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Conceptual Design of Future Undersea Unmanned Vehicle (UUV) System for Mine Disposal

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***Abstract*—A conceptual design is proposed for an effective mine countermeasure (MCM) system, which consists of 3-unmanned underwater vehicles (UUVs) and 10-20 small charged deliverable vehicles. New underwater optical communication systems are introduced to improve onboard mine reconnaissance and decision making with the key technologies focused on system and communication efficiency, capability of data processing, and cost effectiveness of MCM systems. The proposed UUV MCM system is cost effective due to adapting disposable mine neutralization instruments, upgrading data process unit, and configuring optical communication system between heterogeneous underwater and surface vehicle units in operations. At the same time, efficient and reliable underwater optical and electromagnetic wave communication systems are also introduced and analyzed for future system applications.**

***Index Terms*—Mine Disposal System, UUV Technology, Conceptual System Design, System Effectiveness**

I. Introduction

THE sea mine, one of the most cost-effective naval weapons, represents a significant threat even to the most sophisticated warships. While originally equipped with a simple contact mechanism, it gradually became more advanced [1], [2], with incorporating a range of smart detonators. A wide variety of mine types is deployed today, and many of them are highly sophisticated [3]-[5]. Although mines attack individual targets, their effects can be far-reaching at fleet and theater levels. In practical, a naval force at sea might be obliged to modify its course of action due to the perceived or actual presence of mine. The disproportionate effect of a single mine strike might be enough to threaten mission accomplishment of combat forces. Some potential impacts of enemy mining operations include loss or delay in the arrival of carrier based air power, amphibious assault forces, equipment, and supplies pre-positioned afloat or ashore, and logistic support carried on either naval or supporting commercial vessels.

So far, the MCM missions have been executed by dedicated surface vessels and organic airborne operations with helicopter squadrons. With maneuvering helicopters, airborne mine neutralization system (AMNSYS), organic airborne and surface influence sweep (OASIS), rapid airborne mine countermeasure system (RAMICS), and airborne laser mine detection system (ALMD) operations are executed for major naval littoral or expeditionary MCM and marine amphibious operations. These operations are only possible for secured sea lane of communication (SLOC) or ship to a very shallow water operation. Enough distance of standoff and wired communication and control (C2) connection are required for more clandestine and effective mine neutralization operations in mine disposal operations [6].

Military forces in the future will fight in conflicts ranging from major theater war to smaller scale contingencies. Naval forces will often be on the leading edge of such operations as they combine strategic mobility with maneuver to significantly expand the battle space deep into the enemy territorial seas. Including special force operations, many tactical operations, no matter big or small, should be carried out with time sensitiveness and clandestine operations [7].

The unmanned underwater vehicle (UUV) provides strategic and operational advantages to the Navy and security forces by reducing the cost and human risk significantly in the MCM operations, as well as by extending the reach of information, surveillance and reconnaissance. These UUV systems, which can be launched off the naval platform, offer significant protection against major threats including naval mines [8]. With the state of art technology developments [9], it is possible to perceive conceptual design ideas for future MCM UUV system with safety, high effectiveness, and cost-effective systems.

In this study, we design a MCM unit with three UUV systems executing clandestine MCM operation with formidable autonomy in the deep sea at the enemy territory. With powerful data processing capability, networked between UUVs and the mother ship through electro-optic and acoustic communications, and new type of disposal scheme, the proposed MCM unit is linked into a network of unmanned asset and combat system elements. These systems provide a complete unmanned fleet fulfilling multiple operational requirements in mine disposal operations with least human operator interactions.

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14. ABSTRACT
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The status of underwater mine disposal systems is reviewed in Section 2. Design of a prospective MCM system is depicted in Section 3. Conceptual design for future mine disposal UUV system is given in Section 4. System measure of effectiveness is discussed in Section 5. Underwater optical communication is presented in Section 6. Finally, the conclusions are given in Section 7.

II. Underwater Mine Disposal System

Surface ships and helicopter-based systems equipped with remotely operated vehicles (ROV) are commonly used in MCM for mine detection, classification, and neutralization [10]. Theses remotely operated and teleported MCM ROV systems are controlled via hard wire or optical fiber links. While many of these vehicles have some automated functions, they do require human operators in the loop at least in a supervisory capability [10].

With advances in technology, various mechanical platforms and instrumentations for ROV are provided for mine identification and neutralization. Many ROV systems are available worldwide ranging from hand held to tractor trailer sized. The majority of ROVs, especially for MCM operations are built in mid-range capability [11].

The U.S. Navy's AMNSYS has been developed using remotely controlled expendable vehicles identified as Neutralizers, launched from a MH-53E airborne mine countermeasure (AMCM) helicopter [12]. While the neutralizer vehicle approaches toward the target, the targeted mines are monitored, identified by the on-board visual sensors, and destroyed by the shaped charge devices, which are integrated into the neutralizer.

Recently, UUV emerges as a major MCM platform for mine search, detection, classification, and neutralization. While designed to operate independently from continual human control, many of them have some auxiliary communication link used for the transmission of data, but not for direct commands and control. With no hard tether connections, an UUV can cover far greater operational fields than that of ROV, providing a much greater standoff capability from the manned platforms [12].

The major limitation of UUV is, of course, limited independent operations for extended period of time. Data is often collected and stored on the vehicle. Significant time delay may occur before it is available for processing and action by human being in the loop.

With the current state of art technologies, UUVs are already used in mine detection and classification, and several UUV systems are used in real MCM operations (Table 1) with satisfactory performances [13]. Others are forthcoming in near future with matured autonomy and performance capabilities.

III. Future Mine Disposal UUV Systems

The Navy's MCM doctrine has not been significantly changed since the World War II. The future Navy may require significantly less available time to accomplish the MCM missions in the future network centric warfare [14]. Organic MCM forces must be closely integrated into and continuously provide information to the commander with status of hostile mine threats. This situation leads to the usage of a variety of autonomous platforms and sensors, which in turn makes the future doctrine noticeably different from today's doctrine. A new MCM doctrine will be developed, evaluated and revised as the experiences, systems, and operations evolve. Its basic philosophy for the tomorrow's MCM is safe, effective and clandestine operations with relation to the network oriented future warfare [14].

In the future MCM operations, the decision making software and combat information display systems will be cooperated with data collected and communicated from extensive multi-sourced agents. The Command, Control, Communications, Computers, and Intelligence (C4I) architecture will be networked to ensure the existence of communication paths between platform and detachment despite uncertain point-to point links. With all these doctrinal evolvements, up to dated technologies, hardware with appropriate operating software should be accompanied for effective and safe MCM operations in the future [15].

Exact path planning, smart navigation, and mine neutralization depend on the capacity and accuracy of navigation systems, which must avoid mines for the safe transit of ship and must be sufficiently precise to decide the reacquisition of the target. Simultaneous localization and mapping system (SLAM) and real time autonomous identification of underwater environment can be used to accurate target recognition and MCM operations.

Coordinated MCM mission management system optimizes available sensors and sub-systems, regardless of the host platform, to ensure the most effective measure when and where it is mostly needed. Fundamentals to the MCM operational concept are to locate mine fields, identify no-mine areas accurately and clear mines efficiently as soon as possible [16]. This will require detection of mines or enemy mine laying activity anywhere in a large area such as thousands of square kilometers.

Payloads for MCM vehicles generally consist of maneuvering system, neutralization charges for elimination of bottom mines, or cable cutters for moored mines. Auxiliary technology equipment as a part of payload is also playing important role to enhance the computer graphic and visualization capabilities. The payloads contribute greatly to sensor integration, simulation, decision making, and training. The commander must have the capability to avoid mines or achieve the assured destruction or neutralization of a mine threat within the absolutely minimum time. The mine sweeping system must be effective against buried, bottom,

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moored or floating mines from the deep water to the anti-invasion zone on the beach. There are several state-of-the-art weapon systems to dispose mine effectively and economically such as laser gun, acquire gun, and small charge delivery devices.

IV. Conceptual Design for Future Mine Disposal UUV System

The conceptual design for futuristic MCM UUV system is developed with operational, technical prospective based on investigation of wide spectrum of current MCM operations. For complex systems like MCM UUV units, there is no clear boundary between requirement and design. In general, a high-level design on the UUV systems for MCM operations is developed from an abstract specification to detailed specification. The concept of system configuration is proposed in response to some perceived possible problems in the mine warfare (MIW) and operational concept formulation.

Fig. 1 shows the conceptual design process for general systems. The key system design concepts from analyzing missions of future MCM UUV system are structural configurations and effectiveness of system operations [17]. An objective of system design is to build cost effective and efficient MCM UUV systems, which can operate in permissive littoral and ashore environments with water depth of 10-90 m including harbors and shipping channels. These systems will utilize known tactical and target information, which is pre-acquired by previous MCM reconnaissance troops and assets with about 75 hour of endurance and over 160 km of operational range.

Generally, in a conceptual vehicle design, two sets of input parameters are needed: mission description and vehicle configuration options [18]. A vehicle mission is divided into user-prescribed discrete segments. Each segment is defined by its unique parameters, which include vehicle conditions, hotel power, payload conditions, and environmental conditions. The vehicle configuration options are generally obtained from vehicle's top level requirements (TLRs) and the concept of operations (CONOPS). Collaboration between the highly object-oriented autonomous vehicle configurations and the low cost mine neutralization UUV is viewed as an essential element of reliable mine neutralization operations [18]. Guidance, navigation, and control (GNC) of UUV instrument configuration are implemented automatically to derive optimal detailed mission path plan by processing navigation sensor such as sonar imagery, position, range, bearing, and underwater data base information [19].

A. CONOPS

Main concepts of MCM operations using UUV systems are to reduce threats for the naval fleet through employing a robust, highly autonomous vehicle unit which is capable of engagement and execution of mine sweeping or neutralization procedure. Neutralization procedure is either moving mine out of original place or precise delivery of charged device to blast previously localized, in volume, drift, floating, and bottom mines in deep and shallow water zone [20],[21]. The proposed MCM UUV system unit is over the horizon launching system which has a master UUV and two expandable slave UUVs at the two sides of the master UUV. The large master UUV has a main mission control unit and formed charge that can reach and explode designated mines. The two slave UUVs have various mine detection and search sensor systems which can improve mine detection/identification and provide cooperative maneuvering using stereoscopic viewing. This system greatly enhances the maneuvering capability especially in case of no communication such as in accident. The two slave UUVs provide maneuvering of the master UUV using stereoscopic views.

Before actual mine disposal activities, the control unit of the master UUV requests confirmation of mine identification to the mother ship via acoustic and radio frequency (RF) communication links. Responding to the reply, the master UUV deploys charged payload which is small, fast guided devices with high power formed charge with proxy sense and running straight course to the identified mine targets. MCM UUV unit will have overall 75 hour of endurance at 3 knots maneuvering and 160 km of operational range.

In the envisioned CONOPS, a MCM UUV unit uses its high capacity communication links to receive available targeted mine information from MCM operation center at the mother ship. The vehicle initiates an adaptive engagement plan autonomously along its trajectory with available information from own navigation sensors. It navigates accurately to the designated mine target in compensating winds, waves, and currents along the disposal range. All the way to the designated mine position, the launched disposal device identifies the targets from the sonar image. After neutralizing the designated mine, the UUV unit performs a neutralization damage assessment and report that the mission has been accomplished.

B. Structural Configuration of a 3-UUV Mine Disposal Unit

The mission description of MCM fleet operation is divided into five segments: launch, transit, execution of mission, return transit, and recovery. Each of them is defined by key mission and environmental parameters such as range, speed, sea current, obstacles, and underwater terrain. The description of vehicle hardware configurations is parameterized with typical undersea vehicle's fineness ratio; values of three, five and seven, indicating the ratio of length to diameter. Large variations in mission distance and ground speed result in non-pragmatic scenarios. The options for vehicle hardware configuration dictate the set of vehicle design variations which are evaluated by the design requirements. Important options are the fineness ratio and block coefficient, which dictate the

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basic packaging and sizing of all other vehicle subsystems. These kinds of shape and hard stuffs would be characterized later in detailed actual design phase. In the conceptual design phase, several key performance functional characteristics of major MCM operations are investigated.

C. Configuration of the Master UUV System

The proposed mine disposal UUV System Unit (MDUSU) demonstrates a number of capabilities supporting autonomous mine detection, identification, and intervention using system autonomy, communication endurance, and small charge delivery vehicles (SCDV). Advanced technologies for these capabilities include situational reactive intelligent mission control suits, smart sensor systems, dynamic intelligent data classification processes, precise inertial undersea navigation, and compact vehicle autonomous management subsystem [22].

Improvement of vehicle functionality and mission effectiveness of MCM UUV system unit are the primary objectives of this research. The MCM UUV unit provides autonomy of vehicle systems through incorporation with platform-independent autonomous controller which supports high degree of autonomy, highly-precise low-power navigation, and machine vision in support of automatic classification [23].

1) Mission Management Unit

Mission control architectures of MDUSU embrace various degrees of perceptions, intelligent control, and management to define sense-plan-act or sense-react behaviors. The MDUSU architecture and it's relationships to the executors and the data/signal processing are shown in Fig.2. Functional limitations of vehicle sensor systems imposed by the combat environment require to alternative rates of vehicle control, which defined mission goals to be factored in the control system appropriately. A common approach to mission implementation is to develop functions which are grouped and sequenced to perform overall tasks.

These approaches can be grouped as task oriented control architectures with tasks ranging from simple to complex. Application of the defined tasks to accomplish a complex mobile robot behavior becomes a function of sequencing. A great deal of research has been completed in architectures with required different degrees of sequencing. These architectures range from state-defined multi-layered integration to near-chaotic independent function execution approaches. The emerging paradigm with three-level architecture is embodied in a number of UUV mission management algorithms. This system provides the planning or specification of operations at the abstract level, a level of functionality that facilitates the abstraction, and a level which provides the actual functionality [23].

MDUSU embraces this hybrid mission control and vehicle management architecture. It refines a traditional perception-action loop, allows signal processing for low-level sensor, and extracts features to assist mission planner and control system. The management system of MDUSU focuses on object classification and dynamic repositioning which optimizes the aspect relative to the designated mine target. Obstacle avoidance acquires relatively sparse sensor data in the dynamic construction of world models. Combining the perception/classification with dynamical position sensors via a highly maneuverable platform, MDUSU has capability to perceive the object of interest from multiple perspectives which increase the probability of classification for the mine targets. A key concept in MDUSU data fusions includes the employment of heuristic knowledge, which incorporates constraint knowledge associated with target characteristics and vehicle capabilities. It provides basis for interaction with the object of interest and dynamic perceptions for active sensor management and vehicle path planning.

2) Mapping and Navigation Unit

The system's capability of precise navigation and large sensor data collection is critical in ensuring operations and achieving system objectives. To resolve the vehicle position at the sub-meter level, a compact low-power solid state inertial measurement unit (IMU) is incorporated. This unit measures the change of three dimensional velocity and angular velocity, and temperature as well to correct thermally induced drift. The IMU is augmented by a compact Doppler Sonar using the Kalman filter or other filtering techniques. Navigational accuracy of MCM UUV unit may be further enhanced through the integration of long-baseline (LBL) or ultra-short baseline (USBL) acoustic navigation information [24]. Precision navigation compass and clinometers provide heading information and navigation frame correction data.

SLAM techniques as navigational tools are adapted for reconfirmation of designated mine localizations and autonomous navigation with obstacle avoidance in a safe margin. All the information from sensors are filtered, processed, and distributed for navigation, SLAM, and mine neutralization procedure [25]. With updated environmental 3D map and obstacle information, MDUSU can be guided and controlled in optimal path to the targets with accuracy.

3) Data Processing and Mine Classification Unit

An algorithmic approach in data processing is used with machine perceptions, recognitions of acquired data, and feature extraction via real-time image processing. It will support automatic classification of mines and other ordnances, as well as intelligence navigations using data from navigation sensors [26]. The image processing techniques, which have been adapted from video image and sensor signal processing, focus on classification of mines by recovery of explicit feature-based descriptions of manmade objects [27]. All the data from traditional navy data base library systems on MIW, MCM, and tactical oceanography are also installed in main processing unit of MDUSU and fed into the identification and classification processors [28].

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4) SCDV Unit

When the matser UUV of MDUSU reaches the safe standoff range from the mine field after relocalization and confirmation of pre-designated mine or mine group, around 20 SCDV units are lanched to the individual or grouped mine targets. Stand-off distances from the mine field are determined from the safe distances of mine explosion and tactical considerations in underwater environments [29]. The SCDV has high explosives sufficient for mine disposal at the vicinity of targeted mine appropriately. SCDV is a small straight run torpedo system with batteries powered, 200 m range, 35 knots speed, and high formed charge triggered from vicinity/timer sensor.

5) Communication Unit

Reacquisition and relocalization of pre-designated mine or mine fields involve huge amount of data from various sensor systems. The Navy database packages for static mine identification and classification are also available from onboard MDUSU data storage. Data for reconstructing three and two dimensional models are also significantly large. It is very difficult to transfer through current acoustic carrier in underwater environments [30]. Some other information from distance and directional angle of illumination of light source give some incentive weight on reconstruction of mine models.

Identification and reconfirmation of MLOs from real mine targets are critical factors for mine disposal operations. Other kinds of optimized communication carriers are urgently needed during data processing and transmitting in the main control center of MDSUS. They deal with high quality mine detection sensor data from remote area, but lack of computational capability of the existing data processing systems [31], [32]. Applications of RF and laser optic technolgy are considered as potential alternative methods of effective underwater communication systems. Table 2 shows possible candidate (laser optics) for future underwater communication systems which have high capacity in data processing and transmitting with ranges around 100 m.

D. Slave UUV System

With high quality wireless laser communication links or fiber optic wire link, a slave UUV system could have high fidelity detection sensors such as synthetic aperture sonar (SAS), sidescan sonar system (SSS), light detection and ranging (LIDAR), and vintage channel (VC). All the data collected from the sensors onboard slave UUV are transferred to the signal processing unit of the master UUV as soon as possible, where identification and classification of mine and MLOs are processed and re-designated as targets of disposal operation.

Two slave UUV operations benefit the cooperative navigation which help MCM unit navigational sensor and all the sensors on the slave UUV provide stereoscopic signal to the main processing center for identifying mine and mine like objects. The slave UUV Systems are attached each side of the master UUV where they are performing as the navigation sensor, until it is moving to the targeted mine field. In the mine field, where the actual mine disposal operation is supposed to be executed, the slave UUVs are separated from the master UUV and maneuvering 100 m ahead of master UUV. They start to search mines with forward-looking sonar (FLS) at 200 m forward, SSS at 100 m ahead, LIDAR at 50 m, and VC within 10 m ahead of prospective mine targets, and also collect the navigation data for obstacle avoidance. All the data collected in the slave UUVs are transferred to the master UUV in real-time for processing. After, reconfirmation of mines is completed, the slave UUVs return and dock to the side of the master UUV as a navigation sensor for mine disposal operations.

V. System Measure of Effectiveness

A. System Evaluation Model

With state of arts technologies in sensing, communication, and navigation, the future MCM operations with autonomous mission management systems are likely to use multiple heterogeneous UUVs working together to improve effectiveness of overall MCM operations [33]. In the final phase of system design, either conceptual or actual, justification studies for the proposed design should be carried out with functional and cost effectiveness evaluations. It is required to change, modify or compromise original design configurations, if there are better alternatives or deficiencies for the original proposed design concepts, system's structural configurations, instrumentation, and operational systems [34]. Here, analytical frameworks are developed to evaluate the proposed MCM disposal UUV unit based partially on the current US naval underwater ship design procedure.

The parameters of mission effectiveness are organized into hierarchy and weighted utility functions. The evaluation models provide means to relate the effectiveness matrices to the system-level performance parameters. These individual capabilities can be stated in terms of vehicle sub-components such as sensors, data storage, processing unit, communication systems, navigation instrumentations, and disposal payload items [34].

The general approach on the measure of effectiveness (MOE) is to make higher level models as generic as possible, and to increase detail and resolution with each progression into lower level models. This is accomplished by developing separate model sub-components and linking them together to form an overall system model [35]. The results from the effectiveness and risk management models lead to the MOE and comparison between the MOE and cost leads to the decision making, or modifying system model.

B. System Effectiveness Analysis

For an entire MCM evaluation framework, the specific operational requirements on the MOE for MCM UUVs lead to the following important items [36]: 1) near-real time communication with information and data links between unit and host platform of the UUV systems in the future C4ISR environment, 2) system autonomy and mission achievement, 3) covertness of UUV systems measured and incorporated into the MOE, 4) requirements of logistics support for deployment and recovery, 5) requirement of human supervision and oversight as least safety protection measure, 6) risk management, and 7) cost factor for UUV.

For the UUV systems, especially for multiple vehicle systems, covertness and communication abilities depend significantly on the position and operational configuration of the disposal system unit. Thus, for the UUV disposal system unit, the mission time, mission achievement, autonomy, communication, covertness, risk management, and cost effectiveness are the highest level of the proposed MOE hierarchy [36].

1) Mission achievement efficiency

Success of neutralization is the main object of the MCM operations and this MOE represents the estimated probability of search/classification of mine and mission accomplishment for mine clearance. Mine reconnaissance and clearance are the two basic MCM missions. The major objectives of mine reconnaissance are accurate search, localization, and regain of designated mine in the contacts. Search level refers to cumulative probability of mine detection and re-localization, classification, and identification within specified MCM operational area. Search and identification of proposed system are validated through sensor systems, communication efficiency and data processing capability of main control unit.

Degree of autonomy for the vehicle operations is regarding smartness of main operating computer architectures governing guidance/navigation/control of vehicle, mission management and obstacle avoidance/optimal path planning that are required during the MCM mission operations. The nature of the MOE is well defined by numeric symbols on the level of autonomy table which is published by the US department of defense, and shows autonomous system's capability of processing unit, level of machine intelligence, and data base capacity for data resources applied for decision making on the specific missions [37].

The new state-of-the-art communication devices use the laser optic rays and RF carriers rather than conventional underwater acoustic wave medium. The laser optical and RF devices have capability for data transfer with high speed and security, but moderate communication range in the underwater environments [38]. Communication systems related to the mission operations are data communication links where tactical maneuvering information on the MCM missions is exchanged. Each division on communication links are evaluated through communication quality of data, security and interoperability.

2) Risk Management

The purpose of the risk management is to find possible system deficiencies during operations and to integrate quantitative measures with respect to risks. Three types of risks associated with mine disposal UUV unit are (a) technological factors, (b) overall cost of system operations, and (c) scheduled sequences of maneuvering [36]. The technological factors include propulsion, computer systems, communication systems, and weapon systems. These risks with mission executions are managed appropriate back up mission management systems added to the main system operational nodes [36].

3) Cost Analysis

Since this research is a conceptual design for the future systems, the life cycle cost (LCC) and total ownership cost (TOC) [39] and are used for the analysis. LCC is the direct total cost to the government of acquisition and ownership of a system over its useful life. It consists of four parts: development, acquisition, operations/support, and disposal costs. Among the four types of costs, the operations/support cost is generally the highest, followed by acquisition (or investment) cost, development cost, and then finally the disposal cost.

TOC is basically the LCC with indirect components such as the cost of manning. In the ship synthesis model, the labor cost and the material cost are calculated separately. Regarding the TOC of MCM disposal UUV unit, this proposed MCM UUV system unit is economic, intelligence system of systems, reusable as long as it would be operational. The only disposable expenses would be SCDV units, which is both simple system and inexpensive, compared to the other major mine disposal systems.

VI. Feasibility Study on Underwater Optical Communications

A. *Importance of Underwater Communication*

Executions of MCM operations must be carried out in a short period of time before enemy forces to respond. Therefore, planning of MCM operations need to be systematic based on exact combat information over large areas of prospective operations and evaluation for the nature of the operations. Large volume of information is collected from surveillance and reconnaissance on the mine fields, and they should be formatted for quick dissemination to the MCM control center and disposal units respectively.

With advances in technology, UUV can maneuver over a large area of operations, collect information for large mine field, and transfer acquired information to the MCM operation control center promptly. One of the most important issues in MCM operations is underwater technology for high effectiveness in data and information communicating and processing [40]. To assure success of MCM operations, the commander of the MCM units should understand the impact

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of situational awareness about actual environment and current available combat information for the mine fields. The effectiveness of MCM operations depends largely upon underwater environment, accurate combat information, data processing capability, weapon systems, and communication networks among MCM operational units [41].

Due to special characteristic features in the underwater environment, acoustic waves are used as the primary carrier for underwater wireless communication systems due to relatively low absorption and transmission losses. Up to date and extending to the near future, acoustic waves will be staying as the major carrier of wireless communication for the UUV systems. For acoustic wave carriers, the key challenges are identified in communication quality and networking systems such as time delay, data rate, and noise characteristics [42].

With those characteristics of underwater acoustic communications, future MCM operations will face several difficulties on effective and safe MCM operations. We plan to apply new technologies for future MCM operations with RF and optical underwater communication links, which can provide higher speed as well as better quality of operations. These futuristic underwater communication technologies are at their development phase, but have already shown major technological breakthough on underwater communacation systems and applications.

B. Required Information on MCM Operation

In the MCM operations, correct mine recognition with a high probability and exact mine classifications lead to success of MCM missions. The first level of recognition is usually considered perception of mines. If the call for initial mine recognition is false, much valuable time is wasted in investigating possible targets. Correct identification of the target ensures that overall MCM operational sequences are on the correct track of actions.

For most cases, classification of man-made object is enough for the next step, but, this kind of classification is reliable, if and only if identification is possible. Cameras with high resolution and fast shutter speed are, therefore, desirable for search and reconnaissance of mine fields. Higher resolution can obviously yield better target definition while faster shutter speed would produce more multiple looks at the target. New data processing techniques would incorporate multiple looks and statics of the surface to extract better information about the imaged objects. Under current technology, once data are communicated and collected appropriately, powerful data processing unit at main control center has high capability to process, recognize, and decide object identifications within a minimal processing time [43].

Location of a specific mine and relocalization of mine fields are very important for UUV maneuvering in the MCM operations. Identifying the precise location of mines gives the navy commanders the flexibility to choose the best course of future action of operations. Even when the mine threat is widely dispersed, avoidance can be a viable action. If instead, choosing to destroy the threat, time becomes an important factor too, and again, precise location will minimize the wasted time. The accuracy around one meter is needed for truly effective operations [44].

C. Development of Underwater Optical Communications

In the modern MCM operations, time delay and slow data transfer between mine searching sensor system and data processing unit at the MCM control center are great barriers for MCM operations. To overcome such operational weakness and difficulties, the blue laser optical sensor and communication systems are prospective options for the underwater information networks [45]. Use of optical rays for underwater communication has big advantage in data transfer rate, which can potentially exceed 1 Giga bps. However, it has several disadvantages. First, the optical signals are rapidly absorbed in the water. Second, the optical scattering caused by suspending particles and planktons is significant. Third, high level of ambient light in the upper part of the water column is an adverse effect for using optical communication. Fourth, optical scattering is the topic more pertinent to using optical waves for communication [45].

Water quality plays a key role in determining if optical waves can be used for underwater communication. As a result, the applicability of optical communication depends heavily on the environments. Similar to the acoustic and electro-magnetic waves, the underwater optical communication systems work in the environmentally-limited region [44]. Recent interests in underwater sensor networks and sea floor observatories have greatly stimulated the interest in short-range high-rate optical communication [46]. So far, several good commercial optical modems are available specifically for underwater laser communications within 50 m range [47]. For example, SA Photonics is developing Neptune, a high bandwidth, low power underwater communications system that is small and lightweight. Neptune can be used on submarines, ships, UUVs, and fixed undersea data nodes with the communication capability at data rate up to 300 Megabits per second over 50 m range. This system can automatically adjust data rate, modulation format, and laser wavelength based on water quality with optimal transmission and minimal power consumption. Woods Hole Oceanographic Institution (WHOI) has developed an undersea optical communications system, called the “virtual revolution in high-speed undersea data collection and transmission” [43], to provide near-instant data transfer and real-time video from un-tethered ROVs, UUVs, and seafloor data-collection/transmission sites. It is also used in conjunction with acoustic communications, which would take over once the vehicles moved out of the optical range. In any case so far, its designers have achieved data rates of 10 to 20 megabytes per second, through 100 m of water [47].

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VII. Conclusions

In this study, the current MCM systems and their operations in mine fields are investigated for possible technological improvements in future mine neutralization. Key technologies required for the future MCM systems are system efficiency, capability of fast data processing, communication efficiency, and cost effectiveness.

Configuration of 3-UUV system unit has an effective conceptual system design with 10-20 small charge deliverable vehicles. New underwater optical communication systems are suggested to improve mine reconnaissance and decision making procedures in efficient operations. Cost effectiveness of the MCM system operations are studied through analysis on conceptual design configurations with disposable mine neutralization instruments, upgraded data processing unit, and configuration of optical communication system between heterogeneous underwater and surface vehicle unit. At the same time, fine and reliable underwater optical communication systems emerge in very near future, since it is a hot research area with sufficient government support.

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Acronym List

Acronym	Words	Acronym	Words
ALMD	Airborne laser mine detection system	MLO	Mine like object
AMCM	Airborne mine countermeasure	MOE	Measure of effectiveness
AMNSYS	Airborne mine neutralization system	OASIS	Organic airborne and surface influence sweep
bps	Bit per second	RAMICS	Rapid airborne mine countermeasure system
C2	Command and control	RF	Radio frequency
C4I	Command, control, computer, communication and intelligence	ROV	Remotely operated vehicle
C4ISR	C4I and surveillance and reconnaissance	SAS	Synthetic aperture sonar
CONOPS	Concepts of operation	SCDU	Small charge delivery vehicle
FLS	Forward looking sonar	SLAM	Simultaneous localization and mapping
GNC	Guidance, navigation and control	SLOC	Sea lane of communication
H/W	Hardware	SSS	Side scan sonar
IMU	Inertial measurement unit	S/W	Software
LBL	Long base line	TLRs	Top level requirements
LCC	Life cycle cost	TOC	Total ownership cost
LIDAR	Light detection and ranging	USBL	Ultra short base line
MCM	Mine countermeasure	UUV	Unmanned underwater vehicle
MDUSU	Mine disposal UUV system unit	VC	Vintage channel
MIW	Mine warfare	WHOI	Woods Hole Oceanographic Institution

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Table 1.Example of Dedicated MCM UUV Systems.

System	Dimension (m) (l, w, h)	Weight (Kg)	Depth (m)	Speed (KTS)	Payload (Kg)	Endurance (Hour)
Remote Multi-Mission Vehicle(RMV)	(23.0, 4.0, 4.0)		200	15		72
Sea Otter MKII	(3.45,0.96,0.48)	1,000	600	5	160	24
Marlin	(16, 5, 5)	3,500	1,000	5		30 Days
Talisman	(4.5, 2.5, 1.1)	1,800	300	5	400	24
LMRS	21" Diameter		1,500	15		62
MRUUVS	Under Development					

Table 2. Comaprison of different technologies for underwater communication.

	Acoustic Communications	Electromagnetic Communications	Optical Communications
Nominal Speed(m/Sec)	1,500	Light -Speed	Light-Speed
Power Loss	0.1 dB/m/*Hz*	28dB/1Km/100M*Hz*	Turbidity
Bandwidth	K*Hz*	M*Hz*	10-150 M*Hz*
Frequency Band	K*Hz*	M*Hz*	10^{14} - 10^{15}*Hz*
Antenna Size	0.1 m	0.5 m	0.1 m
Effective Range	Km	10m	10 – 100m
Technology	Mature	New	New

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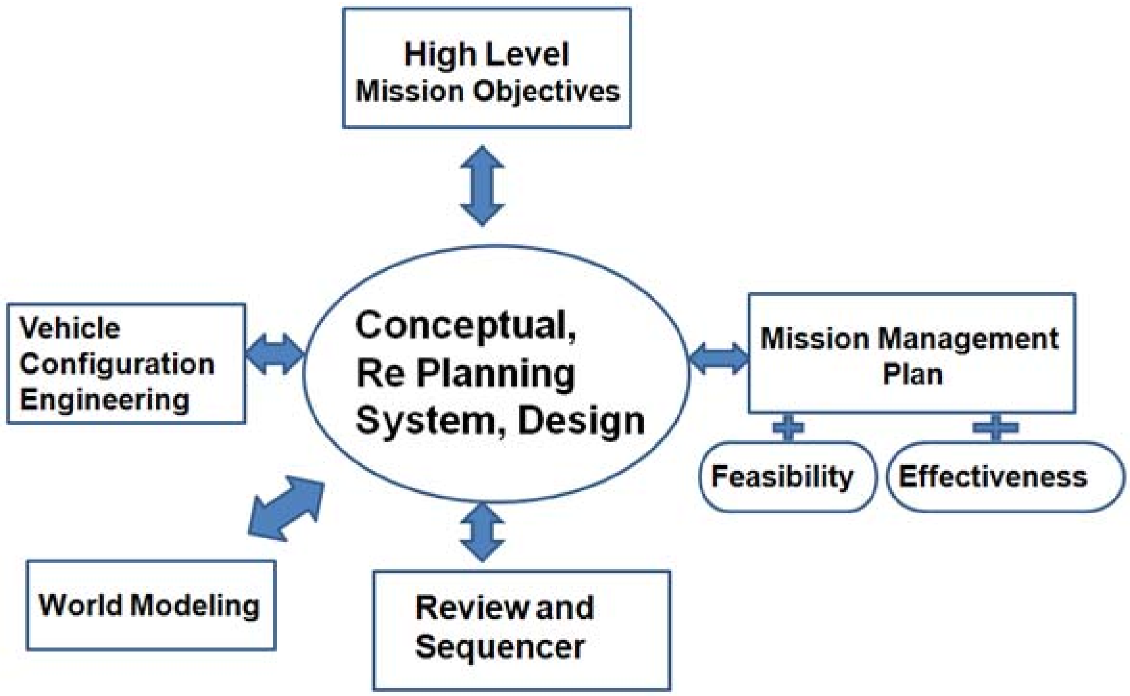

Fig. 1 **Conceptual design process.**

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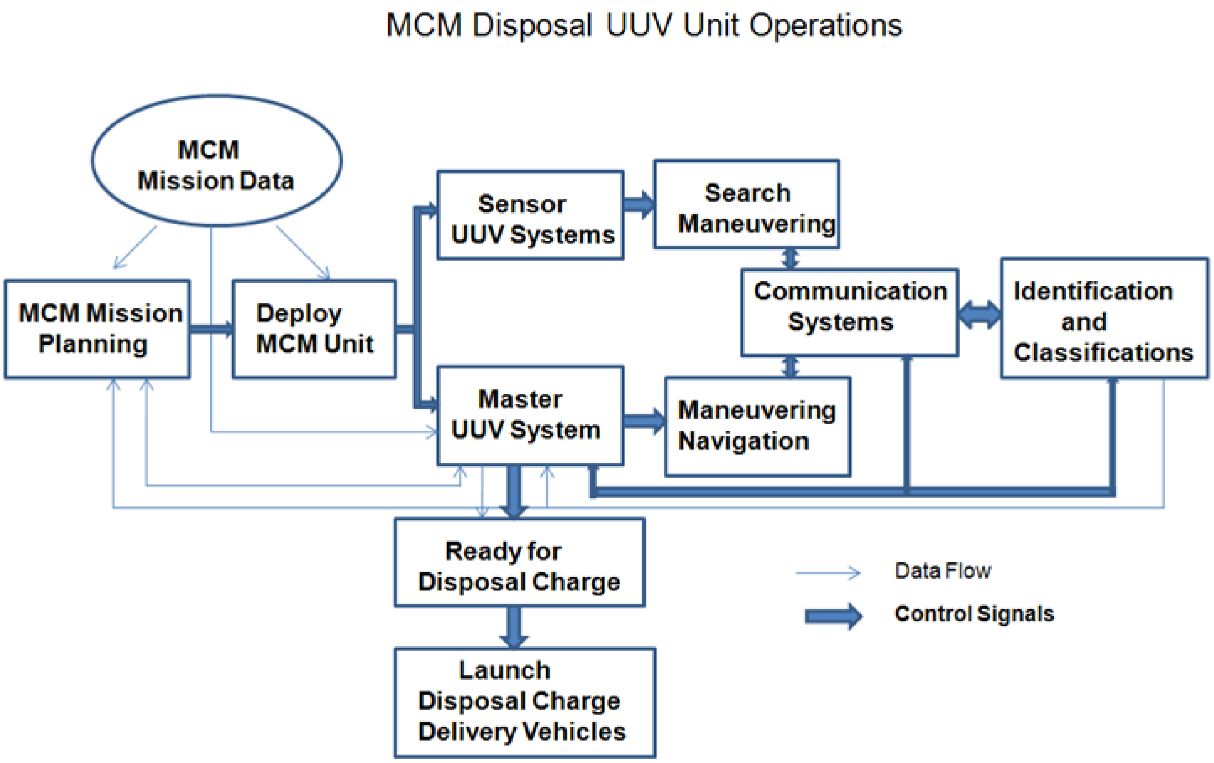

Fig. 2 **Operations of MDUSU**.