JANUARY 2024

Force Development—Undersea Networks: Nord Stream Case Study

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DRM-2023-U-036410-Final

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Abstract

As part of CNA's Force Development initiative, we developed a Monte Carlo simulation model that assesses the potential benefits of undersea networks that can provide communications, power, and sensing data. In this paper, we use the model to examine a real-world event—the September 2022 sabotage of the Nord Stream pipeline—and assess the capabilities that an in-place undersea network would have needed to provide timely warning. For this study, we examined a scenario in which unmanned underwater vehicles (UUVs) are used to monitor the pipeline and a series of underwater nodes provide power and communications. We used open-source information to set the parameters for the UUVs and nodes. Under these conditions, an undersea network would have needed at least 21 UUVs and 23 network nodes to discover and report an act of sabotage within 24 hours on average. The ability to coordinate between searchers potentially provides significant benefits, particularly with fewer searchers and nodes. As such, focusing UUV development on speed, battery life, and coordination appears to have the greatest return on investment for maritime domain awareness missions.

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This work was created in the performance of Federal Government Contract Number N00014-22-D-7001.

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Approved by: **January 2024**

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EXECUTIVE SUMMARY

As part of CNA's Force Development initiative, we developed a Monte Carlo simulation model that assesses the potential benefits of undersea networks that can provide communications, power, and sensing data [1]. This model, similar to the other "building block modules," was designed to explore a particular component of force design—in this case, the promise and opportunities presented by undersea networks. In this paper, we use the model to assess a real-world event—the September 2022 sabotage of the Nord Stream pipeline—to analyze the capabilities that an in-place undersea network would have needed to provide timely warning of the sabotage.

The Nord Stream pipeline is approximately 660 nautical miles long and consists of two natural gas pipelines running from Russia to Germany through the Baltic Sea. For this study, we examined a scenario in which unmanned underwater vehicles (UUVs) are used to search for potential sabotage, with a series of underwater nodes to charge the UUVs and provide them with a communications capability to report back. For our baseline UUV, we used the General Dynamics Bluefin-21, which is used by the US Navy for a variety of missions and has a 25-hour endurance at 3 knots, an assumed maximum recharge time of 4 hours, and an assumed probability of detection (P_D) of 0.7. Based on these inputs, we found the following:

- Many searchers and nodes are required for timely capabilities. An undersea network of at least **21 UUVs and 23 network nodes** would have been required to discover and report an act of sabotage in under 24 hours on average (mean time to report (MTR)). Expanding the timeline to 48 hours enables different, slightly lesser, combinations of searchers and nodes (12 to 20 searchers with 23 nodes, 14 to 20 searchers with 18 nodes, and 20 searchers with 15 nodes).
- The ability to coordinate between searchers provides significant benefits, particularly in cases with fewer searchers and nodes. MTR for 21 searchers and 23 nodes with

In this paper, we use the model to assess a real-world event—the September 2022 sabotage of the Nord Stream pipeline—to analyze the capabilities that an in-place undersea network would have needed to provide timely warning of the sabotage.

coordination is comparable to the random model results (22.3 hours versus 23.3 hours, respectively), but for 6 searchers and 12 nodes, the coordinated MTR is 74.1 hours and the random model MTR is 354.2 hours.

- Based on those two findings, focusing UUV development on speed, battery life, and coordination capabilities appears to have the highest return on investment if maritime domain awareness missions such as this are of interest.
- For 0.7 P_D, approximately 314 combined search hours are required to "cover" the pipeline once. This time drops to 244 hours for 0.9 P_D and increases to 733 hours for 0.3 P_D. MTR is inversely related to the capability of each searcher, but low individual capability can be compensated for by adding more searchers.
- The delay between detection and reporting is at least the time it takes the UUV to transit from the detection to the next node. Spacing the nodes less than half of the UUV's endurance range apart hedges against the loss of a node and reduces the time between detection and reporting.
- Variation in the time to charge each UUV from 16 to 32 percent of search time (4 to 8 hours) affected MTR by 10 percent at most.

As indicated by the above findings, our undersea network model can be used to analyze real-world situations and has the flexibility to assess the effect of changes in system parameters and employment concepts.

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INTRODUCTION

The opacity of the future, from uncertainty over the geopolitical operating environment to future US and adversary capabilities and concepts of operations (CONOPS), drives the need to explore an almost limitless trade space of platforms, capabilities, and CONOPS when conducting force design or force development efforts. However, many of the current techniques used in such efforts, including campaign analysis and wargaming, have a limited ability to examine a wide array of possibilities quickly, making analyzing different force development possibilities difficult. For example, campaign analysis provides value because of its robust number of variables, but this robustness can obscure the relationship between inputs and outputs and limits the sensitivity analysis that can be performed. For that reason, testing quantities, laydowns, and tactics rapidly is largely impossible. Wargaming is another useful tool to understand how forces might be employed. However, performance is an input rather than a variable, so results are biased by assumed performance levels.

In response, in fiscal year (FY) 2022, CNA initiated a series of efforts designed to build modules that could be combined to create more complex assessments. Each focused on a distinct area such as detectability, surface and air communications, and undersea networks with a goal to develop models that explore the parameter space across thousands of options rapidly. These models could then complement methods such as campaign analysis through creation of models that can be parameterized and run rapidly with new values and operational contexts while providing statistically rigorous assessments. Key benefits of this approach include the ability to explore and bound the unknowable (e.g., adversary futures) to help determine what capabilities, capacities, and CONOPS "move the needle" the most. The end state, currently being created, is a robust research program and force design lab with a suite of tools enabling real-time build and first-order iterative assessments of force design options.

A key FY 2022 effort dealt with undersea networks, which could enable a variety of critical undersea missions by providing communications, power, and sensing data to both manned and unmanned undersea platforms. To assess the effects of various concepts for these undersea networks, we developed a Monte Carlo model for search scenarios, which is described in detail in an earlier report [1].

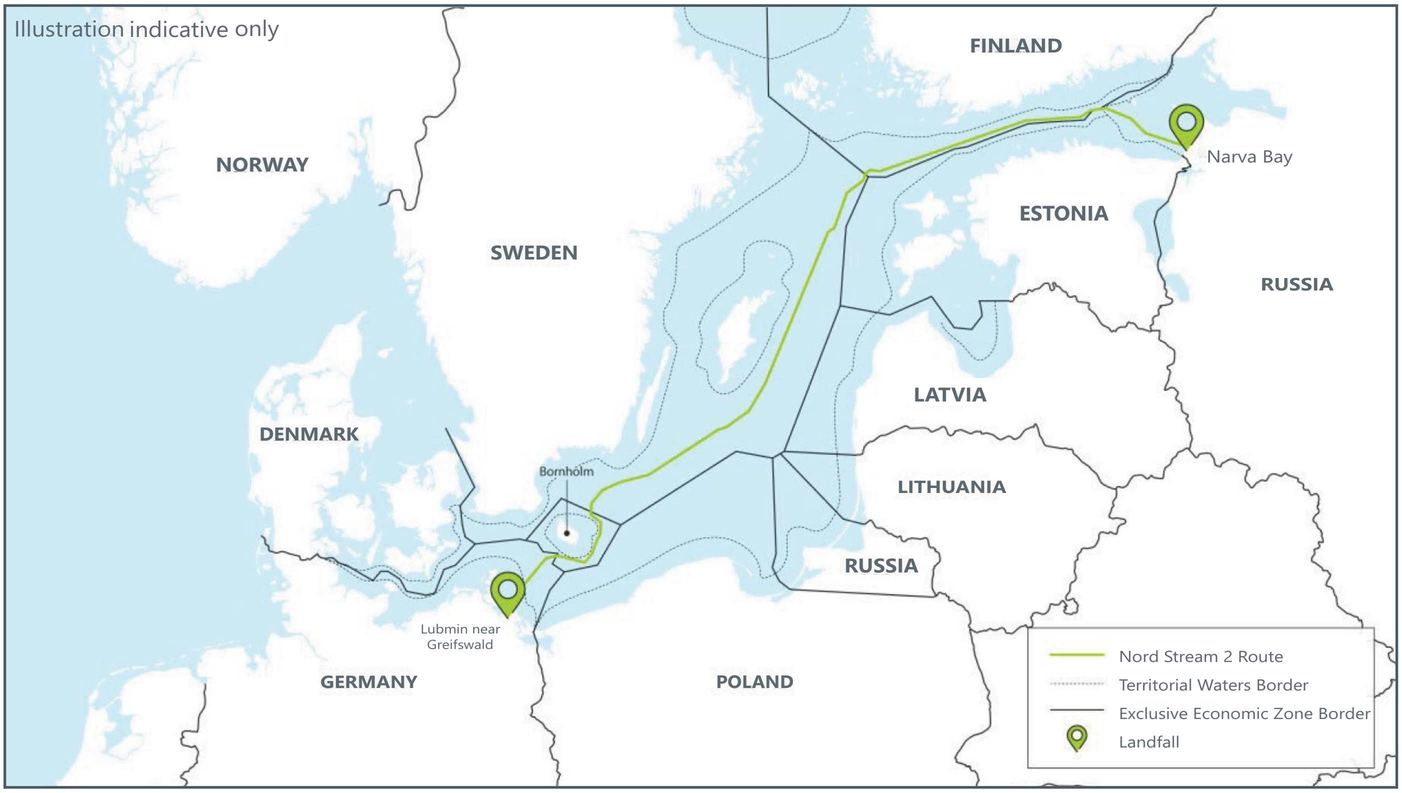
After completing initial work on the undersea network model, we were asked to apply the model to the Nord Stream pipeline system, which had recently been sabotaged, as an example. To do so, we imagined and assessed a scenario in which an undersea network consisting of unmanned searchers and charging nodes is in place and constantly monitoring the pipeline when a bad actor commits an act of sabotage. We can then use the model to examine how long it would take for the sabotage to be discovered and reported. This paper describes how we adapted the undersea network model for the Nord Stream scenario as well as initial results.

NORD STREAM BACKGROUND

Nord Stream geography and political impact

Nord Stream consists of two approximately 1,234-kilometer (666-nautical miles (n.mi.)) natural gas pipelines running from Russia to Germany through the Baltic Sea, referred to as Nord Stream 1 and Nord Stream 2, with each pipeline consisting of two pipes. Each pipe has a diameter of approximately 1,220 millimeters (48 inches), and the combined capacity of the four pipes is 110 billion cubic meters per annum of natural gas. The two pipelines largely follow the same route in the Baltic, with some variation in the origin points—Nord Stream 1 connects Vyborg and Nord Stream 2 connects Ust-Luga. Both pipelines run to Lubmin in northeastern Germany. Along this route, the pipelines pass through the exclusive economic zones (EEZs) of Russia, Finland, Sweden, Denmark, and Germany, as shown in Figure 1 [2].

Figure 1. Nord Stream pipeline map and EEZs

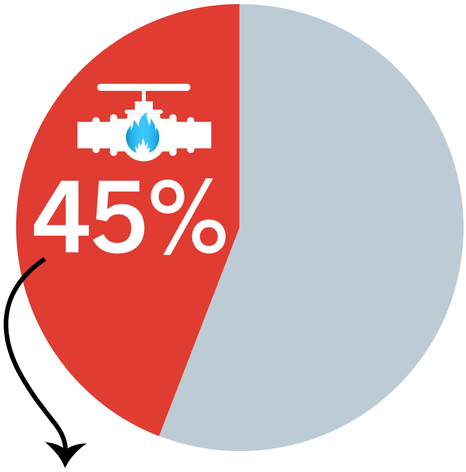


Source: Nord Stream AG [3].

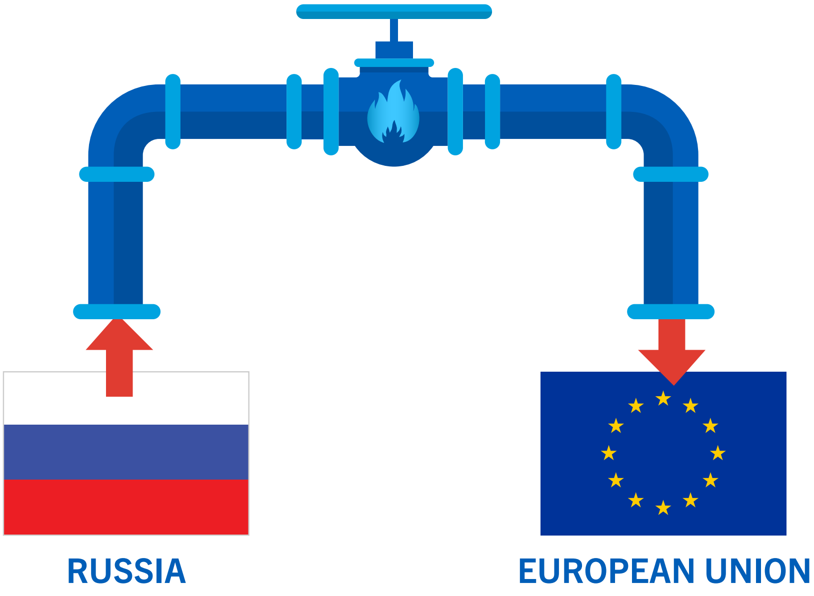
The Nord Stream 1 pipeline was inaugurated in October 2012, and the expanded Nord Stream 2 was completed in September 2021. However, the project has drawn considerable political opposition over its lifetime from multiple US presidential administrations and European nations outside Germany, with opposition growing after the 2014 Russian annexation of Crimea. The primary security concern was that the pipelines would increase European dependence on Russian energy—in 2021, Russian natural gas accounted for about 45 percent of the European Union's (EU's) natural gas imports and almost 40 percent of its total gas consumption [4]. In the event of a Russian conflict with Europe, Russia's ability to cut off energy flow would be a significant economic threat [3]. Indeed, over the course of 2021 and into early 2022, Russia decreased natural gas supplied to the EU market, which contributed to record-high gas prices in Europe in late 2021 and created considerable turmoil in Europe through the winter heating season.

In February 2022, Russia invaded and occupied parts of Ukraine, and the conflict has continued to the present. In response to the invasion, Germany suspended certification of the Nord Stream 2 pipeline, and Nord Stream 2 AG (a subsidiary of Russian state-owned gas company Gazprom that was operating the pipeline) ended business operations. Nord Stream 1 continued to operate, and Europe continued to import natural gas from Russia in the months following the invasion [5]. However, the EU began to take steps to diversify away from Russian energy—importing oil and natural gas from other international sources as well as increasing European coal energy production and subsidizing fossil fuel companies [2].

On August 31, 2022, Gazprom halted gas delivery through Nord Stream 1 for three days, nominally for maintenance. On September 2, 2022, it announced that the pipeline would remain shut off indefinitely, ostensibly because of EU sanctions against Russia resulting in technical problems. Although both Nord Stream 1 and 2 were not operational, they remained filled with natural gas leading up to the sabotage incident.



THE PERCENTAGE OF THE EU'S NATURAL GAS IMPORTS THAT COMES FROM RUSSIA



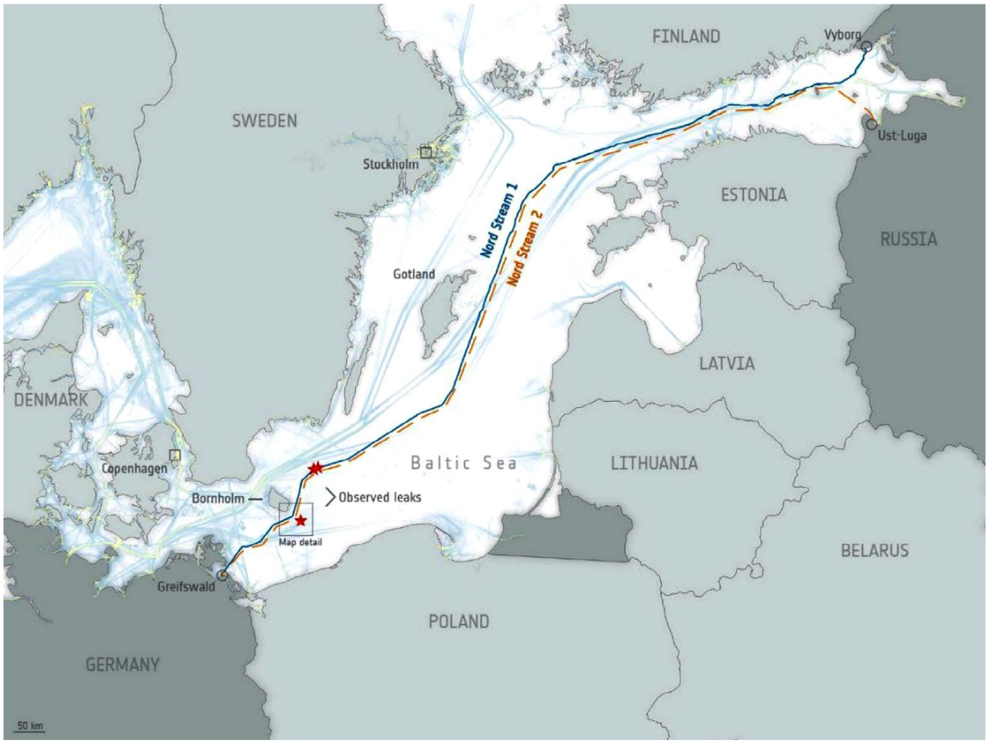
Sabotage incident

On September 26, 2022, at 0203 local time, Denmark observed seismic activity indicating two underwater explosions. Around the same time, Germany observed a loss of pressure in both pipes of Nord Stream 2 and one pipe of Nord Stream 1. Subsequent investigations by Danish and Swedish authorities located four leaks, two each in the Danish and Swedish economic zones, as shown in red in Figure 2 [6]. Satellite observations conducted by the European Space Agency showed large methane plumes above the leaks, indicating large ruptures [7].

Although the Swedish investigation into the leaks uncovered traces of explosives, confirming that the incident was sabotage, the identity and motives of the perpetrators remain unknown [8]. Given the depth of the pipeline and the complexity of using underwater explosives, it seems likely to have been a state actor, but no country has claimed responsibility. Open-source reporting has shown that Russian naval activity was observed in the vicinity of the pipeline with automatic identification system transceivers inactive in the week leading up to the incident [9] [10], but several international media outlets have cited anonymous sources indicating that a pro-Ukrainian group conducted the attack [11]. Russian President Vladimir Putin has accused the US and its allies of sabotaging the pipeline, offering no evidence; the US has dismissed this claim [12].

Regardless of where responsibility ultimately lies, the US has an interest in protecting critical undersea infrastructure, so this sabotage incident is a useful test case for undersea networks.

Figure 2. Leak locations on Nord Stream pipelines



Source: European Space Agency [6].

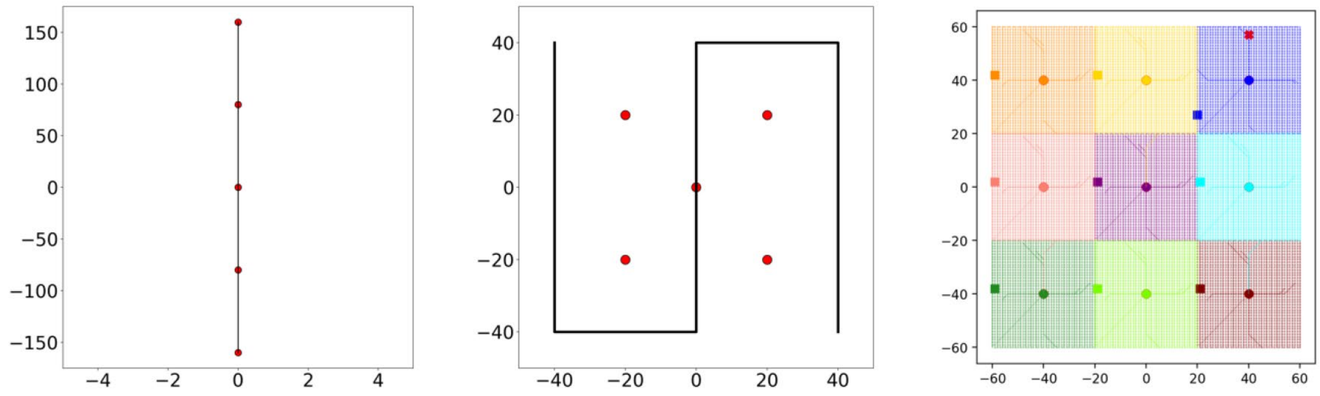
METHODOLOGY

Undersea network model

To assess the benefits undersea networks might have on the Navy's ability to conduct distributed maritime operations and support unmanned vehicles—and the capabilities such networks might need to have—we developed a Monte Carlo search simulation in Python through which we could vary the number and properties of the network nodes and the network users [1]. We are assuming that all systems work as advertised so that we can focus on how much impact the network could have in enabling operations and improving mission effectiveness.

Figure 3 shows an overview of the scenarios that can be modeled, ranging from a simple one-dimensional cable search on the left to a more complicated two-dimensional cable search in the middle to a general two-dimensional area search on the right. The black lines show the location of the cable, and the red dots show locations of network nodes; the colored lines on the far right show the paths that each user takes. The users are assumed to be unmanned underwater vehicles (UUVs) that are searching for a randomly located target within the area under consideration, so we also refer to them as "searchers." We assume that the searchers do not have independent communications capabilities and must return to a node to report a detection. We also assume that each searcher can track its own position accurately and therefore knows the location of the nearest charging node. Finally, we assume that charging time scales linearly with battery level, although that behavior can be adjusted based on the UUV's properties.

Figure 3. Undersea network model scenarios—cable search and area search



Straight cable

Cable with turns

Area search

Source: CNA.

Without the charging nodes, the operating cycle for each UUV would involve launching the UUV from a surface ship and then recovering it once it had completed its mission or run out of batteries. This process adds significantly to the amount of down time for each UUV and increases the amount of human labor required, especially as the number of UUVs grows, wasting precious hours in a search scenario. Therefore, the presence of the charging nodes and the ability of the UUVs to use them is a crucial enabling technology for the effectiveness of these systems.

For each scenario, we can define the following overall parameters:

- Number of trials
- Number of time steps per trial

For the searchers, we can specify these properties:

- Number of searchers
- Endurance: amount of time the searcher can search before needing to recharge
- Search probability of detection (P_D): probability that the searcher will correctly identify the target if the searcher is within range
- Speed

For the nodes, we can specify these properties:

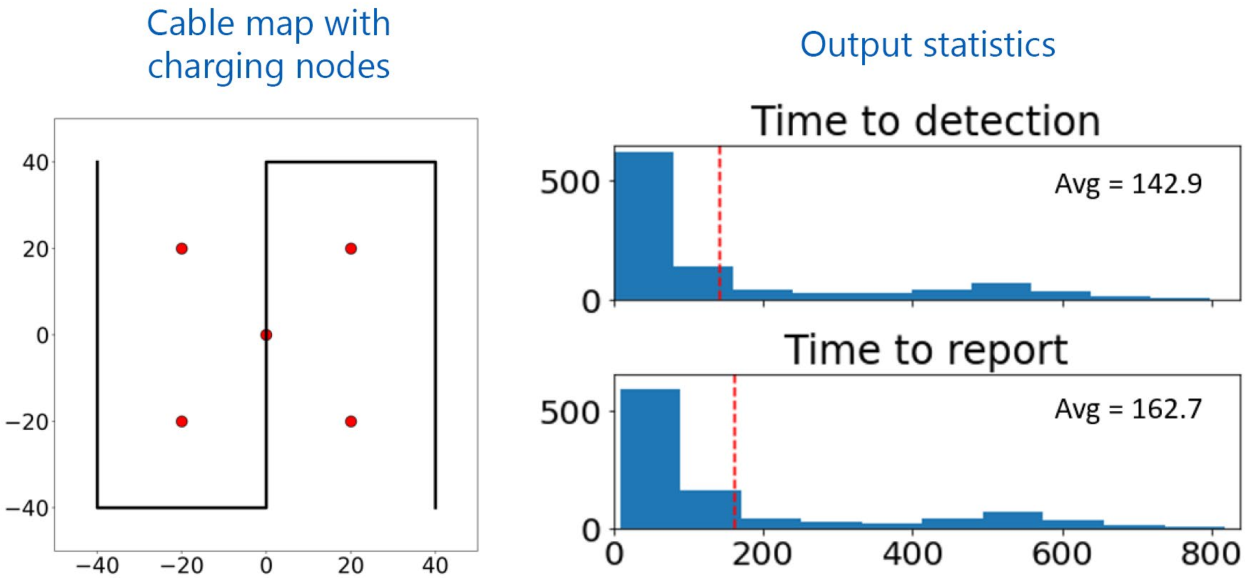
- Node spacing: distance between two nodes
- Location of nodes
- Charge time: how long it takes to fully charge a searcher

We can also define operational properties:

- Searcher starting location: random location or starting on a node
- Charge limit: if a searcher's charge falls below this point, it must return to a node to recharge
- Distance limit: farthest distance from a node that a searcher can go

The presence of the charging nodes and the ability of the UUVs to use them is a crucial enabling technology for the effectiveness of these systems.

Figure 4. Sample model output for a two-dimensional cable search



Source: CNA.

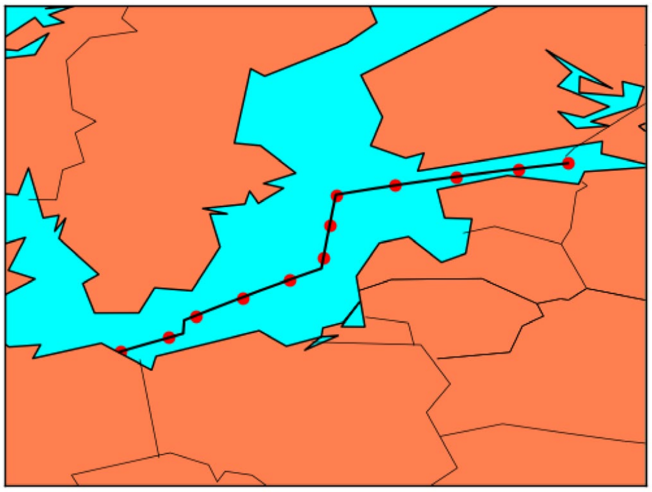
Figure 4 shows a sample output for a two-dimensional cable search scenario. In this case, the model ran 1,000 trials, tracking the time to detection and time to report and plotting the histograms on the right. Time to report is distinct from time to detection because the searchers cannot communicate on their own; when they find the target, they must return to a node to report the target's location. The average for each histogram is shown with the red dashed line, with mean time to detection (MTD) and mean time to report (MTR) the key measures of effectiveness. The model also tracks the amount of time spent charging (i.e., not searching) and the number of trials in which the target is not detected ("time out"). Trials that time out are not included in the average numbers and are reported separately.

As originally written, the model works in abstract coordinates, so we converted to lat/lon coordinates to apply the model to the real-world Nord Stream geography. We defined the Nord Stream pipeline within the model by identifying lat/lon positions of each segment. Because each time step in the model represents one hour of real time, we divided the Nord Stream map into one-hour chunks according to the searcher speed. We then placed the network nodes according to the specified node spacing as well as at the ends of the pipeline, as shown in Figure 5, in which the black line is the pipeline and the red circles are network nodes. We also wrote new functions to work with lat/lon coordinates and identify great circle distances between points and paths from one point to another; in this scenario, there are no obstructions and no routing issues to consider.

Figure 6 shows the searcher tracks for a single trial with the geographical features and pipeline map removed for clarity. The red circles show the charging nodes, and the colored circles and squares show start and end points for different searchers. The smaller colored dots and lines show the paths for each searcher.

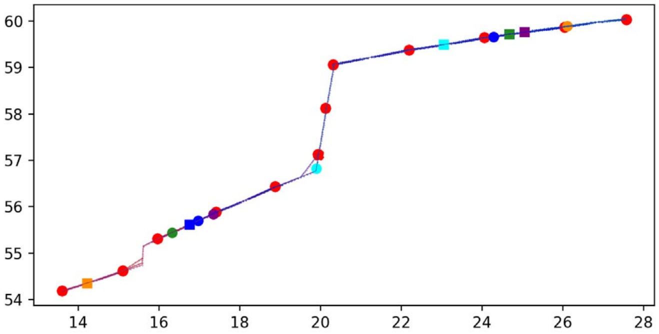
In the scenario that we are considering, an undersea network is in place and continuously monitoring the pipeline for sabotage. Because the searchers cannot communicate with one another, we assume that they are not coordinated and, as such, start in random positions. Alternative modes of operation could include searchers coordinating so that there is a constant gap between searchers and therefore a constant amount of time between searchers passing over any given point on the pipeline. Another option would be dividing the pipeline into equal length segments and assigning each a searcher, shortening the area that each searcher is responsible for but covering any given point with only one searcher.

Figure 5. Nord Stream map with network nodes



Source: CNA.

Figure 6. Single trial search paths



Source: CNA.

Candidate systems

For searcher and node parameters, we identified a few candidate systems that listed basic characteristics on the manufacturer's website.

We identified several UUV systems that could function as searchers for the undersea network. Because the mode of operation that we are interested in is monitoring undersea infrastructure to warn against sabotage, we looked for UUV systems that are capable of mine countermeasures or equipped with bottom-sensing systems. Of these, we selected two, the General Dynamics Bluefin-21 [13], a commercially available system, and the Monterey Bay Aquarium Research Institute (MBARI) Seafloor Mapping Autonomous Underwater Vehicle (AUV) [14], a research platform; the MBARI AUV is pictured in Figure 7. The Bluefin-21 has somewhat higher endurance, with 25 hours of search time versus the MBARI AUV's 19 hours. The search speed of the two is the same, 3 knots. The Bluefin-21 is rated to 4,500-meter depths, and the MBARI AUV is rated to 6,000-meter depths. The manufacturers did not provide sensor performance specifications; however, General Dynamics lists the Bluefin-21 as having applications in mine countermeasure and unexploded ordnance missions, and the MBARI AUV has four mapping sonars to scan its environment and penetrate the seafloor. For that reason, and to provide flexibility for this and other potential assessments, we vary P_D in the model.

Of note, General Dynamics also advertises the Knifefish UUV system as designed specifically for detecting, classifying, and identifying mines in high clutter environments [15]. However, the website does not list specifications, so we did not consider it as an option.

An initial unclassified search did not yield any commercially available undersea charging stations that could serve as a network node, although systems are in development that would allow a UUV to dock and recharge autonomously [16]. We therefore used a hypothetical system that could operate in the Baltic Sea environment and recharge a UUV in four to eight hours, with power to the station provided either externally or through a combination of constant harvest of marine energy and battery backup so that recharging is available on demand [17]. We also assume that the candidate searchers can utilize the node fully (i.e., they can dock with the charging station, fully recharge, conduct communications and report detections, and repeat this cycle indefinitely).

Figure 7. MBARI seafloor mapping AUVs

Source: Monterey Bay Aquarium Research Institute [14].

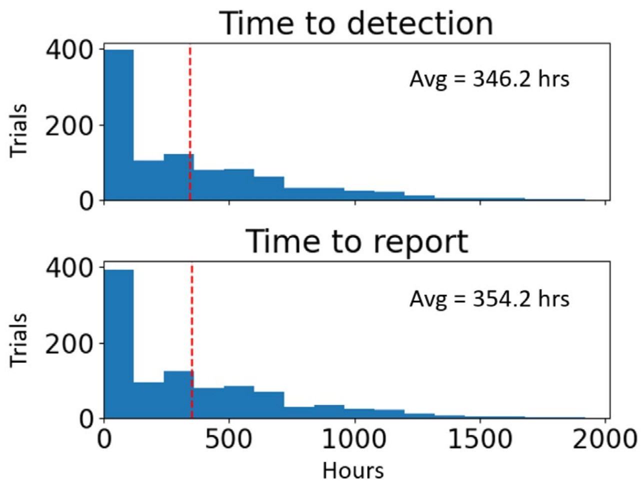
RESULTS

Searcher and node density

With the model adapted for the Nord Stream scenario, we can start looking at results. In this scenario, we imagine that a bad actor has sabotaged the pipeline by planting explosives or some similar method. An undersea network consisting of UUVs and charging nodes is in place and constantly monitoring the pipeline, and we can test how long it would take for such sabotage to be detected and reported. All results shown are drawn from runs with 1,000 trials.

Figure 8 shows results for a single run with 6 Bluefin-21 searchers, 0.7 P_D, 60-n.mi. node spacing (12 nodes total), and a maximum charge time of 4 hours. The bin width for the histograms is 120 hours, or 5 days. Although the faster the sabotage is discovered the better, because the details of the real-world incident are still unknown, we do not know the timeline from sabotage to pipeline rupture. Reporting indicates that suspicious naval activity was observed several days in advance of the Nord Stream attack, so we use an initial benchmark of 5 days. Therefore, the conditions in this run are unlikely to have caught the attack, with average time to detection of 346.2 hours (14.4 days) and average time to report of 354.2 hours (14.8 days).

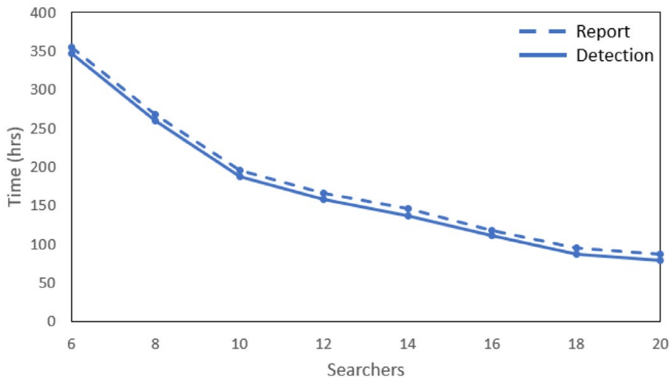
Figure 8. Results for a single run—6 Bluefin-21 searchers, 60-n.mi. node spacing, 1,000 trials



1000 trials
6 searchers – Bluefin-21
0.7 P_D
60 n.mi node spacing

Source: CNA.

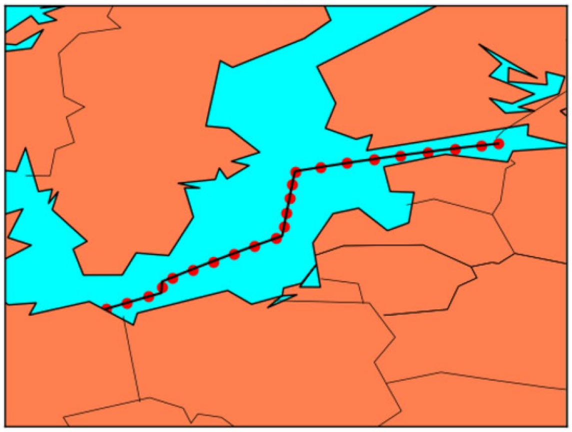
Figure 9. Detection and report time vs. number of searchers—60-n.mi. node spacing



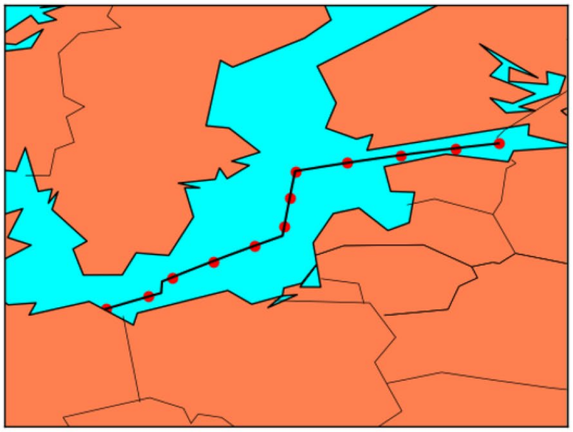
Source: CNA.

Figure 10. Node spacing comparison—30 vs. 60 n.mi.

30 n.mi.



60 n.mi.



Source: CNA.

Adding more searchers will directly increase the search rate and therefore cut down on detection time, so Figure 9 shows results for different numbers of searchers, holding the other conditions constant (0.7 P_D, 60-n.mi. node spacing). The solid line shows detection time, and the dashed line shows report time; the difference between the two is roughly constant, which makes sense because the node placement stays the same and the sabotage point is placed randomly, so the average distance to the nearest node stays the same. Each additional searcher contributes to a larger reduction in detection time at low numbers, whereas at high numbers the marginal effect gets smaller and smaller. For this node configuration, it takes 16 searchers to drop the average time to report below 120 hours.

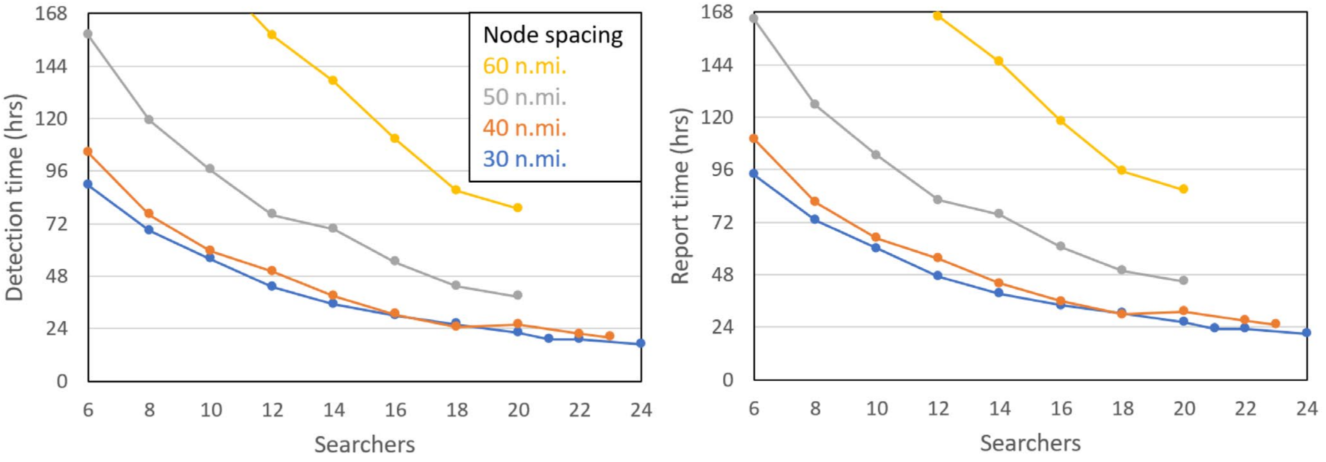
The node density also has a significant effect, up to a point. If the nodes are spaced too far apart, depending on the searcher's properties, parts of the pipeline would become impossible to search. In this case, the Bluefin-21 has 25 hours of battery life and 3 knots search speed, so if the nodes are spaced more than 75 n.mi. apart, a searcher would not be able to travel from one node to another and would be stuck. We also have set the searcher behavior so that a searcher will return to a charging node below a certain battery life threshold, so 60 n.mi. is the maximum distance between nodes that we examined for the Bluefin-21. The MBARI seafloor mapping AUV has 19 hours of battery life and 3 knots search speed, so the range limit is 57 n.mi.; in that case, the maximum node spacing that we used was 50 n.mi.

In addition to the physical range limitations, there are operational concerns to consider. Figure 10 shows a comparison of the node maps with 30-n.mi. spacing on the left and 60-n.mi. spacing on the right. If one of the nodes were removed from the 60-n.mi. map, whether through enemy action or malfunction, a gap would be introduced that a searcher would not be able to search effectively or even cross. Because we cannot predict which node may be removed, making the network denser everywhere would hedge against the removal of any single node and ensure that the searchers would be able to traverse the entire pipeline. Although the denser node map is not immune to this issue, two nodes would need to be removed, so the sabotage would potentially be easier to detect. (In either case, the removal of a node would be a signal to commit other search resources to investigate.) Of note, a linear change in spacing does not produce a linear change in the number of nodes because the two are inversely related—for 60-n.mi spacing, 12 nodes are needed; for 50 n.mi., 15 nodes; for 40 n.mi., 18 nodes; for 30 n.mi., 23 nodes; and for 20 n.mi., 35 nodes.

Figure 11 shows detection time on the top and report time on the bottom as a function of the number of searchers, with different node spacings shown in different colors. Horizontal lines are spaced every 24 hours. We can see that different combinations can yield similar detection and report times, which offers some flexibility in the system's design. For example, 10 searchers with 30-n.mi. node spacing and 16 searchers with 50-n.mi. node spacing both report detections at about 60 hours. Although more searchers and more nodes generally shorten detection times, there is a point of diminishing returns—for higher numbers of searchers, going from 40-n.mi. to 30-n.mi. node spacing does not shorten detection time much and may be within the margin of error for the highest number of searchers examined.

To achieve an MTR of less than 24 hours, at least **21 searchers and 23 nodes** (30-n.mi. node spacing) are required. For an MTR of less than 48 hours, different combinations of searchers and nodes are feasible, from **12 searchers and 23 nodes to 20 searchers and 15 nodes.** We will look at how much different system parameters affect the results in the following sections.

Figure 11. Detection and report time for different combinations of searchers and node spacing



Source: CNA.

Charging node properties

In the model as written, the only charging node properties are the location and the charge time. Because the location is set according to the node spacing above, the only other potential source of variation is the charge time, which we varied from 4 hours to 8 hours, equivalent to 16 to 32 percent of the Bluefin-21's 25-hour endurance. We assume that the charging time is linear with the battery level, although different charging curves could be considered in the future.

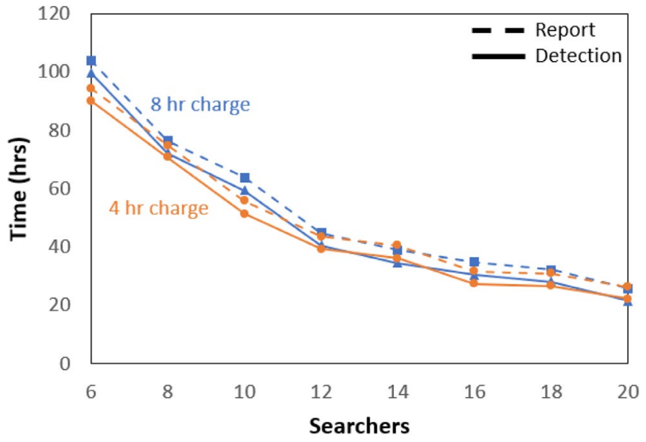
Figure 12 shows detection and report time for two runs, holding everything constant except the charge time. The charge time does not appear to change the results significantly. There is more of an effect at low numbers of searchers, where there is at most a 10 percent difference between the two runs. However, this difference shrinks as more searchers are added, until any difference is hidden by random variation between the runs. Therefore, within the range of charging performance identified, there is not a significant difference.

Searcher properties

We also looked at different searcher properties. Given the publicly available technical specifications on the manufacturer websites for the Bluefin-21 and MBARI AUV, we had to make assumptions about their operational capabilities, including the detection probability of enemy sabotage against the pipeline if the searcher passes over it. In this section, we look at how sensitive the results are to changes to those assumptions.

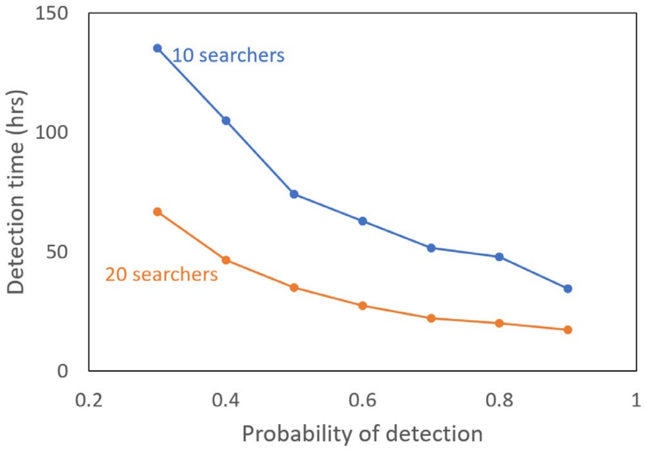
Figure 13 shows detection time for runs using the Bluefin-21 specifications and varying the P_D, with runs with 10 searchers in blue and 20 searchers in orange. Similar to the variation in the number of searchers and nodes, the largest absolute gains come at lower P_D—improving from 0.3 to 0.4 has a greater impact

Figure 12. Detection and report time for different node charging times



Source: CNA.

Figure 13. Detection time versus P_D



Source: CNA.

than improving from 0.8 to 0.9. Conceptually, a P_D of 0.7 implies that 314 hours of total search time are required to “cover” the pipeline once:

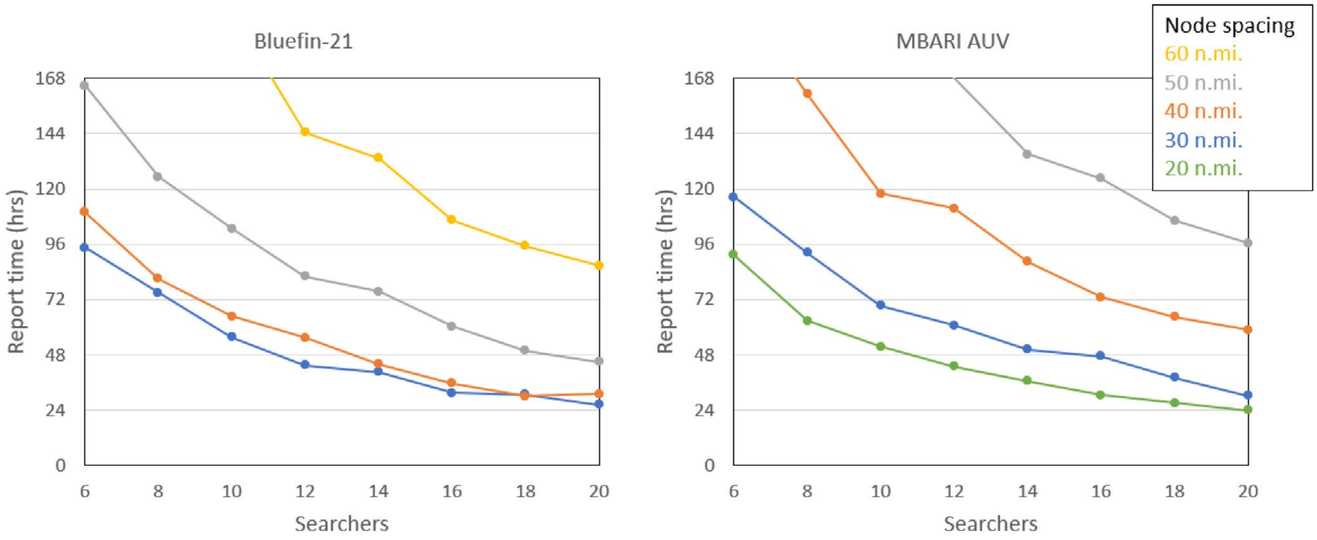
$$search\ time\ required = \frac{length}{search\ speed\ \times\ P_D}$$

Increasing to 0.9 P_D implies 244 hours of search time, and decreasing to 0.3 P_D implies 733 hours of search time. Adding more searchers also mitigates the effect of lower P_D because there are more chances of detecting the target over time.

If we assume the same P_D for the two candidate searchers, the only difference remaining is the battery life. Figure 14 shows the effect of battery life on report time. Note that the node spacings are not all the same between the two—although we did runs with 30-, 40-, and 50-n.mi. node spacings for both, the MBARI AUV’s range did not support a 60-n.mi. node spacing, and we used 20-n.mi. node spacing to demonstrate how a higher node density is required to compensate for a shorter searcher range.

The Bluefin-21’s longer battery life translates to faster MTR across the board under equal conditions, and it could support a lower node density than the MBARI system. For the most searchers and smallest node spacings, this difference is not large (26.4 hours versus 30.4 hours for 20 searchers and 30-n.mi. node spacing). However, at the next step down in node density, the difference is pronounced (31.1 hours versus 58.8 hours for 20 searchers and 40-n.mi. node spacing). The MBARI AUV’s performance with 20-n.mi. node spacing is comparable to the Bluefin-21’s performance with 30-n.mi. node spacing, but 20-n.mi. node spacing requires 35 nodes versus 23 for 30-n.mi. spacing. Therefore, the battery life, and consequently the range of the UUV, is an important driving factor.

Figure 14. Bluefin-21 vs. MBARI AUV report time, 0.7 P_D



25 hrs battery life
(75 n.mi. range)

19 hrs battery life
(57 n.mi. range)

Source: CNA.

Coordinated versus random search

The results in the previous section were all derived from random starting searcher positions, and we did not examine alternative modes of operation such as assigning each searcher a segment of the pipeline or keeping a constant distance between searchers. However, searching in a coordinated fashion versus randomly searching would also cut down on search time.

If we assume that the searchers are coordinated, we can reduce the search problem from the entire pipeline to smaller segments, with endpoints defined by the nodes. Conceptually, the overall hourly P_D for the network would be

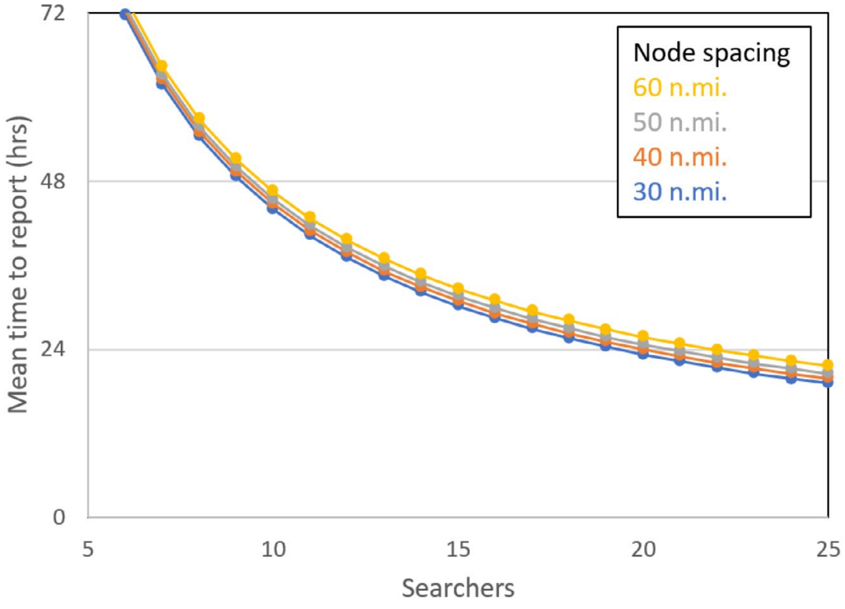
$$hourly\ P_D = fraction\ of\ cycle\ searching \times searchers\ per\ segment \times \frac{searcher\ P_D}{cycle\ time}$$

Where the cycle is defined as the time spent searching plus time spent charging. The MTD would be $1/hourly\ P_D$, and the MTR would be the MTD plus average travel time to a node, or

$$MTR = MTD + \frac{node\ spacing}{2\ \times searcher\ speed}$$

Figure 15 shows the theoretical MTR as a function of the number of searchers using the Bluefin-21 parameters and 0.7 P_D. Note that in the coordinated search, as long as the searcher has enough range to travel between nodes, the node spacing does not affect MTD and affects MTR only after a detection is made and the searcher needs to transit to a node.

Figure 15. Theoretical MTR for coordinated search, Bluefin-21, 0.7 P_D



Source: CNA.

With the coordinated search, it is possible to obtain report times of less than 24 hours with more than 20 searchers and times of less than 48 hours with at least 10 searchers. As noted previously, because the node spacing affects only the time between making a detection and reporting it, the MTR curves for different spacings are separated by constant amounts, with the highest and lowest density curves separated by 5 hours.

Coordinated search also lowers the downside risk significantly, with fewer searchers randomly starting in an unfavorable position. With 21 searchers and 23 nodes, the random search MTR was 23.3 hours, comparable to the coordinated MTR of 22.3 hours. Conversely, the slowest MTR with 6 coordinated searchers is 74.1 hours, compared with an MTR of 354.2 hours in the random scenario. Therefore, the ability to coordinate the searchers would also be an important operational enabler for the network.

CONCLUSION

As the Navy seeks to expand its reach undersea to explore new missions and protect critical infrastructure, undersea networks could increase mission effectiveness by providing communications, power, and sensing data. In this paper, we applied a Monte Carlo model of an undersea network to the real-world example of monitoring the Nord Stream pipeline for sabotage, using open-source candidates for searchers and network nodes, to demonstrate how the model could be used to quantitatively assess the network's value. Our major findings are the following:

- An undersea network of at least 21 UUV searchers and 23 network nodes (30-n. mi. spacing) could discover and report an act of sabotage in less than 24 hours (23.3 hours), assuming random start positions. For different combinations of searchers and nodes (12 to 20 searchers with 23 nodes, 14 to 20 searchers with 18 nodes, 20 searchers with 15 nodes), MTR of less than 48 hours is achievable.
- The ability to coordinate between searchers significantly reduces the effect of node spacing on MTR. MTR for 21 searchers and 23 nodes with coordination is comparable to the random model results at 22.3 hours versus 23.3 hours, respectively, but for 6 searchers and 12 nodes, the coordinated MTR is 74.1 hours and the random model MTR is 354.2 hours.
- For 0.7 P_D, approximately 314 combined search hours are required to "cover" the pipeline once. This time drops to 244 hours for 0.9 P_D and increases to 733 hours for 0.3 P_D. MTR is inversely related to the capability of each searcher, but low individual capability can be compensated for by adding more searchers.
- The numbers of searchers and nodes are both important in the random scenario, with diminishing returns as more of each are added. However, for coordinated search, the node spacing is important only insofar as the searcher's range allows it to travel between nodes. Because different combinations can be viable depending on the desired search time, the specific configuration can be driven by other considerations, such as cost or maintenance. Spacing the nodes at less than half of the searcher's range hedges against the loss of any one node and reduces the time between detection and reporting.
- Within the range we examined, the charging speed of the node was not an important parameter, affecting MTR by 10 percent at most. However, that range was relatively small and short compared to the battery life of the searchers (4 to 8 hours to fully charge a 25-hour battery).

As indicated by the above findings, our undersea network model can be used to analyze real-world situations and has the flexibility to assess the effect of changes in system parameters and employment concepts.

FIGURES

ABBREVIATIONS

AUV	autonomous underwater vehicle
CONOPS	concepts of operations
EEZ	exclusive economic zone
EU	European Union
FY	fiscal year
MBARI	Monterey Bay Aquarium Research Institute
MTD	mean time to detection
MTR	mean time to report
n.mi.	nautical mile
P_D	probability of detection
UUV	unmanned underwater vehicle

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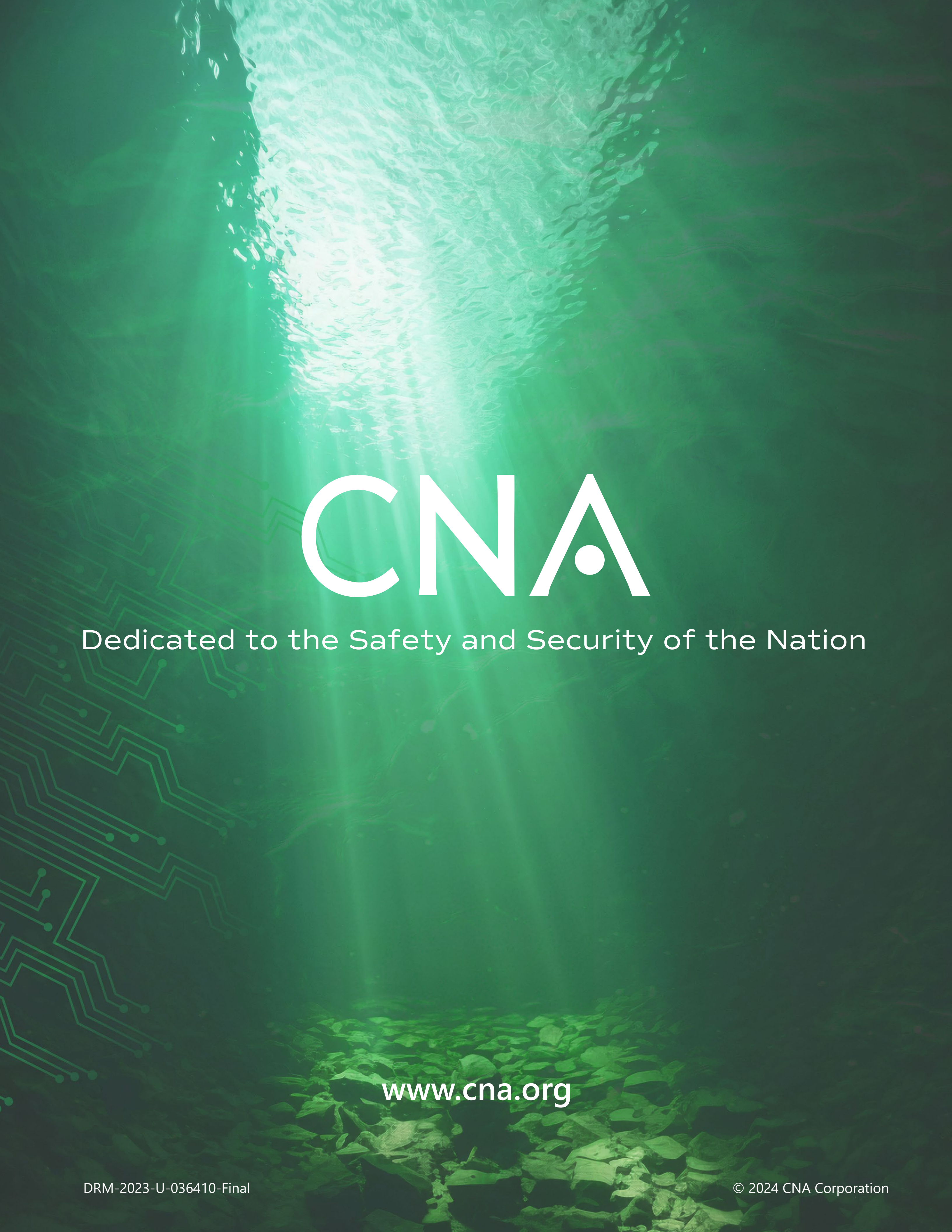

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