Unmanned/Unattended Naval Undersea Sensor Systems: Examples of Today's Technologies and Challenges for the Future

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ABSTRACT

The use of sensors for undersea warfare (USW) missions involves a wide spectrum of approaches. Among the many related research and development thrusts is a healthy focus on computer automation and flexible sensor positioning by low cost semi-autonomous platforms. Automation is being applied to organic sensors on large capital ships as well as distributed sensors detached from a central command center for the purposes of increasing area search rate, managing workload, and reducing cost. Particular capabilities are driven by mission-specific considerations such as large area or barrier search in deep water, shallow littorals, or riverine locations. For example, automation incorporated in undersea sensors on mobile unmanned vehicles will likely be different than approaches implemented on larger ships. Likewise, leave behind sensors on the surface or bottom will provide yet different performance attributes. Autonomous platforms including the unmanned undersea vehicle (UUV), unmanned surface vehicle (USV) and unmanned air vehicles (UAV) will host sensors that play a key role. The resulting landscape includes a fairly intricate set of sensor types, platforms, and operational methods. An overview of selected unmanned and/or unattended naval undersea sensor technologies is discussed, along with some of the inherent capabilities that make them advantageous to specific USW missions. One example of cost savings achievable through extensive use of automation is provided to illustrate potential ancillary benefits. The primary technical challenges that need to be overcome before these sensors can reach their desired operational capability are also discussed.

Keywords: Unmanned vehicles, automation, Navy vessels, area search, barrier search, cost reduction

1.0 Introduction

This paper reviews a selection of undersea sensors in current use or under development that incorporate some form of automation or autonomy to accomplish a specific Navy objectives. Although a variety of missions are currently addressed e.g., anti-submarine warfare (ASW), mine warfare (MIW), and intelligence surveillance and reconnaissance (ISR), we focus here upon the ASW problem. The discussion begins with a review of high level requirements promulgated by the Chief of Naval Operations (CNO) under the well known Sea Power 21 framework. Next a review of Navy platforms and sensor payloads in current use for the initial detection and tracking of submarines in the ocean is presented. Following this is a discussion of likely search strategies for the large area clearance and barrier protection missions. Three different strategies (e.g., parallel line sweeps, sprint and dip, and distributed networked sensors) are presented to accomplish the search and detect mission. The trade-off between deployment methods and required automation and autonomy is discussed. Performance is illustrated through theoretical analysis and simulation. Next, cost considerations are evaluated by reviewing some of the models that quantify the cost of manpower, and the potential total ownership savings attainable if manpower is reduced. Finally, a canonical undersea sensor automation approach is presented as a framework for identifying primary technology gaps currently preventing realization of the full potential of these algorithms.

2.0 Requirements

The justification for much of the current U.S. Navy's focus upon unmanned sensors can be found in Adm. Clark's vision for Sea Power 21.[1] This framework includes three primary concepts called "Sea Shield," "Sea Strike," and "Sea Basing," that are enabled by an overarching network called "Forcenet." The basic concepts are supported by processes called "Sea Enterprise," "Sea Warrior," and "Sea Trials." Since its initial publication, much has been written about the technology gaps that need to be addressed prior to fully realizing the SP-21 vision.[2,3] In Figure I we illustrate this vision with call-

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outs that expand the enabling requirements of each concept related to unmanned sensors. For example, the Sea Shield concept requires sensors to support platform defense and area denial, while the Sea Strike concept requires sensors to support persistent targeting. Simultaneously, the Sea Enterprise process includes reducing platform costs through technology that substitutes for man-power. The overarching theme is high performance sensors to extend the reach of global power protection while minimizing losses to friendly forces, all accomplished at the least possible cost. It is generally recognized that this dichotomy of requirements will be facilitated with the introduction of autonomous unmanned sensors.

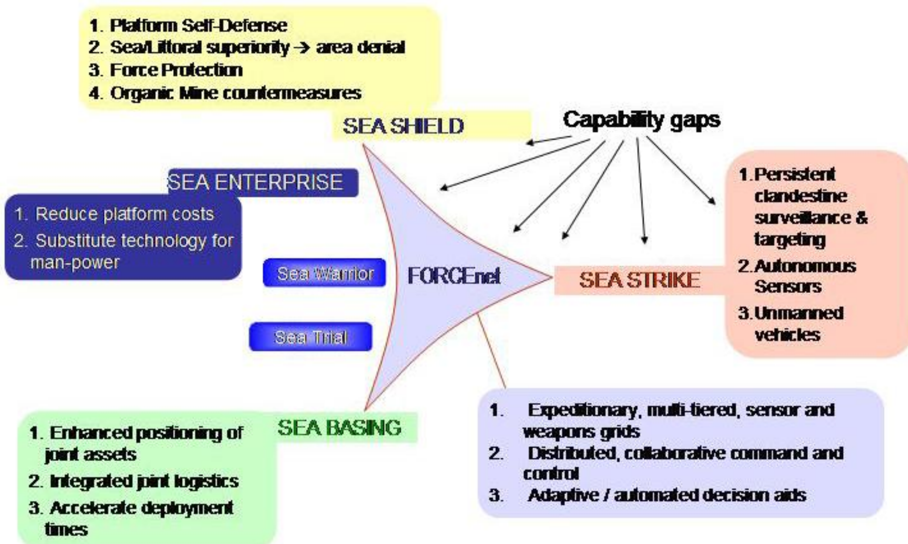


Figure I. Navy Sea Power 21 Requirements Related to Unattended/Unmanned Sensors

3.0 Current Platforms and Sensor Payloads

It is difficult to discuss unmanned and/or unattended sensors without a review of the various platforms required to host such sensors or deploy them in the field. In this regard, the various sensors can be segmented according to their degree of automation (i.e. fully automated versus manned) and the type of deployment platform in terms of mobile manned, mobile unmanned, floating or bottom mounted. Here the "mobile" refers to self powered mechanical propulsion, and "platform" loosely refers to the vessel or device that hosts the sensor. An illustration of the "seascape" of sensors associated with the naval undersea surveillance mission is illustrated in Figure II. The envisioned scene is a complex ensemble of warships, submarines, aircraft, unmanned surface vessels (USV), unmanned undersea vessels (UUV), unmanned aerial vehicles (UAV), floating sensors, and bottom sensors. The distribution and applicability of each platform is likely impacted by the mission location, in terms of deep blue water, shallow green water and riverine brown water. As the water becomes less blue the relative need for unmanned vehicles increases. Unmanned vehicles and their sensor payloads can potentially extend the reach of large traditional ships into contested areas that otherwise impose a higher than acceptable risk to military personnel.

A pictorial summary of deployment platforms for most ASW sensors in the U.S. Navy is presented in Figure III. The traditional submarine, surface ship and fixed/rotary wing aircraft are apparent. Also illustrated, are examples of relatively new UAV, USV and UUV craft propelled under fully or semi-autonomous control. These vehicles offer an affordable force multiplication capability and tactical superiority in locations and scenarios not ordinarily advantageous to traditional platforms.

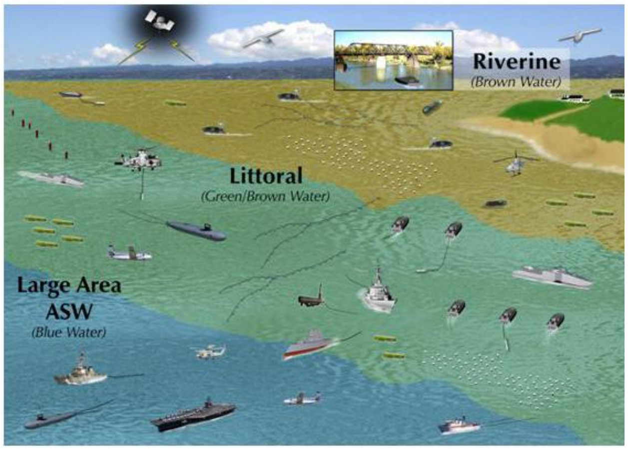


Figure II. Seascape for Undersea Sensors

Figure III. Navy Platforms for ASW Search

Each of the platforms contained in Figure III host a different set of sonar sensors for detecting undersea objects. These include cylindrical, spherical, line, planar, and volumetric arrays of active transducers and/or passive sensors.[4-7] Pictorial examples of these sensor arrays are shown in Figure IV. Operating these sensors unmanned and unattended requires automatic algorithms and autonomous controllers. In all cases, some level of automation or autonomy is applied in an attempt to maximize performance and minimize manual operator requirements. Examples of sensor automation on mobile manned platforms include the Integrated Multi-modal Workstation on the DD(X) destroyer and automatic sonar tracker/classification algorithms on SSN submarines. Automation on mobile unmanned platforms includes the automatic tracker/classifier on dipping sonar mission packages hosted on USVs planned for deployment on the Littoral Combat Ship (LCS)[8] and automatic detection of bottom features from high frequency side-scan sonar on the REMUS UUV.[9]

Figure IV. Example Undersea Sensors as Vessel Payloads

Automation as part of a floating sensor system includes sonar signal detection and classification processors in new active and passive sonobuoy prototypes. Automation is particularly required to minimize the bandwidth of data exfiltrated to a central analysis site. Currently, many sensors incorporate a combination of both automatic and manned sensors due to the immaturity of fully functional automation for many applications. An illustration of distributed sensor deployment for an ASW barrier search scenario using both bottom or floating sensors is shown in Figure V.

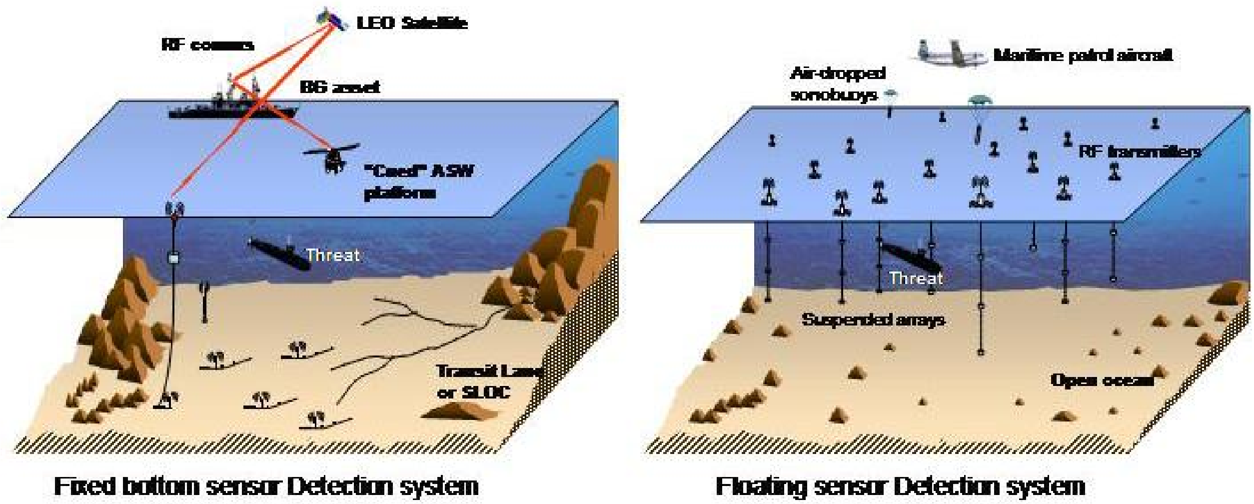


Figure V. Example Distributed Sensors Applied to Barrier Search

While discussing the subject of sensor deployment it is informative to recognize the cost differences between various platform types. An estimate of the initial procurement cost ratios between platforms capable of hosting ASW search sensors is shown in Figure III.[10] It is not surprising that highly manned large capital submarines and warships are significantly more costly than unmanned vessels (and for that matter) the primary platform (i.e. LCS) planned for deploying many future unmanned vehicles. Although these ratios refer to initial ship procurement only (vice total ownership costs), they do illustrate the differences in capital investment associated with traditional capital ships vice other platform options. We shall evaluate other cost considerations related to these vehicles later in this paper.

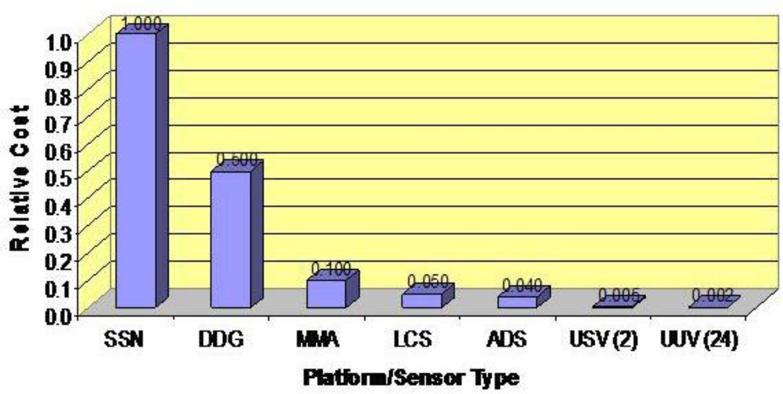


Figure VI. Relative cost per Navy search platform with sensor payload

4.0 Performance Potential from Automation and Autonomous Vehicles for Target Search

Automatic and autonomous sensors are enablers. With respect to ASW, sensors with this capability enable unique search tactics and procedures. In some cases the result is increased performance, while in other situations similar performance is attained at a much lower cost and/or vulnerability to friendly sailors. Evidence supporting this contention is presented via theoretical analysis and results from simulations.

4.1 Models for target search

A primary use of naval undersea sensors is for search and recognition of hostile vessels (i.e. targets) within a wide area or across a linear barrier. This mission is especially important to the defense and survivability of highly valued naval assets such as aircraft carriers, troop transports or supply ships.

A common metric for assessing search performance is the Cumulative Probability of Detection (CPD), $P_{cd}(t)$. The probability of detecting a target within a fixed area after a fixed time *t* with a search platform moving in a uniformly random trajectory is given by Equation (I).

$$P_{cd}(t) = 1 - e^{-WV_e t / A} \qquad \text{(I)}$$

Where:
P(*t*) = CPD at time (t), W = sweep width (calculated from the lateral maximum range).
V_e = max{U,V}, U = target speed, V = searcher speed, with $U \ll V$ or $V \ll U$, t = search time.
A = area to be searched (i.e., area containing the threat).

The argument of the exponential in (I) is referred to as the coverage factor, equal to the sweep width times the distance traveled ($V_e t$) divided by the total area (A). The cumulative probability (first derived by Koopman[11]) assumes uniformly random motion, large difference between target and searcher speed, and a perfect detector when the target is inside the sweep width. Given the systematic characteristics of realistic search procedures, Equation (I) can be treated as a lower bound.

Conversely, the probability of detection of a target moving through a single barrier while the search platform conducts a linear patrol is given in Equation (II).[12]

$$P = 1 - \left[\left(\lambda - \frac{\sqrt{r^2+1}-1}{2}\right)^2 \frac{1}{\lambda(\lambda+1)}\right] \quad , \quad when \quad r \le 2\sqrt{\lambda(\lambda+1)}, otherwise \quad P = 1 \qquad \text{(II)}$$

Where:
r = V/U, U = target speed; V= searcher speed,
λ = (D – 2R) / (2R), D = Barrier Width, 2R = Sweep Width, and R = radial detection range of the sensor.

The total probability of detection of a single target moving through multiple parallel barriers is given by the Binomial Distribution defined Equation (III).

$$P_T = \sum_{k=1}^{n} \frac{n!}{k!(n-k)!} P^k (1-P)^{n-k} \qquad \text{(III)}$$

Where:
n = number of parallel barriers
P = the single barrier probability given in Equation (II).

An illustration of the two generic search methods represented in the above models is given in Figure VII.

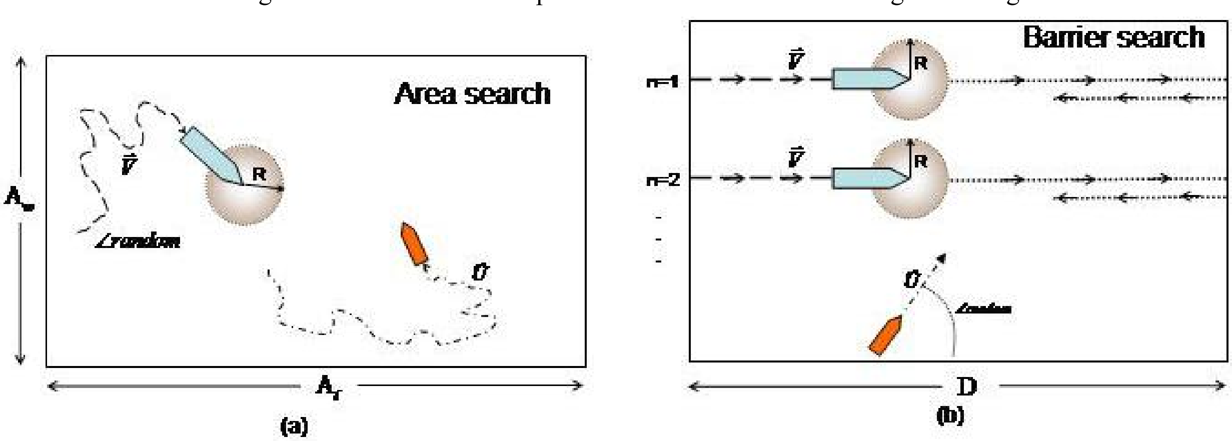


Figure VII. Illustration of Area (a) and Barrier (b) Search Methods

4.2 Operational search methods and platform considerations

A set of realistic systematic search procedures applicable to a variety of manned and unmanned sensors is illustrated in Figure VIII. These include the (a) parallel line search, (b) random sprint and dip, (c) drifting distributed sensor search, and (d) position controlled distributed sensor search. In procedure (a), the horizontal lines and separation from the area edges is set at a small 20% overlap between tracks. Here, defensive "zig-zag" maneuvers are neglected since we are mostly interested in the general direction of transit for search applications in this discussion. In procedure (b), the searcher sprints to a random location, remains stationary for 20 minutes and then sprints to another location. In procedure (c), multiple floating sensors drift slowly (~0.5 knots) across the field resulting in significant gaps at the area edges after elapsed time (e.g., 12 hours). The drift problem is addressed in procedure (d) with fixed or station-keeping sensors that maintain position during the search. Options for procedure (d) include some systematic movement within small area segments at variable speeds.

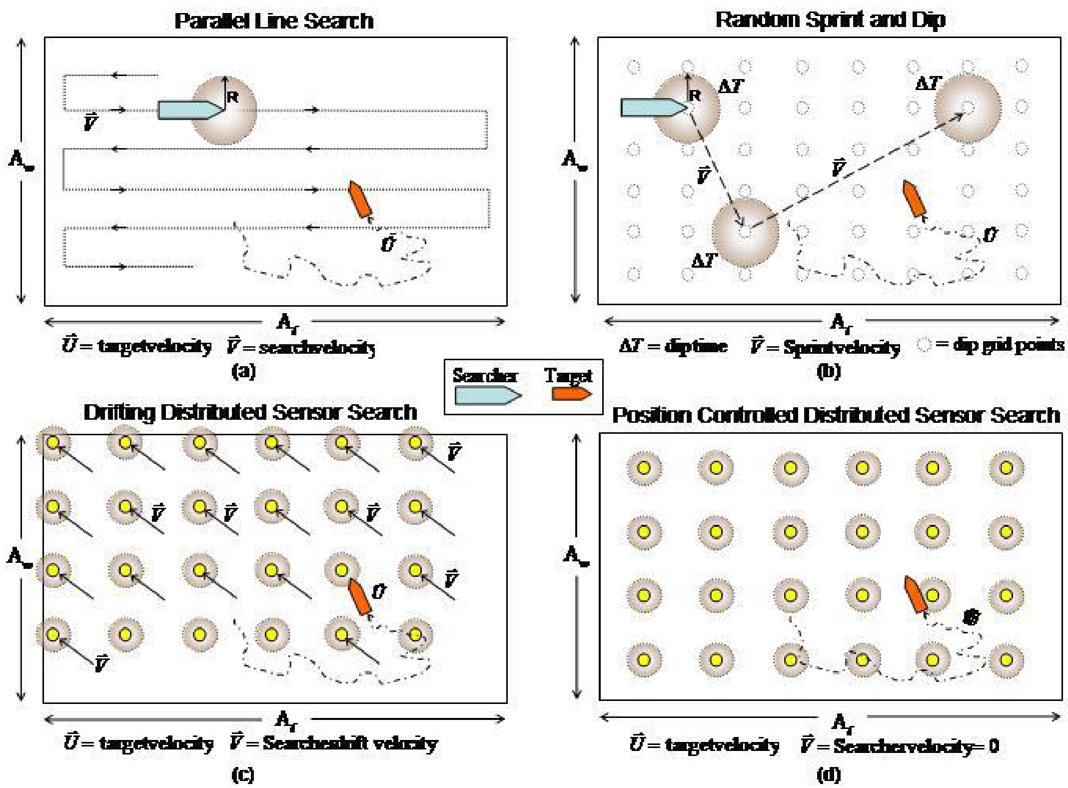


Figure VIII. Illustration of four operationally relevant search methods

Referring to the naval platforms illustrated in Figure III, the parallel line search is most appropriate for warships and submarines with the capacity to host large sensor configurations with wide apertures and/or high transmit power. Although computerized algorithms are often integrated to assist with operator workload, implemented approaches typically represent a minimum level of automation and autonomy. Conversely, the sprint and dip procedure lends itself quite favorably to unmanned surface vehicles or helicopters. The relatively small payload capacity of USVs or helicopters is offset by their ability to quickly launch from a host platform (e.g., LCS), maneuver at high speeds to designated search locations, and deploy a mid-range active/passive sonar. Limits on the bandwidth and maximum range of communication channels can be overcome by appropriate automatic sonar processing on the vehicles. Higher performance automatic algorithms are facilitated by the modest detection ranges required when the area is covered by multiple low cost unmanned vehicles. Next, drifting distributed sensors are realized by one of the many sonobuoy configurations containing single or multiple sensor arrays. They are best deployed in large numbers by maritime patrol aircraft such as the P-3 Orion or (eventually) the Multi-mission Aircraft (MMA). For large areas, many sensors can be required. Finally, position controlled distributed sensors can be realized by either a bottom mounted sensor grid, or by multiple UUV's containing low gain sensor arrays. In both cases, automation and autonomy play a vital role in decreasing communication bandwidth and controlling sensor position in the presence of high ocean currents.

4.3 Numerical Performance Experiments

The detection performance of the aforementioned search methods are evaluated with Equations (I) and (III) and through Monte Carlo Simulation. The area is defined to be 40 x 80 Kyds wide. In the simulation, detection probability is measured as the ratio of the number of successful detections divided by the number of random trials, (i.e. 200 in our experiments). A detection occurrence is identified when a target's position falls inside the sensor detection range for the minimum time duration. The random target trajectory is determined by a Gaussian Density centered on the previous mean course, with congruent reflections off the boundaries. In all cases evaluated here the target speed is 5 knots. Barrier search is evaluated with targets at constant course and speed with uniformly random initial horizontal position and course, under the constraints that the start position is on the lower edge of the area and the end position lies on the upper edge. CPD performance is computed as a function of the sensor detection range. In the area clearance case, performance is evaluated after a 6 hour search, while the barrier detection performance is computed when the target fully crosses the area. The detection range yielding $P_{cd}(t)$ or P_T = 90% is highlighted as an operating point from which to base comparisons.

4.4 Parallel line search

Our implementation of the parallel line search covers the area by successively displacing the linear track in the vertical direction by a distance equal to 80% of the sweep width when the searcher approaches a horizontal boundary. When a boundary is satisfied, the searcher reverses course and direction of track displacement and repeats the process. Figure IX contains the results in terms of CPD versus sensor range for a six hour parallel line search with two sensors against a randomly moving target within the 80x40 Kyd area. The searcher speed is a constant 10 knots and the minimum time required for detection is 120 seconds. The simulation results for this systematic search indicate a minimum sensor detection range required to achieve a $P_{cd}(t) = 0.9$ is approximately 9 Kyds. As expected, the theoretical predictions are much more pessimistic (e.g. 15 Kyd detection range at $P_{cd}(t) = 0.9$), since a totally random search is assumed. The sensor requirements for a barrier search are shown in Figure X. Here the required detection range resulting from simulation is about 12 Kyds for $P_T = 0.9$. Interestingly the theoretical predictions for barrier performance are more optimistic (i.e. 9.0 Kyd minimum range at $P_T = 0.9$) due to the unmodeled inefficiencies in the simulated parallel line search vice a simple repeated linear search assumed in the model.

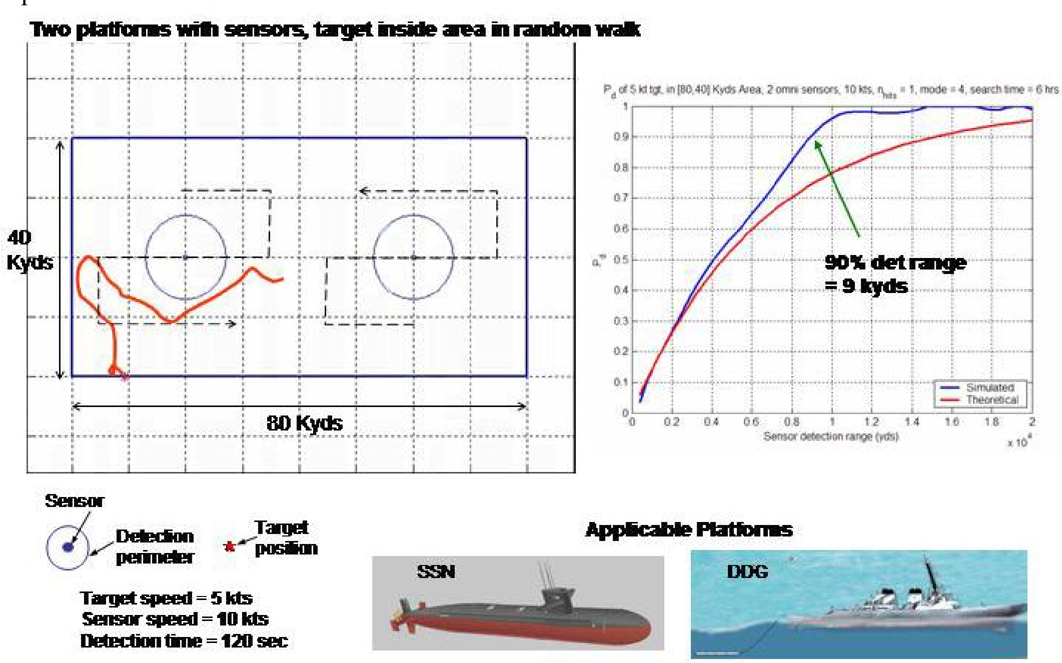


Figure IX. Wide Area Clearance, Tactical Platform Parallel Line Search Example

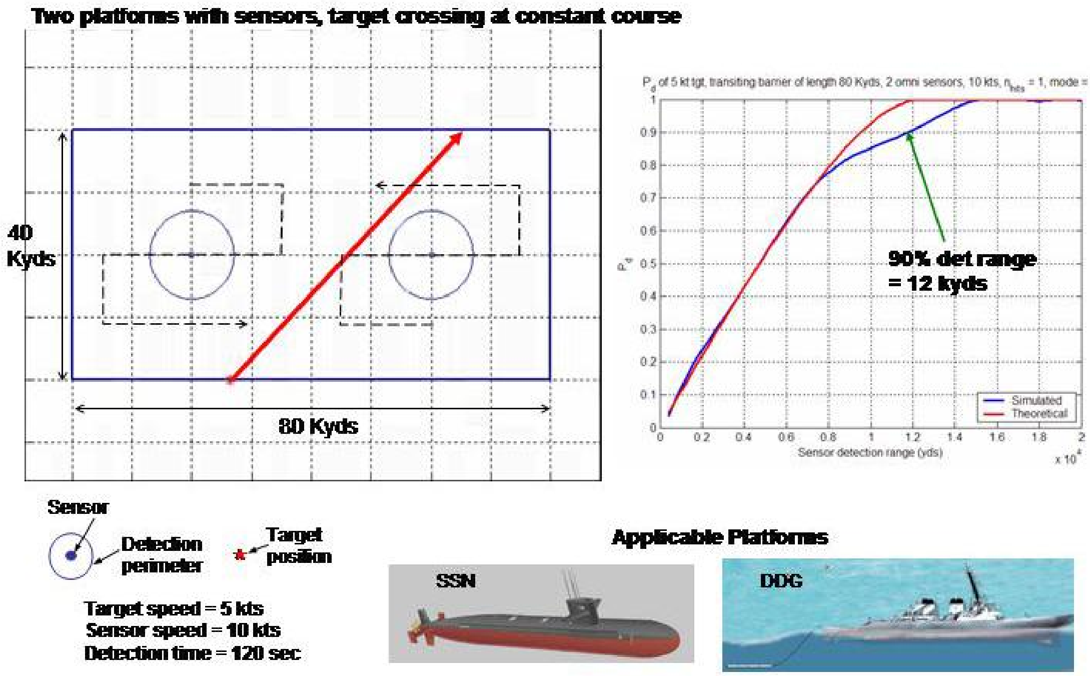


Figure X. Barrier Protection, Tactical Platform Parallel Line Search Example

4.5 Sprint and dip

The simulated sprint and dip method evaluated here employs a grid of 48 dip point locations equally spaced across the area (indicated by the dotted circles in Figure VIII (b)). Transit to each location is determined by sampling a swapped triangle density function defined in Equation (IV) and illustrated in Figure XI. Given that the indexes of grid points are sorted by relative distance, this method increases the likelihood that new locations will be at longer travel distances from the previous dip. This procedure is intended to minimize the effectiveness of counter detection methods by the target (e.g. moving away from the source).

$$P(x \mid x') = \begin{cases} \dfrac{1}{1 + a\left|x - 1\right|} & ,x = 1 \ldots N/2 \quad ,x' \geq N/2 \\ \dfrac{1}{1 + a\left|x - N\right|} & ,x = N/2 + 1 \ldots N \quad ,x' < N/2 \end{cases} \qquad \text{(IV)}$$

where:
x = index of dip locations
x' = index of previous dip location
$P(x|x')$ = probability of next location given previous location
a = 0.25

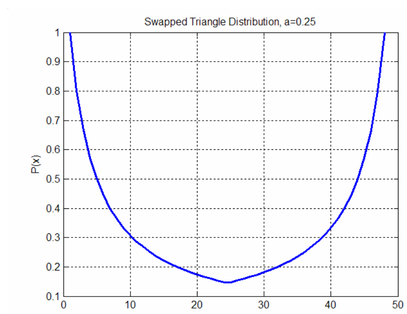


Figure XI. Density Function for selecting next dip location

Simulation results for the area search (6 hours) and barrier search problems using the sprint and dip method are shown in Figures XII and XIII, respectively. Again the minimum time for detection is 120 seconds. Interestingly, the required detection range to achieve $P_{cd}(t)$ and P_T = 0.9, equals 9.0 Kyds in both scenarios. Even more interesting is the fact that a search strategy amenable to small quick vehicles provides equal or better performance potential (in terms of required sensor range) than the traditional parallel line approach used by large vessels.

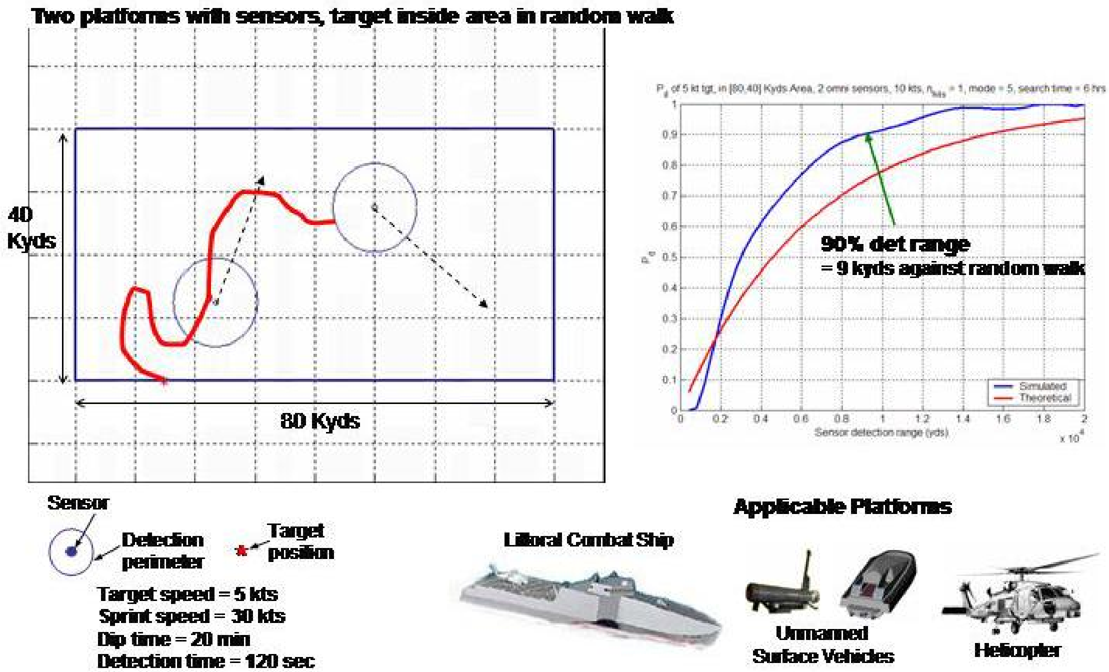


Figure XII. Wide Area Clearance, High Speed Platform Random Search Example

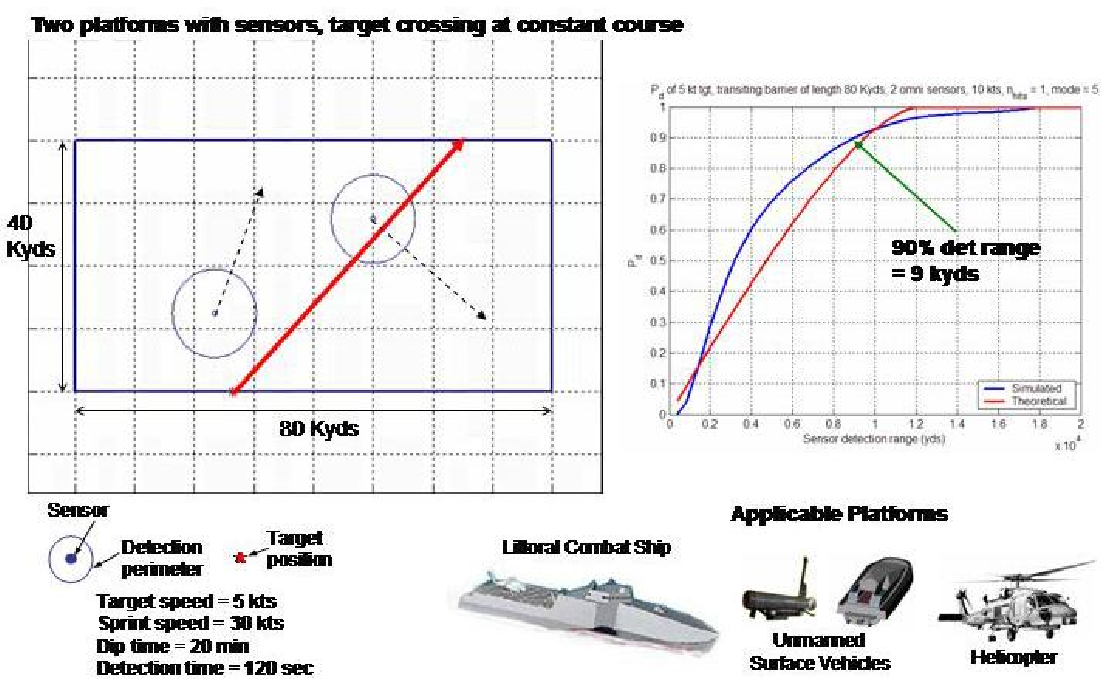


Figure XIII. Barrier Protection, High Speed Platform Random Search Example

4.6 Distributed Fixed/Floating Sensors

Next a distributed sensors problem is evaluated. Figure XIV illustrates a field of 24 stationary sensors spread uniformly across the search area. In this scenario, the minimum detection time is 45 seconds which is more appropriate for short range detection. The minimum sensor range providing $P_{cd}(t)$ or P_T = 90% is 2.0 Kyds when the target moves randomly for 6 hours and 2.5 Kyds against a transiting target with random course. In both cases the target has a constant (5 knot) speed. Interestingly the simulated and theoretical performance (from Equations I and III) agrees quite well.

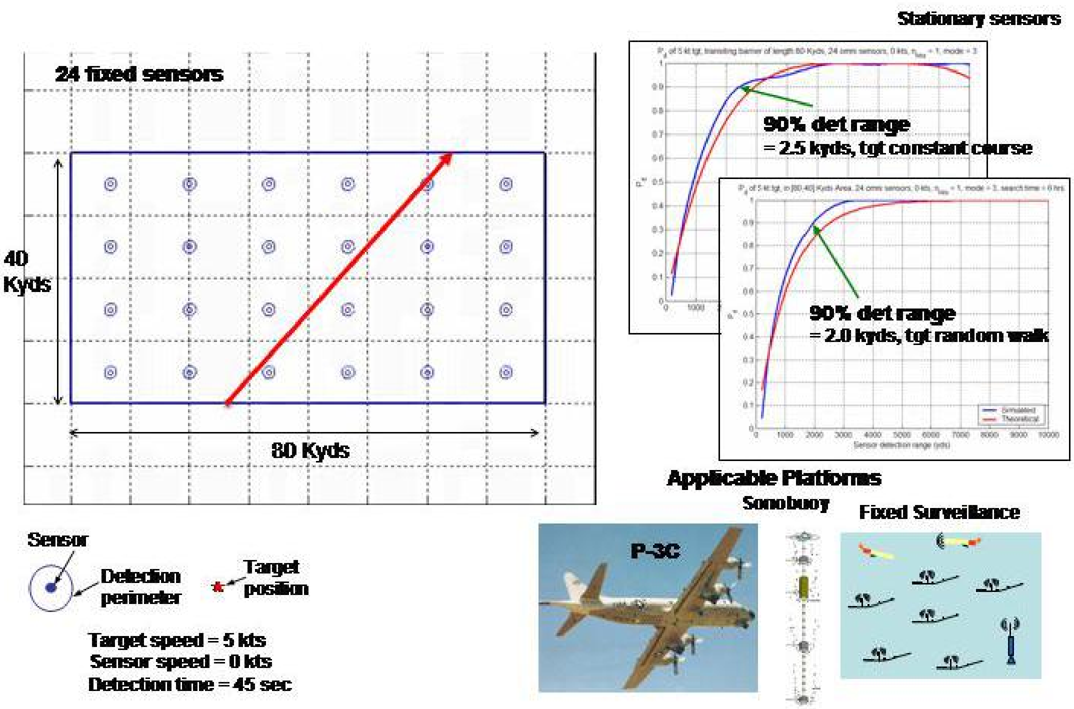


Figure XIV. Barrier Protection / Wide Area Clearance Multiple Fixed/Float Sensor Search Example

The stationary sensor case evaluated in Figure XIV yields very optimistic results if the sensors are floating in a normal ocean current. The impact of sensor movement on the performance of the field can be observed in Figure XV. The sensors have been subjected to a 0.55 knot current (nominal for many open ocean regions[13]) in the North-West direction (relative to the plot) for 12 hours. Figure XV contains a plot of sensor detection range versus cumulative detection probability for both the area search (blue) and transiting (red) target cases, after the sensors were subject to the current induced drift. The performance (e.g. 4.0 Kyd detect range for random target and 5.3 Kyd detect range for transiting target at Pd = 0.9) is now quite degraded with respect to the previous stationary sensor example.

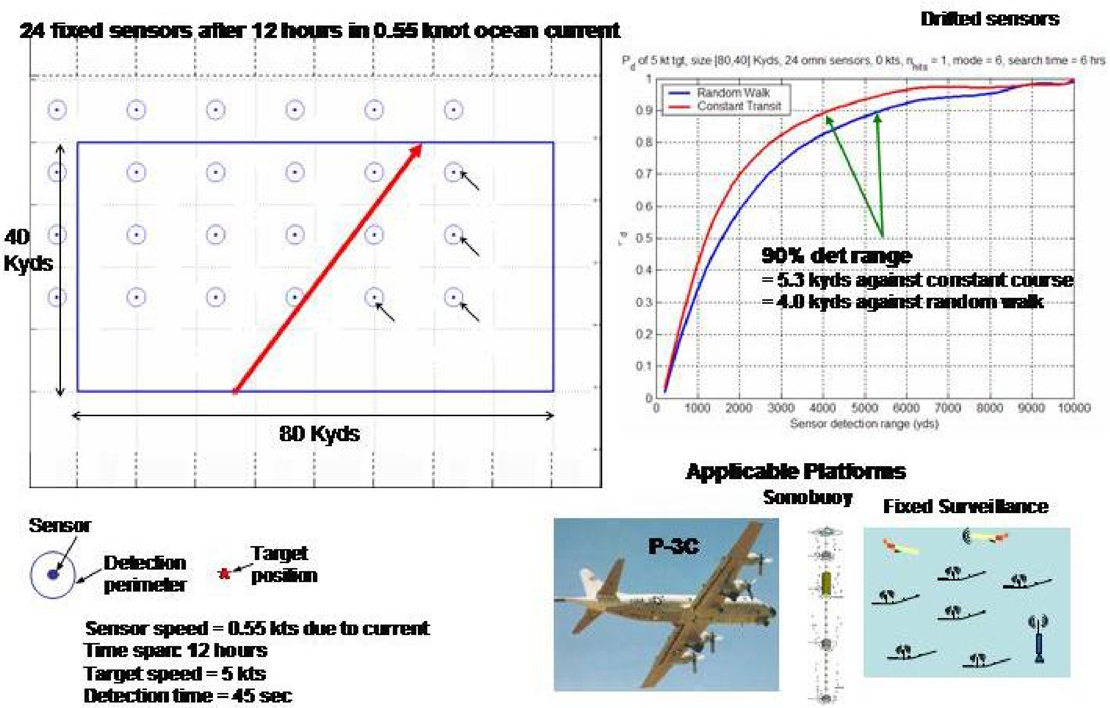


Figure XV. Barrier Protection / Wide Area Clearance Multiple Fixed/Float Sensor Search Example Including Sensor motion (sonobuoy) due to ocean current

Figures XIV and XV illustrate the importance of station keeping when employing distributed sensors for a search problem. One way to accomplish this is to host the sensor packages on unmanned undersea vehicles (UUV), such as those pictured in Figure XVI. An autonomously deployed anchor system could be employed to minimize energy use.

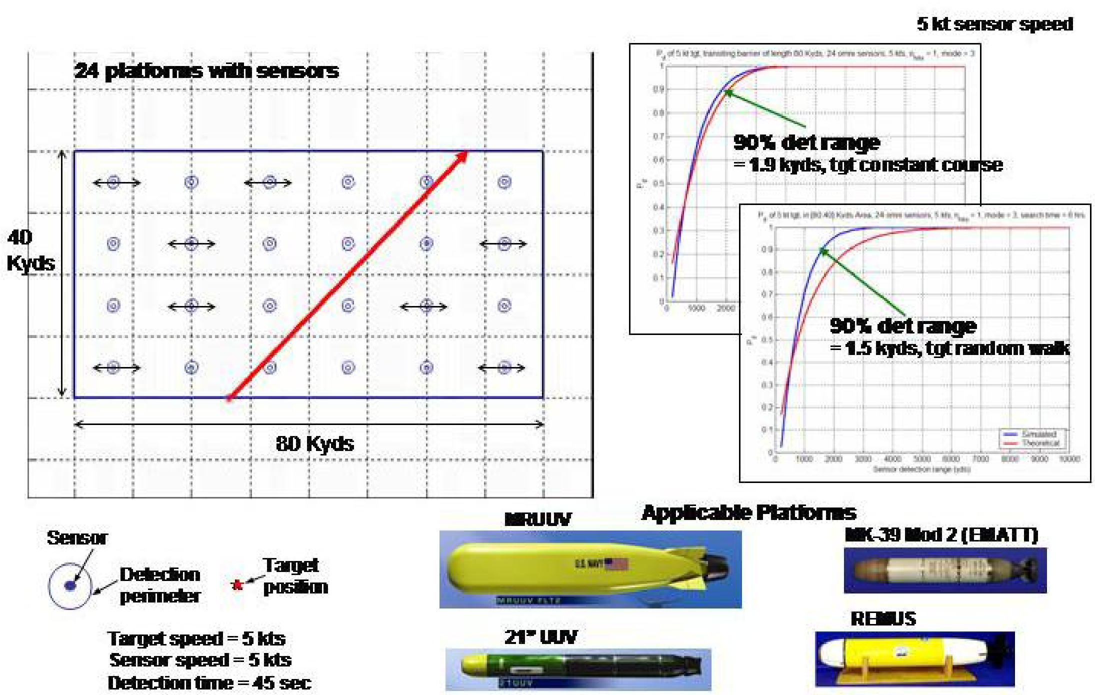


Figure XVI. Barrier Protection / Wide Area Clearance Multiple Mobile Sensor Search Example

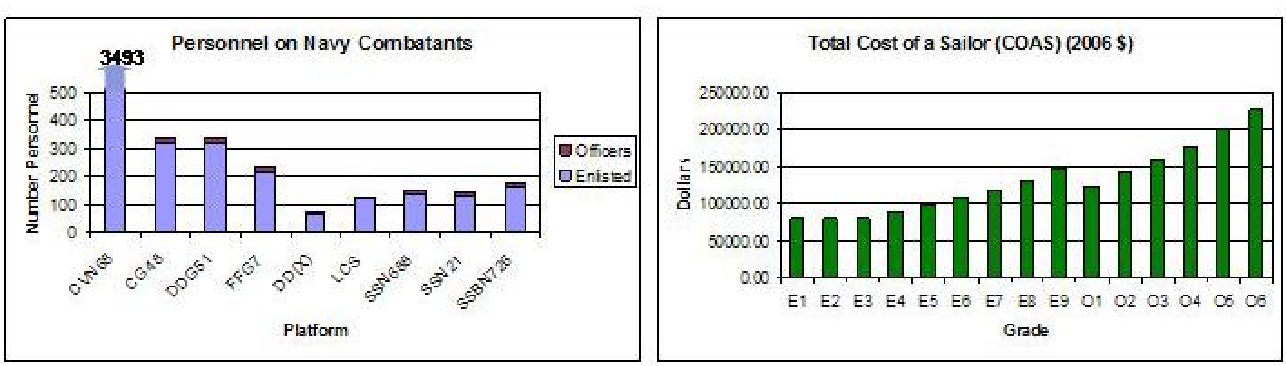
When new schemes for energy replenishment are available, the ability of unmanned vehicles to remain in motion while searching will be a significant advantage. Figure XVI also shows the $P_{cd}(t)$ (area) and P_T (barrier) performance when each distributed sensor moves in a linear repeated motion parallel to the horizontal axis at a speed of 5 knots in non-overlapping equidistant sectors. Such motion decreases the required sensor detection range to 1.5 Kyds for a random target and 1.9 Kyds for the target moving in a constant crossing trajectory. Here speed and sensor quantity work together to increase performance by decreasing the requirements of hosted sensors. Figure XVII shows simulation results for the barrier detection scenario with distributed sensors described in Figure XVI as a function of sensor speed. A 50% reduction in minimum sensor detection range is achieved by continuously moving the sensors inside their respective subsections at a 10 knot speed.

Figure XVII. Impact of Sensor Motion Multiple Mobile Sensor Example for Barrier Protection

It is likely that the vehicle speed and endurance simulated in the example above is only available with fairly large and somewhat costly vehicles. However the results show some of the benefits in terms of ASW search that can be achieved when the host vehicle capabilities (e.g., speed, endurance and cost) improve.

5.0 Cost Considerations

Unmanned/unattended sensors offer the potential to reduce the cost required to perform certain naval missions. Since the cost of building, operating and maintaining naval vessels involves a variety of factors, the focus here is upon the savings from reducing man-power otherwise required on search platforms. To begin the discussion, data is presented in Figure XVII that indicates the cost of manning many of the U.S. Navy's large ships and submarines.[14] Figure XVIII(a) plots the total number of sailors for each ship, while the total "cost of a sailor" (COAS) is plotted versus personnel grade in Figure XVIII(b).

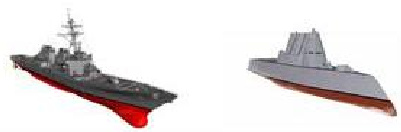


(a) (b)

Figure XVIII. Cost Considerations for Unmanned/Unattended Technologies

The COAS incorporates an acceleration factor (the so-called “70-7” rule) that accounts for personnel ashore supporting sailors afloat. The model recognizes that approximately 70 sailors and 7 civilians are required to support each 100 sailors on a ship. These indirect costs are added with the direct costs associated with pay and benefits to arrive at a total cost of a sailor. The costs given in Figure XVIII(b) represent an average across the entire Navy population and have been extrapolated to 2006 dollars.

The manning reduction planned for the Navy’s newest DD(X) destroyer represents a specific example of potential cost savings from automation and autonomy. Figure XIX provides a table listing the number of watch standers required on a current DDG-51 destroyer (during General Quarters) and the associated number planned for DD(X), according to a Government Accounting Office (GAO) report published in 2003.[15] We note that these numbers are still in flux until additional analysis and sea trials are completed. However, the estimates serve to illustrate the total ownership cost savings possible after a 40 year life cycle if the manpower savings (in this case 123 personnel) are realized. As shown, the total savings after 40 years is approximately $447M per ship. In the Undersea Warfare (USW) Department responsible for operation of the various sonars and non-acoustic USW sensors, the anticipated manning reduction is nine personnel. Sub-systems such as the integrated mult-modal watch-station that incorporate automatic detection and tracking capabilities are expected to provided the workload reduction necessary to eliminate the required billets on DD(X).[16]



Unofficial data for illustrative purposes only **

	DDG-51		DD(X)*	
	All Departments		All Departments	
	Watches	Costs ($)	Watches	Costs ($)
TOTALS 1 WATCH:	61	6078723.61	20	2348238.78
TOTALS 3 WATCHES:	183	18236170.82	60	7044716.34
TOTALS 40 YEARS:		729446832.67		281788653.68

	DDG-51		DD(X)	
	USW		USW	
	Watches	Costs ($)	Watches	Costs ($)
TOTALS 1 WATCH:	5	444958.46	2	208910.67
TOTALS 3 WATCHES:	15	1334875.39	6	626732.01
TOTALS 40 YEARS:		53395015.72		25069280.53

Example enabler:
Integrated Multi-modal Watch station

Human-centered design and reasoning system

* Note: DD(X) manning allocations still in flux
** Cost mapping used "unofficial" allocation of manpower billets

Total Projected Savings for DD(X) vs DDG all Departments ~ $447M / ship

Total Projected Savings for DD(X) vs DDG USW Department ~ $23M / ship

Figure XIX. DD(X) Manpower Reduction Example

6.0 Directions in Undersea Acoustic Sensor Automation

At a high level, the functional flow of automation algorithms associated with various undersea acoustic sensor systems generally follows the canonical form illustrated in Figure XX. Systems include passive only, active only and some with both passive and active sonar functions. Processing begins with spatial beamforming that might include adaptive methods to compensate for non-isotropic noise. Passive detection includes specific methods (e.g. filtering, transformation, normalization, integration, etc.) for broadband, narrowband and transient signals. Automatic tracking across bearing-range-frequency space links detections through time. When the sensor provides sufficient aperture length, algorithms exploiting wave-front propagation characteristics estimate target position. Classification algorithms exploit both physics-based clues and the unique time-frequency responses of various source platforms of interest. Active sonars include waveform generation, coherent detection receivers, ping-to-ping trackers, and echo classification algorithms. A multi-sensor contact fusion function associates various tracks to a common contact list and combines kinematic estimates into a single state for each contact.

In general current research in automation is focused upon passive and active sonar classification (including false alarm reduction) and multi-sensor fusion in high contact density situations. Additionally, new methods for reducing the impact of loud interferers when sensors provide limited degrees of freedom while minimizing artifacts into the beam output stream will continue to be a priority.

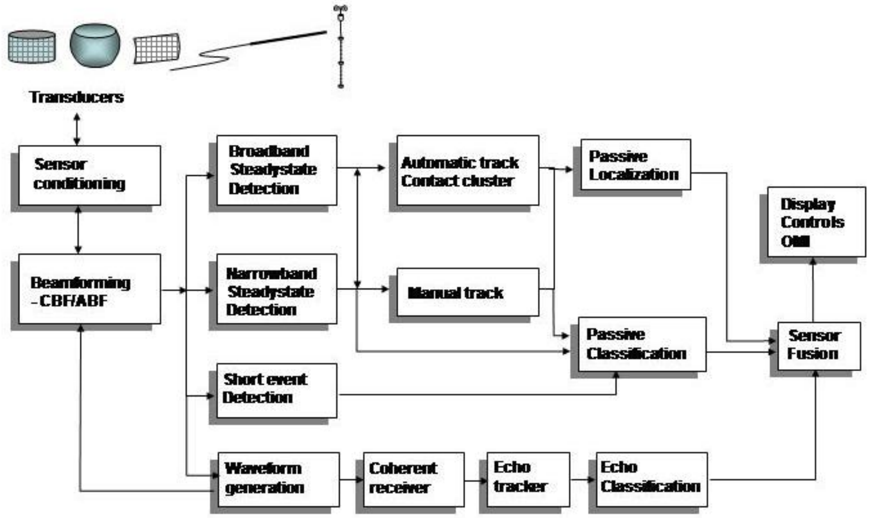


Figure XX. Canonical form for undersea sensor signal processing and automation

7.0 Remaining Technology Gaps

Although some of the capabilities from unmanned vehicles with sensor payloads were discussed, several additional technologies require further development to enable their full performance potential. Such desired capabilities include (in priority order) a) enhanced vehicle endurance, b) reduced sensor false alarm rate c) higher bandwidth electro-magnetic and acoustic communications, d) improved underwater navigation, e) equipment miniaturization, f) robust sensor gain, g) enhanced stability and mobility in high seas, h) improved deployment flexibility and i) improved reliability.

A major enabler for the search strategies described in Figure VIII (b) and (d) is a compact vehicle with sufficient energy supply to operate at required speeds for several days before energy replenishment. Many current USVs operate on diesel fuel providing an endurance of about 24 hours for nominal operations. Tactical considerations such as deployment platform vulnerability and wide area search are motivations for extending the endurance to 48-72 hours. Methods for decreasing fuel consumption by off-loading hotel loads to other energy sources such as replenishable photovoltaic generators require further development. Regarding UUV's, the Defense Advanced Research Project Agency (DARPA) is sponsoring a program aimed at replenishing power from natural sources such as methane hydrates, microbial transport, or anaerobic fermentation of phytoplankton which might offer further opportunities for increasing endurance.[17]

False alarm rate reduction is a continued focus given its potentially severe impact on performance in high clutter environments. In passive sonar, discriminating between desired sources and the numerous clutter sources from passing merchant craft, biologic vocalizations, or surface and internal waves usually requires high fidelity models of all likely signal types. In active sonar, reflections from bottom features, biologics, and surface clutter represent a similar problem and also require numerous recorded exemplars in environments of interest to construct a high performance discriminant function. Enhancements in sensor aperture to increase fine bearing resolution and parametric methods for reducing vertical side-lobes offer potential to help.

Next, the availability of a reliable long range, high bandwidth, underwater communications mechanism would be a significant tactical enabler supporting multi-vehicle collaboration, on-demand identification friend or foe (IFF), and data exfiltration to a central command center. Underwater devices to communicate with UUVs would be particularly useful if they required low power and transmitted waveforms having low probability of intercept. Approaches are not limited to acoustic methods. For example a very low cost, low volume, disposable floating device deployed from a UUV, capable of floating to the surface and sending an RF message via satellite would be quite useful for the exfiltration problem.

The remaining technology gaps are treated briefly. Improved methods for underwater navigation are needed to help maintain the integrity of the search plan without frequent fixes from the Global Position System (GPS). Electronic and mechanical miniaturization (potentially offered by MEMs technology) will enable deployment of distributed sensors from vehicles having limited payloads. Robust sensor gain against noise refers the traditional problem encountered by all ocean sensors regarding the ability to notch out interferers without degrading the signal. Enhanced stability at high seas mostly relates to the problem of USV sensor payloads where sea worthiness during rough conditions can be a significant operational limiter. Improved deployment flexibility refers to the need for deploying unmanned/unattended sensors in areas that could impose limits on air superiority or access to traditional naval vessels. Sensors which are sufficiently portable for deployment by small expeditionary craft would be advantageous. Finally, the reliability of unmanned/unattended sensors in terms of on-station availability cannot be sacrificed while meeting the performance requirements, since opportunities to provide in situ maintenance and repairs will not likely be prevalent.

8.0 Summary

This paper presented examples of various USW search strategies relevant to conventional capital ships, unmanned surface vehicles, and unmanned underwater vehicles. Through simulation and analysis, the performance potential of various search scenarios was explored to highlight the potential differences. It was noted that the capabilities of USVs with dipping sonars rival (in terms of required detection range) the performance of capital ships engaging in traditional search methods. Also, distributed fields of small sensors can be significantly enhanced by hosting the sensors on small UUVs due to the advantages of receiver motion and their inherent capability for station keeping against ocean currents. The potential cost advantages of automation and autonomy was demonstrated by the simple example of the DD(X) versus DDG manning reduction potential. Finally a canonical form for automatic sensor processing was presented to provide a context from which areas requiring additional research and development were recommended. The discussion of technology gaps was expanded to include other pressing issues such as limited vehicle endurance and underwater communications.

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