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Software Defined Sonar Architecture for realising Torpedo Defence Systems

Jomon George and T. Santhanakrishnan

Naval Physical and Oceanographic Laboratory, Thrikkakara P.O., Kochi-682021, Kerala, India.

Abstract

Conventional torpedo defence system for surface ships are realised using custom designed hardware modules to perform complex signal processing functions for torpedo detection, localisation and deployment of counter measures. Adding new requirements or modification of existing features after system finalisation may generally lead to changes in the hardware, which is time consuming and expensive. Software Defined Sonar (SDS) is an emerging trend in realising sonar systems. SDS systems are realised using programmable embedded hardware modules to perform signal processing, information and display processing functions. In SDS, software decides the sonar configuration. This enables the use of general-purpose hardware platform to perform different functions. With the presence of multiple reusable modules running on a generic hardware platform, the system can instantly change functionality based on the selected system configuration. New features and capabilities can be added to existing infrastructure without requiring major new capital expenditures. The software centric torpedo defence system is realised using the flexibility of programmable embedded commercially-off-the-shelf hardware modules. With suitable inputs, the system can be configured to switch between different modes of operation.

Keywords: Sonar, Torpedo Defence System, Software Defined Sonar, Hardware architecture.

1. INTRODUCTION

Torpedoes are considered as the deadliest underwater weapon against surface ships [1]. Protecting surface ships from torpedo attack is considered as the most important task in underwater warfare. Torpedo Defence System (TDS) is a complex Sonar system fitted onboard surface ships for defending underwater torpedo attacks [2] [3]. TDS can be considered as a unique model of System of Systems because of its complexity [4]. Torpedo detection, classification, localisation and countermeasures against torpedo attack are the major functions of TDS. These systems are realised using large complex electronic hardware modules tuned for executing specific functions required for defending torpedo attack. In case of damage or a slight modification of the existing hardware or for the addition of a new functionality to the existing systems, the only option left is to discard the hardware to get it replaced with the new one. Continuous up gradation of TDS is an essential requirement for obtaining torpedo defence capability in line with new torpedo technology developments to maintain tactical supremacy. Software Defined Sonar (SDS) architecture is proposed in this paper as a unique solution to meet this requirement. SDS is an emerging technology, which is devised for realising flexible and reconfigurable sonar systems. Fast realisation, ease of maintenance, ease of up gradation with new features and capabilities without major hardware changes are some of the major advantages in using SDS architecture.

The concept of SDS is originally taken from Software Defined Radio (SDR) technology [5]. The aim of SDR approach is to implement as many of the system functions as possible in software using programmable general-purpose hardware for realising radio communication systems. SDR technology was later adapted to realise Radar systems. A software-defined radar is a versatile radar system, where most of the processing like signal generation, filtering, up and down conversion etc. is performed by software [6] [7].

Software Defined Sonar is the latest advancement in the field of the acoustic target localisation systems. In sonars based on SDS architecture, some or the entire functions of the sonar are implemented using software defined reconfigurable modules. These configurable modules can be rearranged with suitable inputs in order to realise multiples of basic modules. Major portion of the functionality is implemented through programmable signal processing devices to include new features and capabilities. A software defined approach reduces the content of analog components and emphasises digital signal processing to enhance overall receiver flexibility. SDS performs significant amount of signal processing in high-speed programmable general-purpose processors. The objective is to produce a single hardware platform to handle different sonar functions using the reusable components with the necessary inputs to handle complex scenario. These are emerging in commercial and military infrastructure. This growth is motivated by the numerous advantages like ease of design, ease of manufacture and use of advanced signal processing methods. As a result, the impact will be enhanced range and improved system performance while reducing overall infrastructure cost for the service provider.

2. SOFTWARE DEFINED SONAR TECHNOLOGY

Software defined sonar is defined as, "sonar in which some or all of the physical layer functions are software defined". Traditional hardware based designs have the disadvantage of cross-functionality and its modification is made through physical intervention. These designs decide the number of sensors, maximum operating frequency, band of operation, sampling frequency and type of sensor array at the very development stage itself. Once developed, these systems cannot be modified and remained static throughout its life cycle [8] [9]. This poses higher production costs and minimal flexibility in supporting multiple functions. In contrast, SDS technology gives an efficient and comparatively cheap solution to this problem, allowing multi-mode, multi-band and multifunctional devices that can be enhanced using software-centric technology insertion. The use of SDS technology allows new sonar features and capabilities to be added to existing sonar systems without requiring new hardware. Benefits of SDS technology are listed below.

1. Software/hardware reuse across SONAR platform reduces development costs of new features and functions.
2. Remote programming allows sonar to upgrade while it is in operational mode, thus reducing the time costs associated with it.
3. New features and modules can be added to existing infrastructure as and when needed without extra expenditures.
4. Common SONAR platform architecture reduces logistical support and operating expenditures

SDS defines a collection of hardware and software technologies where some or all of the sonar. SDS is not restricted to operation on a single frequency or proprietary transducers. As such, it can serve a wide variety of legacy sonar applications and can support rapid development and deployment of novel sonar solutions. Significant amounts of acoustic signal processing are done in software rather than dedicated hardware. The system increases underwater tactical capability, improves functionality, enhances signal processing and substantially reduces costs - all while replacing racks of legacy sonar equipment. A typical SDS system configuration is given in Fig. 1.

Main system functions of SDS are implemented through modifiable software or firmware operating on programmable embedded processor modules. The software-centric design integrates the flexibility of programmable Digital Signal Processors (DSP) with the reconfigurable logic of Field Programmable Gate Array (FPGA) or an embedded Single Board Computer (SBC). Waveforms can be executed efficiently with signal processing streamlined using the DSPs, hardware-intensive functions processed on the FPGA and network protocols and Human Machine Interfaces (HMI) can be implemented on a reconfigurable embedded SBC.

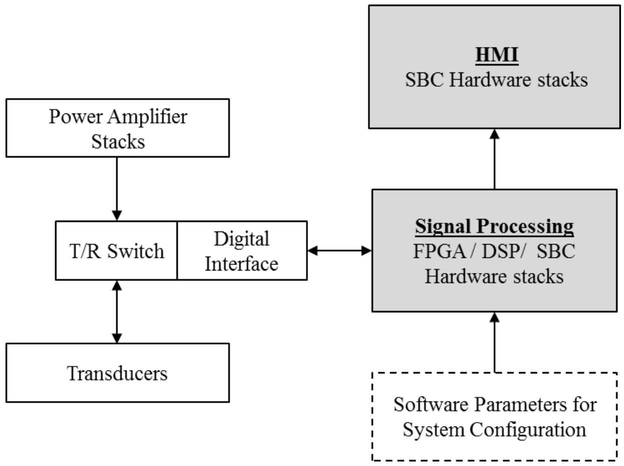

Fig. 1. Typical SDS system configuration

General purpose hardware platforms are stacked together to meet computational requirements for realising complex sonar systems. These stacks are integrated using standard backplanes like VME or VPX and data communication is through standard Ethernet protocols. The SDS hardware platforms exploits commercial processing development and enables onboard computing power to grow at the same rate as commercial industry. This facilitates regular updates to both software and hardware with minimal impact on operational scheduling. Software Defined Sonar can substantially reduce system cost while at the same time significantly improving existing and future tactical capabilities.

Sonar processing can be configured through software parameters. These parameters can be selected through HMI or through configuration software running on a system PC.

3. TORPEDO DEFENCE SYSTEM BUILDING BLOCKS

TDS can be viewed as a combination of multiple systems working together cohesively to achieve the common goal of defending torpedo attack on a surface ship. The two essential functionalities of a torpedo defence system are to detect the torpedo and to help the platform to evade its attack [10]. Main objectives of a torpedo defence system are:

- detection and tracking of targets around the platform at maximum range
- identification and classification of torpedo targets
- localisation of torpedo targets
- threat analysis and recommendation of evasive manoeuvres,
- effective use of countermeasures to evade torpedo attack.

Major elements of a torpedo defence system are:

- set of acoustic and no acoustic sensor arrays to sense inbound torpedo threat,
- signal processor to detect and track targets,
- information processor to classify and localise torpedo targets,
- HMI processor to provide human machine interface through displays,
- a set of range of countermeasures to protect platform from torpedo attack.

Building blocks of a torpedo defence system are given in Fig. 2.

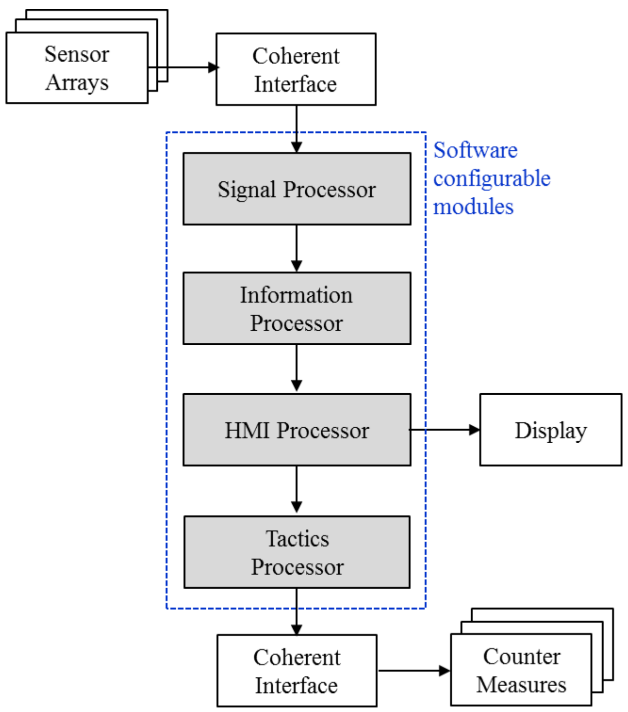

Fig. 2. TDS Building Blocks

3.1 Sensor Arrays

Torpedo detection is achieved typically using passive mode of sonar operation. A set of acoustic and non-acoustic sensor arrays operating in the passive mode are used to collect input signals required for detection processor. Hull mounted array, Towed array, Intercept array, Flank array and Non-acoustic sensors are the different types of sensors used for torpedo detection.

3.2 Coherent interface

After front end processing, sensor array data is digitised and converted to Ethernet format and forwarded to signal processor for extracting information from sensor data. Coherent interface module ensures simultaneous sampling, time synchronisation, signal gain control and seamless interface with signal processor module.

3.3 Signal Processor

Detection, tracking and identification of torpedo targets are the primary requirement of TDS. Target parameters extracted from the signals received through different sensors are used for torpedo detection and classification [11]. Torpedo bearings, frequencies, modulation frequencies are some of the features used for torpedo classification. Signal processor does audio processing also to aid detection and classification of targets.

3.4 Information Processor

Classification of torpedo targets and computation of target motion parameters are the main functions of information processor. Target parameters extracted by signal processor are used for torpedo classification. Target motion parameters like range, course and speed are estimated from the passive target bearing information. Target motion parameters can also be derived using data association technique. The target bearings observed by different sensors located at different geometrical locations are used for computing target parameters.

3.5 HMI Processor

Signal processor and information processor outputs are presented in display for user interface by HMI processor module. Processed information is presented in multiple display formats like detection page, track page, target parameters page, classifier page, fault diagnostic page and tactics page. User inputs like system configuration parameters, inputs for signal processor algorithms and display processing parameters are also fed through HMI processor.

3.6 Tactics Processor

In a multi-torpedo attacking scenario, threat evaluation and threat prioritisation are essential for effective torpedo defence. Recommendations for evasive maneuvers and tactics for counter measure deployment are finalised based on the threat scenario. Evasive maneuver is finalised as per the torpedo counter attack tactics [12]. Sequence of operation of counter measure devices and their modes of operation are finalised as part of torpedo defence tactics. Tactics processor analyses the situation based on available information and take tactical decisions to maximise escape probability in a given scenario.

3.7 Counter Measures

Counter measures are used to help the platform to evade torpedo attack. Countermeasure systems are interfaced with tactics processor through coherent interface module for ensuring signal integrity, compatibility and for providing time synchronisation. Soft-kill and hard-kill counter measures are used to counter torpedo attack [13] [14]. In soft-kill, the torpedo is lured away from the platform and controls its trajectory using decoys till its battery-life gets exhausted. In hard-kill, the attacking torpedo is destroyed by another torpedo, which is an anti-torpedo torpedo. Acoustic homing torpedoes can be seduced and misguided using false acoustic sources called decoys. Towed, expendable and mobile decoys are commonly used against both active and passive homing torpedoes. Wake-disturbing decoys are against wake-homing torpedoes. Anti-torpedo devices are used as explosives to destroy attacking torpedoes. The last stage in torpedo defence is attacking enemy launching platform through a counter attack to prevent further attacks.

A set of auxiliary systems like data storage systems, configuration manager and system to interface platform data are also part of TDS system configuration.

4 TDS WITH SDS ARCHITECTURE

Operational, functional and physical requirements of a torpedo defence system can be realised using SDS architecture. The hardware design approach proposed for the realisation of TDS using SDS architecture is based on a set of performance matrices. These criteria include:

1. *Flexibility and Reconfigurability*: The capability for configuring algorithms and protocols to interface with variety of sensor arrays and operating modes merely loading new software onto the platform or by reconfiguring exiting software.
2. *Adaptability:* The SDS platform should be able to adapt its capabilities as per the changes in network or traffic operational requirements.
3. *Computational Power*: The processing power of the SDS platform, namely Giga Floating-Point Operations per Second (GOPS).
4. *Capability to include new features*: Capability to include new feature like Artificial Intelligence (AI) for effective torpedo detection and classification with reduced reaction time and false alarm rate.
5. *Energy Efficiency:* The total power consumption and total heat energy dissipation. This is a major parameter required for finalising cooling requirements.
6. *Cost:* The total cost of the SDS platform, including time-to-market, development, and hardware costs.

TDS can be realised using SDS architecture with three groups of hardware modules as shown in Fig. 3. The first group is a set of sensor arrays with coherent interface modules, second group is the configurable processing hardware modules and the third group is the set of countermeasures with coherent interface modules. The first and third group is realised using custom made hardware modules with limited flexibility. The second group is realised using programmable and configurable Commercial Off-The Shelf (COTS) hardware modules. Availability, ease of use, maintenance support and multiple vendors are some of the advantages in using COTS components [15].

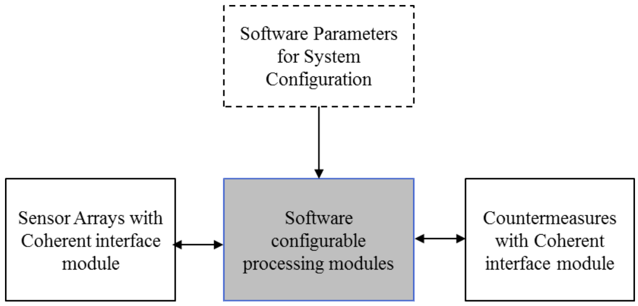

Fig. 3 Hardware modules for TDS with SDS architecture

4.1 Requirement analysis

Translating operational, functional and physical requirements to specifications is an important stage in system design phase [16] [17]. System requirements need to be captured as per systems engineering standards. Operational requirements such as basic mission requirements, performance needs, operational needs and boundaries need to be defined for finalising the building blocks of the system [4]. Functional requirements are to be defined for finalising computational requirement and selecting the hardware modules. Physical requirements of the system decide the final system configuration and location of various system units onboard platform.

4.2 Hardware architecture

Hardware configuration of TDS with SDS architecture is given in Fig. 4. Sensor array signals are interfaced with signal processing modules through Gigabit Ethernet data network. Output of signal processing modules are interfaced with information processor and other processing modules through Gigabit Ethernet control network. Separate data and control networks are maintained to control data rate in the networks. Data rate in data network is high compared to control network. Processing modules are realised using embedded processor boards with configurable software modules integrated on VME/VPX backplanes. Configuration manager configures the processing modules as per selected system configuration parameters.

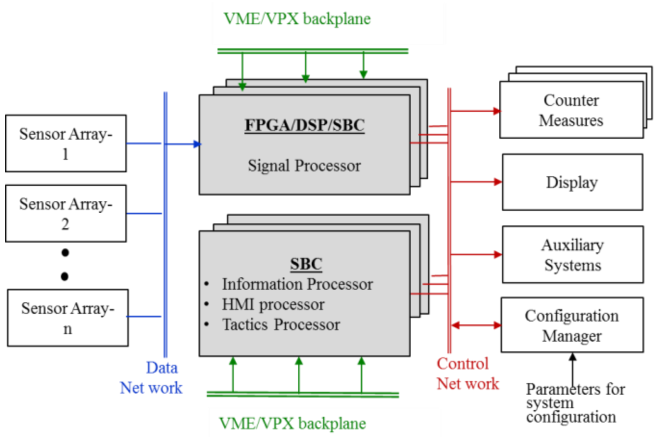

Fig. 4 Hardware configuration for TDS with SDS architecture

4.3 Processing modules

Processing hardware is realised using embedded processor boards integrated on a VPX or a VME back plane. These boards are to be selected based on the computational requirements. Signal processor is having the most computational requirement and embedded processor boards with FPGAs, DSPs or embedded SBCs with general purpose processor is used for this purpose. Embedded SBCs are used for realisng information processing, HMI processing and tactical processing. Performance comparison of DSP, FPGA and SBC boards are given in Table 1. Number of boards required for a system will be decided based on the computational requirements of the system.

Table 1: Performance comparison of embedded processor boards based on DSP (TMS320), FPGA(Xilinx Virtex-7) and SBC(Intel Quad Core- i7)

Processing hardware	DSP	FPGA	SBC
Clock frequency (GHz)	1.25	0.50	3.5
Processing power (GFLOPS)	160	750	180
Power Consumption (Watts)	50	35	70

4.4 Networking and data communication

Input-output interface for processing units are through Giga bit Ethernet or 10G. Separate networks are maintained for data and control interface. Systems are communicating using UDP/IP or TCP/IP. System to system interface parameters are clearly defined and data transfer is done using standard protocols. Network diagram of TDS is shown in Fig. 5.

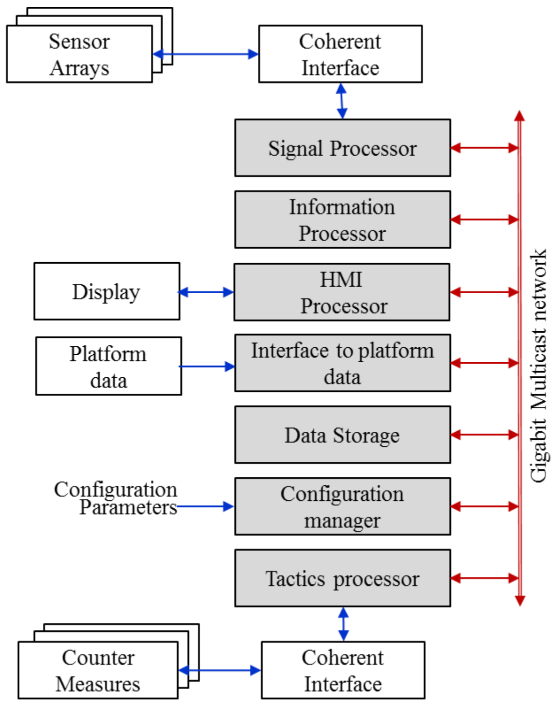

Fig. 5 Networking and data Communication scheme

VME64, VME64x or VPX are the common backplane standards used for realising embedded systems for mission critical systems. Data transfer rates of common interface standards are given in Table 2. Selection of back plane depends on the data transfer requirements and compatibility with selected embedded processing modules.

Table 2: Throughput in Mega bites /Sec and Mega samples/ Sec (16 bits/sample) of common interface standards

Interface	Mbits/s	MS/s
VME64	640	40
VME64x	1,280	80
VPX	10,000	625
Ethernet	100	6.25
Gigabit Ethernet	1,000	62.5
10 Gigabit Ethernet	10,000	625

4.5 Software architecture

Hardware obsolescence is a major concern in maintaining systems with longer lifecycle [18]. TDS systems are intended to be in service for 15-20 years. Hardware obsolescence is a major problem for system maintenance. Hardware independent software development strategy is proposed as a solution for tackling obsolescence issues. Processor independent software design need to ensure reusability and use of open source operating systems, libraries and functions. System software modules should be running on any hardware module with the help of a middleware. This middleware will ensure the compatibility of software with processing hardware. This development approach will ensure seamless replacement of obsolete hardware with available processing hardware any time during the lifecycle of the system without major software changes.

4.6 Parameters for System configuration

Configuration manager configures the processing modules to perform intended functions as per selected system configuration parameters. Configurable processing modules are marked in Fig. 2. Typical parameters required for configuring hardware modules are:

Sensor array parameters: Sensor array type, number of sensors, element spacing, frequency band, sampling frequency and ADC parameters.

Signal processing parameters: Beamformer parameters, detection processing parameters, integration time, CFAR processing parameters, target track parameters and spectral processing parameters.

HMI, Information and Tactics Processor parameters: Number of HMI pages, display parameters, platform parameters, countermeasure parameters, inputs for deployment and evasive tactics.

5. CONCLUSIONS

Detection and evading high speed modern torpedo within complex acoustic environment under high biological and shipping noise is a major challenge for modern TDS. Modern signal processing techniques like adaptive beamforming, tonal based tracking and advanced classification algorithms are essential for detecting and localising these targets. Flexible and configurable processing hardware modules with high computational power are essential for realisng state of the art TDS systems.

SDS architecture for TDS along with a possible implementation scheme is presented in this paper. Hardware configuration using COTS modules, data interface and system configuration scheme are discussed in detail. Scheme for hardware obsolescence management through software design is also discussed. This architecture can be expanded indefinitely in terms of number of arrays and channel count. This architecture promises considerable system flexibility, maintainability and upgradability. SDS architecture is capable of developing compact, reliable and cost effective torpedo defence systems.

Systems with wireless data communication protocols, auto configurable processing modules, hardware independent software modules without the use of custom-made middleware, development of flexible and programmable frontend interface modules are some of the areas of future research.

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