NEURAL NETWORK IMPLEMENTATION FOR TORPEDO DESIGN AND OPTIMIZATION

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Clustering neural networks were used to support the concurrent development of engineering design and warfare tactics for revolutionary undersea weapon systems. The analysis identified specific combinations of design and tactical parameters that were required to produce a highly effective military system. The most important result from a virtual product engineering perspective is that the predictive analysis approach directly generated complete system concepts that can be readily grouped in terms of their ultimate military utility. The potential to concurrently evaluate both the engineering and tactical characteristics of the system also provides the design team with the additional insights required to effectively respond to emerging military threats.

Introduction

This paper describes a project performed under the auspices of the Navy's Undersea Weapon Design and Optimization (UWDO) program that investigated the use of commercial business intelligence tools to support the design and optimization of submarine torpedo systems. The UWDO program is a collaborative effort involving industry, academia and government. Sponsored by the Office of Naval Research, the objectives of the program are to:

- Enable the timely development of highly effective, inherently affordable weapon systems through high-fidelity, system-level assessment of emerging technology payoffs/tradeoffs prior to design commitment.
- Provide a foundation for information-based engineering and programmatic decision-making with regards to performance, cost and risk.

CleverPath Predictive Analysis Server, a suite of adaptive pattern recognition tools developed by Computer Associates was employed to analyze notional submarine warfare simulation data. The analysis identified promising combinations of design and tactical parameters hidden within large, complex datasets that were required to produce a highly effective military system. The results indicated that, although building a system that neutralized an enemy submarine was a relatively easy proposition for the scenario described by the simulation, a very specific combination of attributes was required to both neutralize the enemy and survive the battle. Interestingly, the combination of required attributes was counterintuitive, providing new insights for further evaluation.

The Torpedo Design and Optimization Problem

This project focused on the optimization of a notional torpedo system for a single submarine-on-submarine (sub-on-sub) engagement. In this scenario, a submarine carrying a single, highly optimized weapon initiates an attack on a threat submarine. When the threat submarine detects the attack, it returns fire on the aggressor and attempts to evade the incoming weapon. The only advantages afforded the aggressor in this scenario are the characteristics of the weapon it carries and the ability to initiate the attack without detection. In this context, a perfect weapon is one that always hits the opposing submarine (referred to a "kill") and does not result in the loss of the submarine that fired it (referred to as a "counterkill").

In the undersea warfare environment, the military effectiveness of one submarine relative to another can be viewed as a function of the relative capability of the platform/submarine itself and the capabilities of the weapon systems/torpedoes it carries. From an engineering perspective, weapon system design targets are largely a product of the current understanding of the larger system-of-systems within which they will operate. Thus, the interactions between the weapon and its surrounding environment must be continuously re-assessed throughout the development process to ensure the system will ultimately satisfy the overarching needs of the warfighter. The increasing technological complexity of military systems has resulted in an explosion in the number of closely coupled design elements and has challenged many of the established processes that support the translation of mission needs into engineering design guidance.

The military community has historically utilized high-level, Monte Carlo simulations to both guide the development of new systems and assess their ultimate warfighting utility. However, the analysis techniques currently employed to translate the data produced by these simulations into actionable insights are highly resource intensive and, thus, these simulations tend to be used sparingly. This trend towards the sparing use of simulation and analysis is counter to the business need of the military community to develop timely and effective responses to emerging military threats. The development of efficient organizational processes to provide a continuous and proactive analysis capability that promotes the development of effective engineering

responses to emerging military threats is a fundamental business need within the military community.

Rationale for a Predictive Analysis Approach

It is commonly assumed within the undersea weapon design community that the solution to sub-on-sub engagement problem does not favor a single weapon design, but rather, results in several different families of effective weapon systems. Traditionally these families are characterized in terms of a single defining characteristic and are frequently studied in isolation using highly resource intensive excursion analysis techniques. For example, the speed of the torpedo or its stealth may be studied but not the interaction between speed and stealth. Figure 1 depicts the current approach to weapons design.

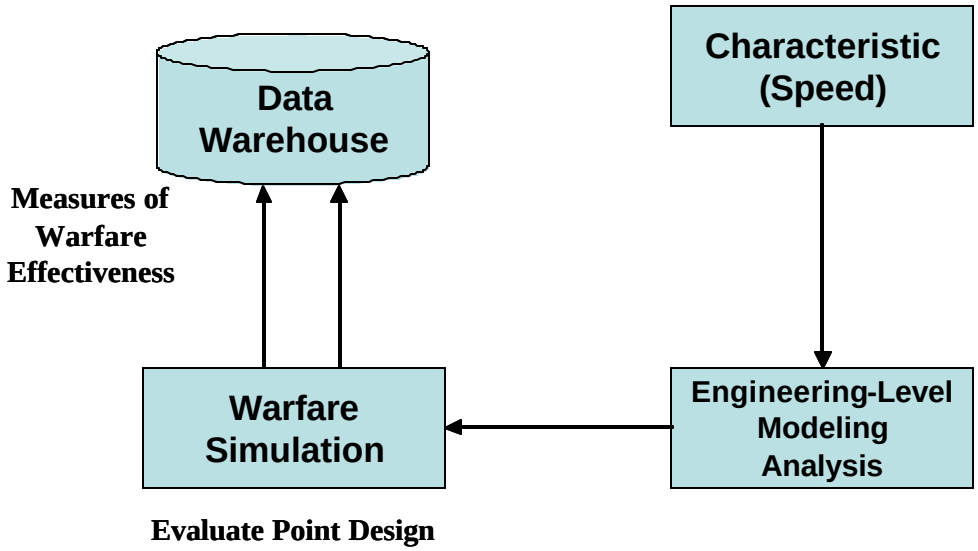

Figure 1. Current Approach to Torpedo Design

This approach provides a high fidelity, performance validation tool for a given design of interest; however, a number of limitations for identifying promising design principles at the conceptual level for analysis are presented. The limitations include:

1. There is a difficulty in handling large number of complex interactions among the various simulation elements.
2. It is a time consuming and resource-intensive process.
3. The problem is defined in terms of a relatively few number of characteristics.
4. The choice of variables to study in isolation is constrained by a reliance on intuitive processes bounded by limited human information processing capabilities.
5. The data asset is much richer than the data that is being used.
6. Hidden relationships exist within the data that may provide key insights to effective weapons design.
7. Interactions among design factors and tactics are left unexplored.

A predictive analysis approach to the design and optimization of torpedo systems addresses the limitations described above. Incorporating advanced adaptive pattern matching algorithms to analyze large amounts of data, predictive analysis identifies inherent relationships in the data and creates reusable intelligent models. The advantages of predictive analysis for the torpedo design and optimization problem include:

1. It finds hidden relationships among variables in very large, complex data sets.
2. It works with datasets that have a large number of highly non-linear interactions.
3. It enables the concurrent assessment of complete system concepts, permitting the incorporation of both design and tactics in the analysis.
4. It may provide results in days/weeks rather than months.

Figure 2 describes the predictive analysis approach. Adaptive pattern recognition tools are used to identify relationships in the data with high potential payoffs for the design of torpedo systems. These high payoff concepts are then forwarded for further intensive analysis using simulations. The results of the simulations are then fed back into the adaptive pattern recognition tool for further refinement and analysis.

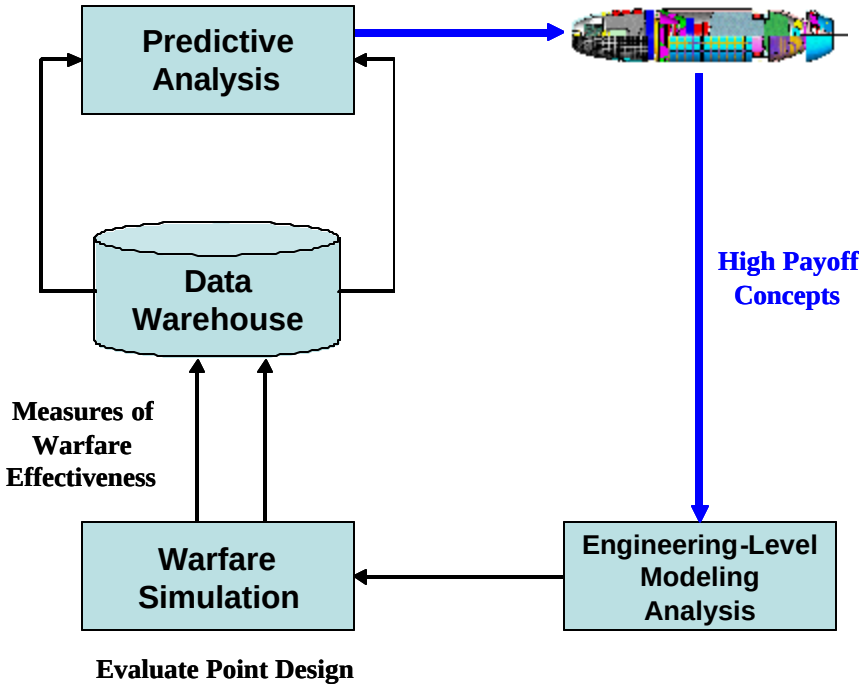

Figure 2. Predictive Analysis Approach

Applying Predictive Analysis

The established goal for the predictive analysis project was to identify relationships among torpedo design factors and warfare tactics that have the greatest utility for submarine warfare. The project utilized three basic elements to achieve these results:

- Generating data.
- Construction of the predictive analysis model.
- Interpretation of the predictive analysis results.

Generating Data

The first tasks were to select a representative set of design and tactical input variables, define the outcome variables and create a submarine warfare simulation. A highly notional submarine-on-submarine engagement simulation was employed to evaluate the performance of candidate weapon systems in an operational setting. The simulation was exercised using various torpedo configurations randomly drawn from the feasible design space and the simulation inputs and outputs were stored in a relational database. All of the data presented in this report is based on the analysis of 4375 simulation runs made with different torpedo configurations. These simulation runs were performed using a probabilistic variant of the publicly distributed, ACEM sub-on-sub engagement simulation.[1]

The simulation between the two rival submarines is symmetric in the sense that each submarine actively seeks to win the battle and each submarine carries a single offensive torpedo. Given that both the design of the weapon and the tactics employed may impact the outcome of the battle, the simulation inputs included both torpedo design and tactical parameters. Thus, the data contain hidden relationships that not only describe the design but also provide guidance for how the system should be used. Figures 3 and 4 describe the torpedo design and tactical parameters.

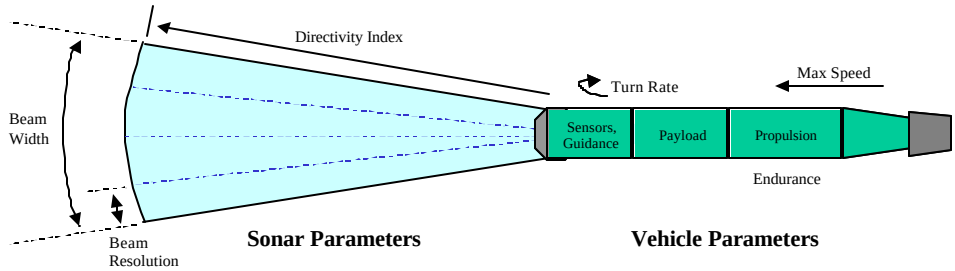

Figure 3. Torpedo Design Parameters

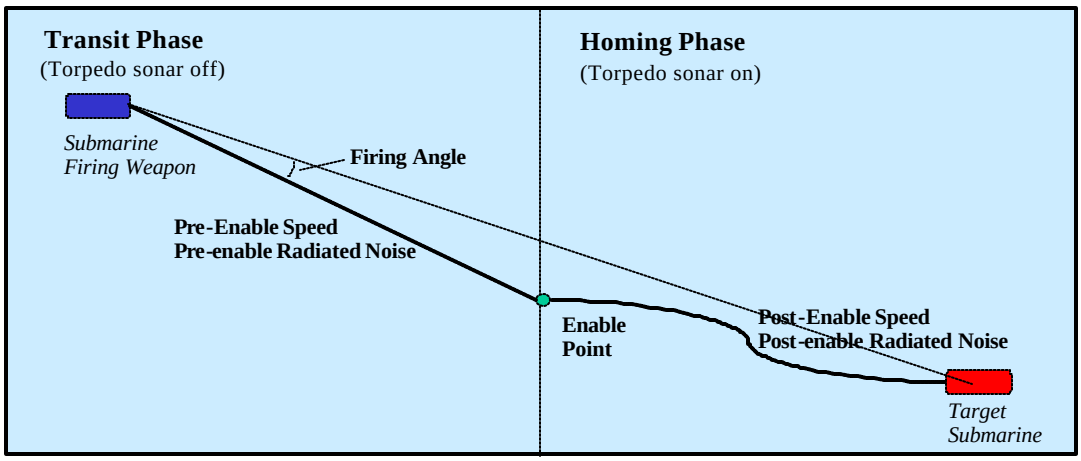

Figure 4. Torpedo Tactical Parameters

Table 1 provides a description of the output variables. The desired outcome is to launch a torpedo and kill the enemy submarine while at the same time escaping being hit by a retaliatory torpedo launched by the enemy.

Table 2 provides a more detailed description of the input variables for the simulation.

Table :1. Sub-on-Sub Engagement Simulation Outputs

	Results	Description	Valid Range	Desired Value
A	Probability of Kill (P_k)	Was opponent's submarine hit?	0 to 1	1
B	Probability of Counterkill (P_{ck})	Was my submarine hit?	0 to 1	0

Table 2. Sub-on-Sub Engagement Simulation Inputs

	Weapon Design Parameters	Description	Torpedo Subsystem
1	Directivity Index	Ability of sensor to differentiate target from noise	Sonar
2	Beam Width	Field of view for sensor system	Sonar
3	Beam Resolution	Ability of sensor system to determine location of target within sonar beam	Sonar
4	Turn Rate	Maximum turn rate	Guidance & Control
5	Firing Angle	Angle of first leg in torpedo run profile relative to target bearing.	Tactics
6	Enable Point	Transition point in run profile from transit phase to homing phase	Tactics
7	Speed (Pre-Enable)	Speed of weapon during transit phase	Tactics
8	Speed (Post-Enable)	Speed of weapon during homing phase	Tactics
9	Radiated Noise (Pre-Enable)	Weapon noise level during transit phase	Propulsion
10	Radiated Noise (Post-Enable)	Weapon noise level during homing phase	Propulsion
11	Endurance	Maximum range for vehicle	Propulsion

Construction of Predictive Analysis Model

Cluster analysis was chosen as the primary predictive analysis tool for the torpedo design project. Cluster analysis employs adaptive pattern recognition algorithms to find patterns or associations among the variables based on the values of those variables within a given dataset. Similar entities are grouped together and dissimilar entities are placed in different groups. A form of classification modeling, cluster analysis may be used to identify the grouping and values of variables for torpedo design that are associated with the desired outcome (kill enemy and escape) and perhaps as important, groupings that are associated with undesired outcomes.

Alternative system concepts were generated through the cluster analysis of the simulation input parameters and the outcome variables. Eight unique clusters were identified for each of following datasets:

1. Randomly generated designs with corresponding P_k information (Design/P_k Clusters)
2. Randomly generated designs with corresponding P_{ck} information (Design/P_{ck} Clusters)
3. Randomly generated designs with corresponding P_k and P_{ck} information (Design/P_k/P_{ck} Clusters)

The preliminary analysis of the data involved interpreting the cluster analysis outputs within the torpedo design context. To aid in the analysis, a simple Visual Basic tool was developed to support user interrogation of the outputs and the depiction of that output in visual terms.

Interpretation of Predictive Analysis Results

The most important result from a virtual product engineering perspective is that the predictive analysis approach directly generated complete system concepts that can be readily grouped in terms of their ultimate military utility. Having an unbiased evaluation of the combinations of attributes that will produce either effective or ineffective systems enables the product development organization to gain new perspectives on existing problems and to counter the ever-increasing complexity of the challenges they face. The potential to currently evaluate both the engineering and tactical characteristics of the system also provides the design team with the additional insights required to effectively respond to emerging military threats.

The results contained five clusters that each correspond to an alternative system that performs better than the ACEM baseline system in terms of both the P_k and P_{ck} metrics. The predictive analysis results were validated using additional ACEM simulation runs.

Analyzing the "good" clusters suggested that constructing a weapon that meets all the desired objectives requires the careful combination of several different design attributes. For example, intuitively, one would expect that quieter and faster the torpedo the better. A quiet torpedo is more difficult for an enemy submarine to detect and a faster torpedo gives the enemy less time to evade. Although all five clusters contained systems that were quieter and faster than the baseline system, none of these systems were either the fastest or the quietest system evaluated. Therefore, the effect of torpedo speed and stealth on the outcome is also dependent upon the values of the other variables.

Given the interactions present in the variables, a noisier torpedo in combination with the other factors produced a better result. This suggests that predictive analysis may have the potential to identify the degree to which a variable must be present in combination with other variables to improve the overall military utility of the system. This is an important result because the traditional approach isolates one variable and identifies a fixed value for that variable that is recommended to be best over all conditions. Predictive analysis has the potential to suggest varying degrees of a factor dependent on the values of the other variables. This may allow the designers to loosen the design constraints making it easier and less costly to incorporate design guidelines into the weapon system.

A noteworthy result stemmed from the fact that the combination of variables in the "good" cluster contained an interaction that was counterintuitive. Upon reflection, the counterintuitive result was interpreted to provide a key insight into possible high payoff torpedo design concepts. This insight may not have been possible, given the more traditional approach of focusing in on one design variable at a time for intensive analysis.

Focus of Current Research

The power of predictive analysis to identify interactions among design and tactical variables in complex simulation settings has significant potential to contribute to the conceptual understanding of torpedo design. Preliminary analysis suggests that several of system concepts identified by the cluster analysis exhibit non-traditional operational characteristics that warrant further investigation. Currently work is being conducted in the area of advanced visualization to augment the current predictive analysis process with interactive simulation and cluster analysis capabilities. Future research is also planned related to multi-weapon and multi-mission warfare scenarios.

Conclusions

The capability to proactively identify the defining characteristics of both effective and ineffective system alternatives is essential to the success of any research and development organization. In the undersea weapon community, decades of intensive analysis efforts have produced a broad range of system alternatives that are known to be effective given current mission parameters. However, in this era of evolving military threats and rapidly changing technologies, the ability to efficiently support the continuous identification of high-payoff, next generation system alternatives to guide technology investment decisions has never been more critical. Current practices have demonstrated their value at looking at specific concepts in great detail but have proven problematic in identifying new concepts for consideration. This project has demonstrated the potential for predictive analysis to contribute to the design and optimization of underwater weapon warfare by identifying high payoff concepts for serious consideration in the design process. More specifically, predictive analysis:

- Identified specific combinations of design and tactical parameters that were required to produce a highly effective military system.
- Discovered counter intuitive relationships hidden in the data.
- Generated high payoff system concepts for further analysis.
- Enabled a number of simulations to be conducted without having to design a specific simulation for each problem.

Combined with current practices, predictive analysis can augment the capabilities of the research and design effort for underwater weapons systems.

References

1. ACEM Sub-on-Sub Engagement Simulation, Computer Source Code, Naval Undersea Warfare Center (NUWC) Simulation Based Design (SBD) Laboratory, http://sbd.npt.nuwc.navy.mil/acem.