar systems can possibly meet the requirements specified. • Hull/bow mounted sonar • Towed active passive sonar array • Intercept sonar • Soft kill acoustic decoys, towed and expendable
Operational sequence	• Early target detection using towed array or Hull/Bow mounted sonar. • Target localisation • Target classification using target information processing • Target motion analysis using target parameters.	
Operating sea states	• Hull/mounted sonar - sea state 4. • Towed systems - sea state 3.	
Critical events to which system must respond	• Auto detection and evading torpedo attack. • Acoustic countermeasure against torpedo	
Platform operational constraints	• Maximum ship speeds with towed sonar @ 22 knots -24 knots. • Maximum ship speeds without towed array @ 28 knots-32 knots.	This may vary depending upon the type of platform.
Basic mission requirements	• Scouting of fleet movement • Battle field sanitization • Torpedo detection and decoy	
Operator requirements	• Minimum human intervention. • Automatic operation	
System operational control	Ship ASW officer	System status indicator panels for info

quality as the digitization happens very near to the hydrophone.

(e) Automatic track initiation is done using techniques like Hough transforms.

(f) Target range computation using Kalman filter.

(g) Passive classifier system receives spectral inputs-like DEMON, LOFAR, and broad spectrum from track processor and does the feature extraction and classification.

(h) New display techniques: Multi-function consoles, Windows like GUI, context sensitive menu, touch input device, Frequency-azimuth display, FDS with network view, map overlay, web interface, radar target information overlay, ECDIS information overlay, etc.

6. REQUIREMENTS ANALYSIS - PHYSICAL VIEW

The different components of ISS are Hull mounted sonar working in active and passive modes, active towed array sonar system, torpedo defence system and intercept sonar. Each of these sonars work in different frequency ranges and contributes to data association. Thus the physical configuration of ISS consists of wet end system, weather deck equipment and on-board electronics as shown in Fig. 2.

The wet end system is composed of subsystems which are in direct contact with the sea water. Thus

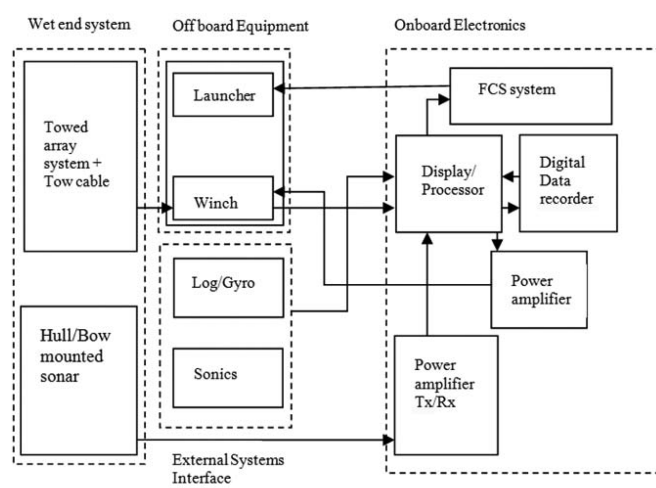

Figure 2. Typical configuration- integrated sonar suite.

in the case of ISS, the hull mounted sonar sensors, the towed array sonar and the tow cable all form part of the wet end system. The towed array is required to be linear and stable under steady state towing conditions. The design and component densities are chosen such that the array is neutrally buoyant. It is kept in straight configuration by the drag forces in towing. The towed array is lowered to the desired depth of operation using the tow cable. The cable is negatively buoyant. Depth keeping of array is achieved by adjusting cable paved out length and speed of the platform.

Weather deck equipment are those which are installed on the sheltered and unsheltered environment in the platform. Winching systems are critical and used for quick launch and recovery of towed array sonar and cable. The winch system has multiple speeds and also is designed with a number of safety interlocks to protect the towed array sensors. Automatic spooling of towed array and cable ensures even winding of the same on winch drum.

A pneumatically powered launcher is used for deploying the expendable decoy. These units should fit in the quarter deck area of standard frigate class of ship. Typical volume space available for installation is of the order of 2 m x 2 m x 2 m and static weight of the system shall be of the order of 5 tons.

The onboard electronics consists of sonar processing and display subsystems apart from power supplies and power amplifiers. They are to be located inside the ship with proper ambient temperature control. The major subsystems are processing cabinets and display unit, fire control processing electronics cabinet, digital data recorder unit, power amplifiers and power supplies, etc. These subsystems are to be protected from environmental parameters like shock, vibration, etc.

Detection and classification of target in ISS: Early detection of the target shall happen in either Hull mounted sonar or passive towed array. The low frequency analysis and ranging (LOFAR) information of the target and demodulated noise (DEMON) data is obtained from the passive towed array sonar data. From active sonar mode, the operator gets a feel about the size of the target. Also every time an unknown target is picked up, all essential parameters like the frequency, pulse width, pulse repetition rate, etc. of the received signal are all monitored, annunciated and stored. In addition, the operator is also able to identify a target based on perceptual features like timber, tone, echo decay, etc. With pattern recognition, it is possible to easily identify a known target data. Thus any unknown signature can be easily identified by estimating its frequency and bandwidth.

7. VALIDATION OF REQUIREMENTS ANALYSIS STUDY

IEEE P 1220 system engineering standard[14] clearly specifies fifteen requirement analysis tasks that should be consulted while preparing design and development activities to help, identify and structure appropriate activities. Also these tasks are not sequential even though they build on each other. Every task contributes an understanding which will prompt us to revisit the previous task decisions.

IEEE P 1220 is holistic and a quick compliance study. Using this standard helps us to verify whether the requirements analysis activity is complete and all the user requirements, system life cycle requirements, etc. are completely addressed.

The requirements study and analysis carried out on ISS is now compared with IEEE P 1220 standard for its compliance. The matrix of compliance is given in Table 2.

Table 2. Requirements analysis comparison with IEEE P 1220 standard

Tasks as per IEEE P1220	Result	Remarks
User expectations		
1 Operational requirements	√	
2 Functional requirements	√	
3 Mission needs	√	
4 Duty cycle	√	
5 Availability of system	√	
6 Configuration of the system	√	
Project constraints		Shall not form part of requirements analysis
1 Subsystem design base lined with existing systems	√	
2 Project performance monitoring	X	
3 Costs	X	
4 Project team structure	X	
Hardware and software standards		
1 Communication standard	√	
2 Hardware configuration	√	
3 Documentation standard	√	
Whether operational scenarios are defined	√	
Measures of effectiveness/ acceptance criteria	√	Shall not form part of requirements analysis
Upgradability of software and hardware	√	
Life cycle support requirements	X	
System boundaries - Effect of environment and external elements not under design control (eg: Target signature, strength, etc)	√	
Interfaces with other systems	√	
Operational environments	√	
Identify key life cycle processes	√	
Functional requirements	√	
Performance requirements	√	
Modes of operation	√	
Technical performance measures	√	
Physical characteristics (e.g., color, texture, size, weight, buoyancy).	√	
Human factors (e.g., physical space limits, climatic limits, eye movement, reach, ergonomics)	√	

8. LIMITATIONS

The subject data and methods available for analysis in this paper present several important limitations owing to its classified nature. Tactical information pertaining to ASW and details on ASW missions are not elaborated due to classified nature. Any use of the values herein will be tempered by above said limitations.

9. CONCLUSIONS

The paper gives an overview of the integrated sonar suite and presents methods to elicit user requirements by application of principles of systems engineering. Requirements study and analysis of ISS is carried out and preliminary system configuration is evolved based on operational, functional and physical requirements. This approach using systems engineering principles improves the development quality of the prototype system. Also discussions of CONOPS shall set the basis for evaluation and validation of prototype system.

10. FUTURE WORK

After completing the concept design, it is essential to continue the pre-engineering activities by generating the performance based specifications. The important functional and performance requirements are generated using systems engineering concepts like 'House of quality'. Further abstraction tools and functional analysis shall generate the functional architecture. Using standard procedures like brain storming etc, solution principles can be evolved for the basic system problems and candidate solutions can be synthesized. Using multiple trade off studies, the number of candidate solutions can be reduced to the feasible ones.

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