A Method to Optimize Ship Maneuvers for the Coordination of Hardkill and Softkill Weapons within a Frigate

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Abstract

The coordination of anti-air warfare hardkill and softkill weapon systems is an important aspect of command and control for a Frigate. Since the effectiveness of a particular weapon varies depending on the orientation of the Frigate with respect to the threats faced, a key element of the coordination process is to maneuver the Frigate to most effectively use all the weapons available. This paper shows that the environment surrounding the Frigate can be divided into six fundamental sectors for weapon engagement. The method to determine the general effectiveness of each sector for the threats faced is shown. A naï ve Bayes method that determines the optimal positioning of the Frigate to most effectively use the hardkill and softkill weapons is presented. Also discussed are the different types of planners that were investigated for planning engagements for the hardkill and softkill weapon systems. Preliminary results comparing and rating these planners are shown, both with and without the recommended maneuvers.

1. Introduction

The Combat System of a typical Frigate includes anti-air warfare (AAW) weapon systems for hardkill and softkill. Increasing complexity in threat technology, and increasing speed and diversity in open-ocean and littoral threat scenarios makes efficient and effective planning for weapons resources more and more difficult. To counter these problems, research is ongoing to design and implement resource management decision aids, based on intelligent agent technology and techniques for multi-agent coordination, to perform and coordinate AAW hardkill and softkill planning for a Frigate. A key element of the coordination process is determining ownship maneuvers that optimize the use of both hardkill and softkill weapons.

With hardkill and softkill weapon systems that act "independently", both negative and positive interactions may occur between them. These interactions often occur unexpectedly and without being totally understood. Their origin can generally be traced back to a lack of consideration during the design phase of the implications of the integration of these weapon systems with each other and with other (possibly future) systems [Thé, 1995].

It is very important to take control of unexpected or uncontrolled interactions that can make sensor and weapon performance uncertain. In fact, even positive interactions are not necessarily advantageous if there is a lack of knowledge of how to exploit them. This paper presents a description of the possible interactions between hardkill and softkill determined by considering the effective areas of individual weapons as well as their overlapping regions. The negative and positive interactions between hardkill and softkill are identified, an evaluation is provided of the impact of such interactions, and a determination is made to optimize weapon effectiveness.

In light of these results, it is then possible to maneuver the Frigate in order to position it so that it offers the most effective combination of hardkill and softkill weapons to deal with threats.

2. AAW Hardkill and Softkill Systems for a Typical Frigate

The AAW hardkill weapons are weapons that are directed to intercept a threat and actively destroy it through direct impact or explosive detonation in the proximity of the threat. The range of different types of hardkill weapons varies, and the effectiveness of these weapons depends on a variety of factors, like distance to the threat, type of threat, speed of the threat, environment, etc. The AAW hardkill weapons for a typical Frigate include surface-to air missiles (SAMs) that have the greatest range, an intermediate range Gun, and a Close-In Weapons System (CIWS) that is a short-range, rapid-fire gun. Closely allied to these weapons are two Separate Tracking and Illuminating Radars (STIRs) that are used to guide a SAM to a threat, and to point the Gun. This effectively provides two concurrent fire channels for the AAW hardkill weapons. The CIWS has its own pointing radar.

The AAW softkill weapons use techniques to deceive or disorient a threat to cause the threat to destroy itself, or at least lose its fix on its intended victim. Again, the range and effectiveness of these weapons varies considerably. The AAW softkill weapons for a typical Frigate include chaff and jamming systems. The chaff system launches a shell that produces a burst at a designated position. The resultant chaff cloud has a significant radar cross-section that can be used to screen the Frigate or produce an alternate target on which a radar-guided threat can fix. The jamming system uses electromagnetic emissions to confuse the threat's sensors to cause the threat to either lose its fix on its intended target, or to improperly assess the position of its target.

Due to their different mechanisms, the hardkill and softkill weapons have historically led independent existences in terms of design and operational deployment. Generally, the hardkill and softkill weapons are supervised by separate control personnel. Thus, the complex task of optimally combining the two weapon types falls squarely on the shoulders of the person responsible for overall air defense. The inherent differences between hardkill and softkill weapons, and the nature of their deployment history on typical Frigates, lead naturally to a representation of hardkill and softkill as two software agents that each determine an anytime plan for their resources and that coordinate plans between them.

The exact nature of the specifications and capabilities of the various AAW hardkill and softkill weapons on real Frigates is obviously very complex, and much of that information is Classified. To avoid this issue, and in order to maintain emphasis on the research interests and not be burdened by the complexity and fidelity of the representation of hardkill and softkill, a considerably simplified model of the relevant AAW hardkill and softkill weapons was used. This model is a simple, non-classified version of AAW hardkill and softkill for a typical Frigate. The results could eventually be applied to the Canadian HALIFAX Class Frigate. The details of the model for hardkill can be found in [Blodgett et al., 1998]. The model for softkill is described in more detail in section 4.2.

3. Determination of the Effective and Overlapping Areas (or Sectors) of Individual Weapons

The determination of the effective areas of individual weapons and their overlapping areas can be done in terms of the angles that discriminate the different engagement capabilities of hardkill and softkill weapons.

3.1 *Engagement Possibilities for Hardkill Weapons*

Figure 1 shows the various angles that discriminate the different engagement capabilities of the hardkill weapons. These angles are also described below.

- **SAM**: It has no blind zones for launching. For threats within range of the SAM and STIR, the two STIRs can separately guide a SAM to threats from 0 to 30 degrees, 150 to 210 degrees, and 330 to 360 degrees (where 0 degrees is directly left of the Frigate).
- **GUN**: It has a blind zone of ±35 degrees while looking to the back of the Frigate. Otherwise, the ability to do targeting of the Gun with a STIR follows the same rules as the SAM for STIR availability.
- **CIWS**: It has a blind zone of ±15 degrees while looking to the front of the Frigate.

All other angles are defined as the “Normal” state for hardkill weapons, where for threats within the range of the weapons, at any one time one STIR is available for a SAM and a GUN engagement, and the CIWS can engage a target.

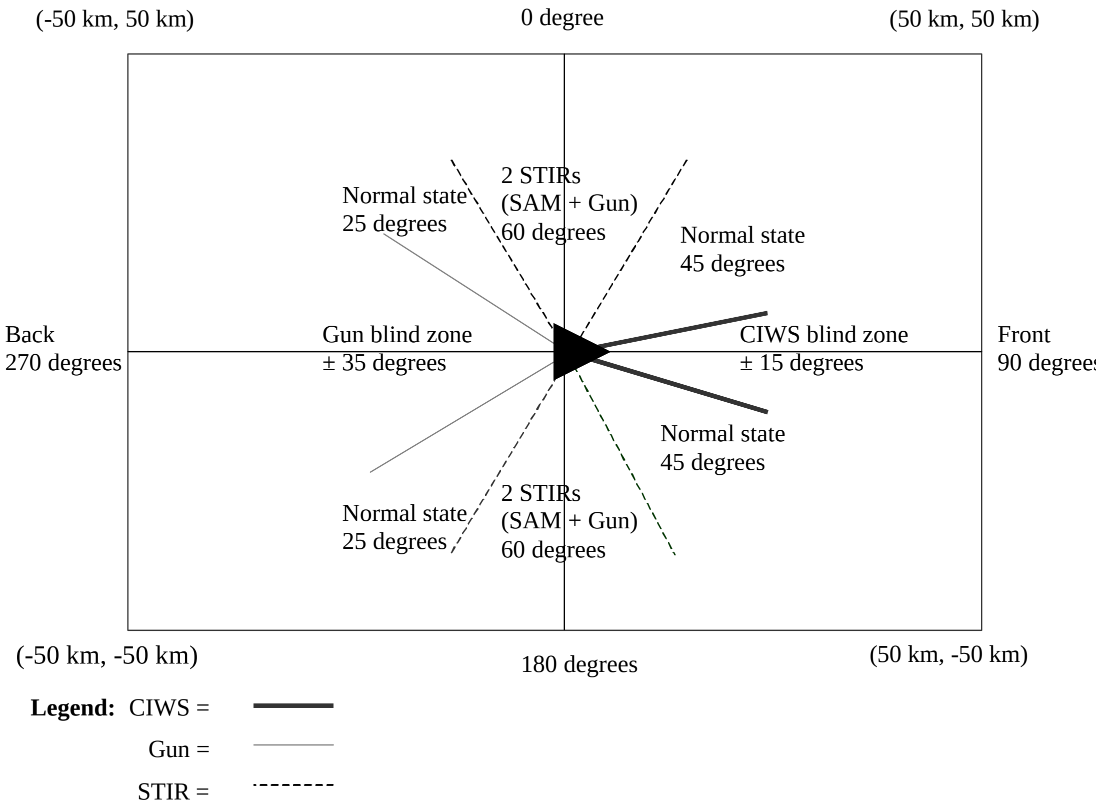

Figure 1: Engagement possibilities for the hardkill weapons.

3.2 *Engagement Possibilities for Softkill Weapons*

Figure 2 shows the various angles that discriminate the different engagement capabilities of the softkill weapons. These angles are also described below.

- **JAMMING:** Either of two antennas can be used for jamming on threats within range (and hence two different jamming engagements are possible) at ±10 degrees, both to the front and to the back of the Frigate.
- **CHAFF:** Chaff can be used in any direction when needed, and so will not directly influence the orientation of the Frigate.

All other angles are defined as the “Normal” state for softkill weapons, where at any one time there is one possible jamming engagement, and chaff is available.

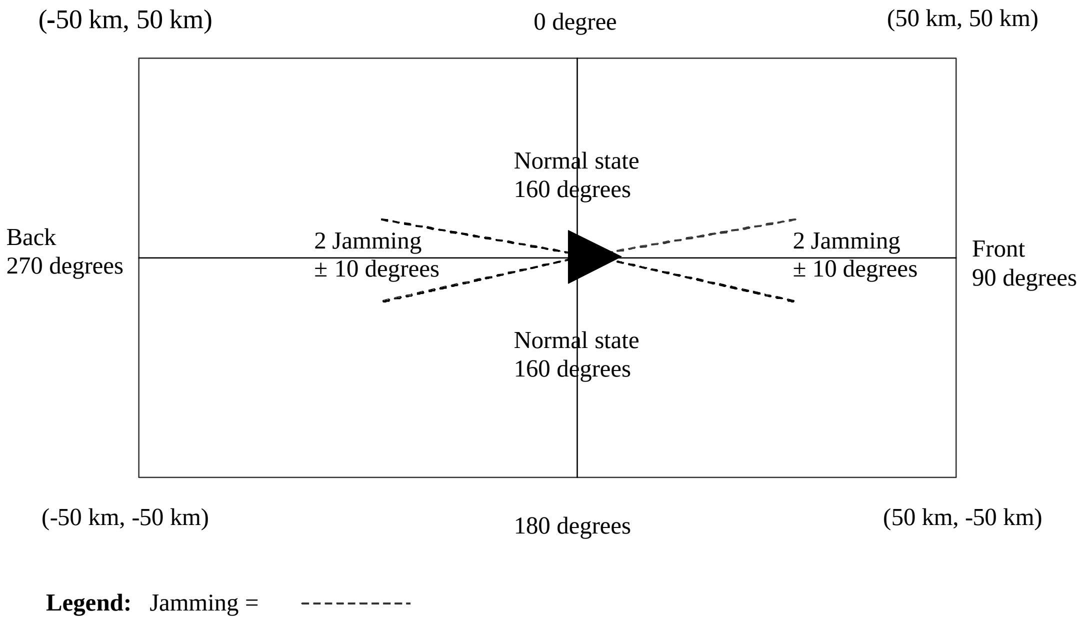

Figure 2: Engagement possibilities for the softkill weapons.

3.3 *Some Considerations for Movement of the Frigate*

It is important to understand the Frigate's capabilities for movement in order to build plans that incorporate movement of the Frigate. Obviously, these plans must call for realistic maneuvers for the Frigate to be able to implement them.

As a guideline, it is assumed that it takes at least a minute to turn the Frigate by 180 degrees. It is extremely probable that such a maneuver will not be necessary because the various zones that will influence the displacement of the Frigate are quasi-symmetrical. On the other hand, the Frigate does not merely rotate on a point when it turns. Again as a guideline, it is assumed that the Frigate turns by moving through an arc with a turning radius of 270 meters. Appropriate fractions of these numbers are used when turns are smaller.

3.4 *Effective Sectors for Hardkill and Softkill Weapon Engagements*

To find the optimal positioning of the Frigate, the environment can be divided into twelve sectors surrounding the Frigate based on the hardkill and softkill engagement possibilities shown in Figures 1 and 2. These sectors will have to move along with the Frigate, and maintain the same relative orientation to the Frigate. Table 1 describes these twelve distinct sectors, showing the angular coverage of a sector and the difference in the weapon engagement capabilities of a sector compared to the Normal state. The Normal state at any one time has one STIR available for a SAM and a Gun engagement, the CIWS able to engage threats, one possible jamming engagement, and chaff available.

Sector	Angles Covered	Difference from Normal State
A	330 to 30 degrees	One additional STIR
B	30 to 75 degrees	No difference
C	75 to 80 degrees	No CIWS
D	80 to 100 degrees	No CIWS, but one additional jamming engagement possible
E	100 to 105 degrees	No CIWS
F	105 to 150 degrees	No difference
G	150 to 210 degrees	One additional STIR
H	210 to 235 degrees	No difference
I	235 to 260 degrees	No Gun
J	260 to 280 degrees	No Gun, but one additional jamming engagement possible
K	280 to 305 degrees	No Gun
L	305 to 330 degrees	No difference

Table 1: Description of the effective sectors for hardkill and softkill weapon engagements**.**

All the sectors in Table 1 that have the same state (as indicated in the "Difference from Normal State" column), can be amalgamated to form a new representation of the sectors:

New Sector 1 = Sector A + Sector G
New Sector 2 = Sector B + Sector F + Sector H + Sector L
New Sector 3 = Sector C + Sector E
New Sector 4 = Sector D
New Sector 5 = Sector I + Sector K
New Sector 6 = Sector J

This establishes six distinct sectors, for which a series of tests were conducted to determine their respective effectiveness. The effectiveness of each sector was determined using varying numbers of threats at short, intermediate and long ranges, under various planning modes of defense. The effectiveness was specified as the probability to kill a threat in a sector. With these measures of effectiveness for the various sectors, it was possible to estimate the optimal positioning of the Frigate using the Bayesian method discussed in section 5.2.

4. Coordinating Hardkill and Softkill Planners

The next step is to consider possible hardkill/softkill interactions. As per [Malone and Crowston, 1994], coordination is generally viewed as the management of interactions. Dealing with hardkill/ softkill interactions is therefore a problem of coordination between the hardkill weapons system planning and the softkill weapons system planning (each represented by separate planning agents). When faced with one or several threats, these agents plan the use of the weapon resources of the Frigate for countering the threat(s). Planning weapon resources in this context means allocating and scheduling the deployment of the Frigate's weapon resources against threats with a precise order to the intervention times. The hardkill and softkill planning agents were implemented according to the simplified model of hardkill and softkill for the Frigate discussed above.

This investigation into coordinating the use of hardkill and softkill weapons used independent planners for the hardkill and softkill weapons systems. These planners had the following capabilities:

- They make *timely* responses in a changing world. This was the most critical consideration for this particular application.
- They *react to changes* in the environment.
- They exhibit *robust behavior* in dynamic, unpredictable environments.
- They do not require rich world models, and thus *can function in the presence of uncertainty and incomplete knowledge,* as is the case for this application.
- They do not need to simplify the search space, which often introduces unrealistic static world assumptions.

4.1 *Hardkill Weapons System Planning*

For the hardkill weapons system, two very different types of planners were investigated: Partly planner, and Holistic planner.

4.1.1 *Partly Planner*

The Partly planner uses very low-level reasoning techniques for a simple response to a situation to give a very short reaction time. This is very important in our context because defending Frigates brings a very hard and usually very short time constraint.

For this planning mode, the hardkill agent maintains a list of threats moving towards the Frigate. This list is sorted (from the most to the least dangerous threat) according to some form of threat evaluation. For this implementation, threat evaluation considers only the closest point of approach (CPA) of the threat to the Frigate, and the time for the threat to reach CPA. Then, the hardkill agent applies some predefined rules for allocating the resources. These predefined rules are: i) Allocate a SAM and the Gun to the most dangerous threat; ii) Allocate a SAM to the second most dangerous threat; iii) Allocate the CIWS to all threats (one at a time) that enter into the CIWS's range. The first two rules are inspired by the fact that there are only two STIRs available, which must be used in conjunction with the SAMs and the Gun.

Though these rules are simple, they allow using all available resources in an efficient way. Unfortunately, the SAMs and the Gun are only allocated at a given point in time to the two most dangerous threats, and all others in the list (if any) are not considered by this specific planner (this is why it is called "Partly"). In the case where a kill assessment indicates that a hostile threat has been destroyed, the resources that have been allocated to this threat become available for the next most dangerous threat in the list.

4.1.2 *Holistic Planner*

This planner views all the detected threats constituting a complex organization surrounding the Frigate. It works as follows. A decision tree is first produced that explicitly considers, in a probabilistic manner, all possible outcomes of a particular action. Such a tree reflects in fact a plan with different conditional branches. The conditional branches permit taking into account the results of actions. For instance, during the plan execution, one should follow one branch or another depending on the result of an engagement to some threat *x*. If this engagement has succeeded, then one continues the plan by following a branch where one does not consider the threat *x* anymore. If the engagement has failed, then one pursues a branch where other engagements are planned for *x*. All these conditional branches reflect in fact contingent plans and are very important in the sense that engagements to threats are uncertain. Notice that without conditional branches, the time horizon of the plan would be very limited, and it would be necessary to re-plan each time that an engagement fails. The latter can take a long time, thus causing problems for the subsequent threat engagements.

4.2 *Softkill Weapons System Planning*

The softkill weapons system planning is accomplished by a softkill agent. This agent manages two types of resources, jamming and chaff. In this application, there are two jammers and four chaff launchers. Jammers can act on two threats each. Starting from these considerations, the softkill agent elaborates a Partly planner. To do that, it starts from the list of threats attacking the Frigate (sorted by order of importance, from the most to the least dangerous) and then applies a simple rule which consists of allocating jamming and chaff in order to the four most dangerous threats.

During an attack, jamming and chaff must act concurrently and in a complementary way. First, jamming is used to break the threat's radar lock on the Frigate. Once the missile has lost its target, jamming creates a false target position on the threat's radar. Then chaff is deployed at a position consistent with the false one provided by the jammer. In this way, the threat's radar locks onto the chaff cloud as its new target.

4.3 *Methods of Coordination of Hardkill/Softkill*

There are many ways to coordinate the hardkill and softkill agents. For instance, a Central Coordinator can be used that merges two separate plans after receiving them from each agent. If there are some negative interactions between the planned actions, it will modify the plans to eliminate these negative interactions, or if not possible, it will try to reduce their effects.

Another option is to use a direct method where agents communicate with each other and try to coordinate their actions. In this case, communications can be used for commitments and convention as suggested by [Jennings, 1994], and they can be used for synchronizing plans and conflict solving.

A third method might be a kind of whiteboard (a common data space) in which the hardkill and softkill agents will construct a coordinated plan by some successive refinements. In this case, the coordination will be implicit because they will work on the same plan.

Similar to the whiteboard is the mediator, which in fact plays the role of a Central Coordinator with the possibility of communication and negotiation with softkill and hardkill agents on synchronizing plans and conflict resolution.

The method that uses communications for commitments and conventions, the whiteboard method, and the mediator approach all seem to be time consuming, and consequently they can probably decrease the ultimate success of the plan for our time critical application. For this reason, the initial investigation is for a Central Coordinator that does not use communication between agents, and for which the coordination process is only based on some simple rules.

5. Determining Frigate Maneuvers

It is important to have a robust method to modify the positioning of the Frigate. It is not simply a matter of adding an engagement to the current plan when it has been determined that there is an advantage to maneuvering the Frigate to add such an engagement. Indeed, it is possible that the movement of the Frigate to support a new engagement could lead to a reduction in the probability of survival of the Frigate. There are two primary concerns:

- An engagement may be impossible to use in the plan currently being developed. For example, the Frigate could be moved to support a new jamming engagement, but a previously planned CIWS engagement may no longer be feasible (because the target would now be out of range or at the wrong angle).
- The movement of the Frigate could suddenly terminate an engagement currently in action. For example, suppose a SAM is already in-flight to a target. If the proposed movement of the Frigate puts the SAM in a blind zone of the STIR that guides it before the “kill assessment” can be carried out, the SAM engagement will not be successful.

Both of these situations must be addressed before moving the Frigate to add a new engagement. In the following subsections, they will be. A general algorithm for positioning the Frigate will be presented, along with the Bayesian method that can be used to find the optimal (i.e., non-conflicting) position of the Frigate.

5.1 *Method and Algorithms*

Liang [Liang, 1995] suggests four regions of effectiveness for a Frigate: i) a region where both hardkill and softkill are effective; ii) a region where only hardkill is effective; iii) a region where only softkill is effective; and iv) a region where neither hardkill nor softkill is effective.

Understandably, the defense system will try to have the maximum number of targets in the “both effective” area and as few as possible in the “neither effective” area. Although it increases the chance of weapon interaction, it is in the first case that the Frigate will have the most chance of survival. A complex and effective method is proposed here that considers these facts. The method does not try to position the Frigate in order to have the maximum number of threats in one or the other effective areas and the minimum in the blind zones. Instead, the method will maximize the average probability of killing all threats, by moving the Frigate to the optimal position.

To determine appropriate Frigate manoeuvres, a learning module is used. The construction of the learning module is another problem that requires some thinking. A fundamental issue is how to assure that the chosen positioning is the optimal solution. Firstly, at the time of learning, a technique is used that supposes that the Frigate turns at a infinite speed. It will be necessary to make this assumption to avoid falling into local optima, in other words, to depend on the current position of the Frigate to choose the next one. It is very probable that the Frigate will not have time to effect a turn of 180 degrees to defend itself, but if the Frigate had been elsewhere, it may have been likely more able to make the move. The objective then is to find the optimal position for the Frigate at the time of learning according to certain threats.

The algorithm used to find the optimal position of the Frigate follows:

```
while doing the Hardkill plan
    if we can't use a weapon because of the positioning of the Frigate
        if we have the time to move to use the weapon
            Memorize the engagement
        else
            Do nothing
        end
    end
end
send to the Mediator the Hardkill plan and all the memorized engagements that
could be executed if we moved the Frigate

while doing the Softkill plan
    if we can't use a weapon because of the positioning of the Frigate
        if we have the time to move to use the weapon
            Memorize the engagement
        else
            Do nothing
        end
    end
end

send to the Mediator the Softkill plan and all the memorized engagements that
could be executed if we moved the Frigate

Once all plans from hardkill and softkill agents have been received and
merged, the Mediator tries various positioning combinations according to a
Bayesian method
end
```

The last point of this algorithm is now examined in more detail in section 5.2.

5.2 *Naïve Bayes Classifier*

A particular position for the Frigate is chosen over another using the Bayesian method. This method has been adopted because:

- It provides a solution for the evaluation of the position of the Frigate in the forms of probabilities. Thus, each position of Frigate will have its own chances of success and therefore it will be easier to compare the effectiveness of each suggested position.
- Under certain conditions, it provides a solution that is comparable to neural networks or a decision tree.

Bayes theorem states:

$$P(h|D) = P(D|h) \cdot P(h) / P(D) \qquad \textbf{(5.1)}$$

where $P(h)$ is the initial probability that hypothesis h is true before having observed the training data, $P(D)$ is the probability that given training data D is observed, $P(D|h)$ is the probability to observe data D when hypothesis h is true, and $P(h|D)$ is the probability that h is true according to observed training data D. The maximum a posteriori (MAP) hypothesis, which is the assumption that has the highest probability $P(h|D)$ after having observed the data, is given by [Russell and Norvig, 1995]:

$$h_{MAP} = \underset{h \in H}{argmax}\ P(D|h) \cdot P(h) \qquad \textbf{(5.2)}$$

The method of naïve Bayes classification is used to find the optimal position of the Frigate. This method is known as "naïve" because it is based on the simplifying assumption that the attributes' values are conditionally independent given the target value. Whenever this assumption is satisfied, the naïve Bayes classification is similar to the MAP classification. Therefore, the hypothesis that has the strongest chance to be true a posteriori is obtained. Mathematically, this assumption is translated by supposing that the probability to observe the conjunction $a_1, a_2, \ldots, a_n$ is only the product of the individual attributes' probabilities:

$$P(a_1, a_2 \ldots a_n \mid v_j) = \prod_i P(a_i|v_j) \qquad \textbf{(5.3)}$$

It should be noted that a means attribute and v means value. What is needed is the attribute couple that maximizes the value of an assumption h coming from a group of hypotheses H. The Naïve Bayes classifier gives:

$$v_{NB} = \underset{v_j \in V}{argmax}\ P(v_j) \prod_i P(a_i|v_j) \qquad \textbf{(5.4)}$$

In this equation, v_{NB} denotes the target value output by the naïve Bayes classifier. In this method, the number of distinct $P(a_i|v_i)$ terms that must be estimated from the training data is just the number of distinct attribute values multiplied by the number of distinct target values.

Our experiments show that this method is appropriate for the determination of the optimal position that the Frigate must have when it is attacked by one or more anti-ship missiles (ASMs). In our specific application, the terms of equation 5.4 are as follows:

- V is the set of possible positions that the Frigate can take as proposed by the hardkill and softkill planning algorithms;

- *P(v_j)* is the number of times that a position was retained compared to the ensemble of the possible positions *V*. At the time of learning, the threats come at a random direction towards the Frigate. So, the probability that a threat comes from a certain angle is the same that it has from another angle. Thus, this term can be considered as a constant and by this fact, ignored.
- *P(a_i|v_i)* represents the probability of the Frigate defending itself from a certain threat when the Frigate is at a certain position. *P(ASM #2 | 15 degrees) = .85* means that the Frigate has an 85% of chance to survive to missile #2 when it is at the 15 degrees position. The probability of survival is given by the learning module. Table 2 shows a situation with five threats, evaluated for different Frigate orientation angles, and indicating the product probability for surviving all threats.

	Proposed Positions				
Threat	**30 degrees**	**105 degrees**	**210 degrees**	**235 degrees**	**330 degrees**
#1	0.90	0.88	0.90	0.85	0.88
#2	0.95	0.91	0.78	0.89	0.90
#3	0.88	0.89	0.75	0.92	0.96
#4	0.77	0.83	0.86	0.97	0.98
#5	0.90	0.92	0.98	0.95	0.79
Product Prob.	0.52	0.62	0.44	**0.64**	0.59

Table 2: *P(a_i|v_i)* for each threat when the Frigate has different orientation angles.

Thus, the highest overall survival probability is 0.64, i.e., the Frigate orientation angle of 235 degrees is "ideal" for the Frigate to face these threats. So for this method to give a MAP hypothesis, it is necessary that different attribute values (a_j), which are the ranges of the observed ASMs from the Frigate, are conditionally independent, given the target value (v_j), which is a position of the Frigate. Therefore, it is necessary that the various ASM angles are independent from the positioning of the Frigate a priori. This is obviously the case because initially, there was no Frigate movement, so the ASM angles don't *directly* affect Frigate positioning. In the method described here, the ASMs are in relation to their respective sectors and not to each other.

6. Results

Each sector was tested with five different scenarios for each case of from 1 to 15 threats (a total of 75 scenarios per sector). Both planning modes were used. Table 3 shows the total number of instances of an ASM reaching the Frigate during all the tests, by sector, for the two different planning modes. The final column in Table 3 shows ó/N for each planning mode, where ó is the standard deviation of the number of instances in each of the sectors, and N is the total number of instances in all the sectors.

Planner Mode	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	ó/N
Partly Planner	70	104	139	119	81	72	0.0478
Holistic Planner	24	67	89	60	63	58	0.0581

Table 3: Instances of an ASM reaching the Frigate, by sector, for the two planning modes**.**

Table 4 summarizes the total number of instances where an ASM reaches the Frigate during the tests for the two planning modes, with and without using positioning of the Frigate:

	Partly Planner	Holistic Planner
Instances of ASM reaching the Frigate without positioning	85	82
Instances of ASM reaching the Frigate with positioning	77	59
Improvement using positioning	10%	39%

Table 4: Instances of an ASM reaching the Frigate, with and without Frigate positioning, for the two planning modes.

7. Discussion

The differences in the success rates of the different planning modes in preventing ASMs from reaching the Frigate can be attributed to two primary factors.

The first factor is whether the plan takes into consideration all the visible threats. Under the Partly mode, there is no re-planning of an existing plan to counter a threat when a new threat is detected. The Holistic planning mode offers a plan for all visible threats. It is important to have a view of all incoming threats to choose the optimal position of the Frigate. In contrast, under the Partly mode, the Frigate will have a good position to face only a fraction of the threats, and evidently this “partial view” is less effective.

The second factor deals with the standard deviation for the six different sectors. The greater the standard deviation between the different sectors for a given planning mode, the greater will be the percentage of improvement of using the positioning of the Frigate for that particular mode. For example, the worst case would be when the six sectors all have the same effectiveness, so that the re-positioning of the Frigate would have little improvement. But if there are sectors that are better than others, the Frigate will position itself to face the majority of the incoming threats in these sectors, thereby improving the defense success. The proportional standard deviations for each planning mode are shown in Table 3. It can be seen that the Holistic mode has the highest standard deviation. So, this factor helps the Holistic mode to improve the success of defense of the Frigate by using maneuvering.

Table 5 summarizes the differences in these primary factors between the planning modes. The Holistic planner mode is better in both primary factors, which is why the percentage of improvement (shown in Table 4) for this mode is better than the improvement of the Partly planner mode.

	Partly Planner	**Holistic Planner**
Planner uses all visible threats	No	Yes
Standard deviation	Low	High

Table 5: Summary of the differences between the two planning modes.

8 Conclusion and Future Work

The effectiveness of the Frigate's weapons varies depending on the orientation of the Frigate with respect to the threats faced. A key element of the coordination of hardkill and softkill weapon systems is to maneuver the Frigate to most effectively use all these weapons. In section 3.4, it is shown that the environment surrounding the Frigate can be divided into six fundamental sectors for weapon engagement, and these sectors are defined. The method to determine the general effectiveness of each sector for the threats faced is shown. A naï ve Bayes method that determines the optimal positioning of the Frigate to most effectively use the hardkill and softkill weapons is presented in section 5.2. Also discussed are two very different types of planners that were investigated for planning engagements for the hardkill and softkill weapon systems. Preliminary results comparing and rating these planners are shown in section 6, both with and without the recommended maneuvers.

Many follow-on studies to this investigation are planned. More complex weapon and threat models will be used to provide a more realistic test environment. Further enhancements will be made to the hardkill and softkill planners, particularly in regard to expanding capabilities while maintaining real-time performance. New constraints will be added to the coordination of hardkill and softkill, like minimizing the radar cross-section of the Frigate that is exposed to threats against which softkill has been used. Finally, the coordination method will be expanded to include other weapon systems (e.g., anti-submarine warfare) and multiple platforms.

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